# MEDIUM VOLTAGE INDUSTRIAL VARIABLE SPEED DRIVES

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***Abstract* – This study presents different technologies and topologies of medium-voltage (MV) drives available on the market. The paper describes the advantages and disadvantages of each configuration and the impact in the quality of energy in the mains and motor sides when using them is also analyzed. Technical requirements and practical considerations for end users and system designers are identified for a proper selection in this field.**

**In addition, results of experimental tests are presented using a Neutral Point Clamped High Voltage IGBTs (NPC-HV-IGBTs) on a Voltage Source Inverter (VSI) operating in three different control modes: Volts/Hertz, Closed Loop Vector Sensorless and Closed Loop Vector with encoder. These results are shown with the intention of analyzing the performance of this topology.**

***Keywords* - Medium Voltage Variable Speed Drives (MV VSDs) - Energy Quality - NPC-HV-IGBT Voltage Source Inverter.**

## I. INTRODUCTION

Due to technology advancements in semiconductor devices such as insulated gate bipolar transistors (IGBTs), modern medium voltage (MV) drives are increasingly used in petrochemical, mining, steel and metal, transportation industries among others to conserve electric energy, increase productivity and improve product quality. The development of MV drives was also motivated by the proved improvement in the efficiency, weight and volume of the motor and in the reduced installation costs in cabling, cable trays etc.

Available MV drives cover power ratings from 0.4 MW to 40 MW at the medium-voltage level of 2.3 kV to 13.8 kV. The power rating can be extended to 100 MW where synchronous motor drives with load commutated inverters are often used. However, most of the installed MV drives are in the 1 to 4 MW range with voltage ratings from 3.3 kV to 6.6 kV.

The high power MV drives have found widespread applications in industry. They are used for pipeline pumps in the petrochemical industry, fans in the cement industry, pumps in water pumping stations, traction applications in the transportation industry, steel rolling mills in the metal industry and other applications. Market research has shown that around 85% of the total installed drives are for pumps, fans, compressors and conveyors where the drive system might not require high dynamic performance.

Induction motors are also being used extensively in applications requiring fast and accurate control of speed and position using a technology known as Vector Control.

A dynamic response at least equivalent to that of a DC motor can be achieved. It is widely known that induction motors are simpler in structure than other motors: they are more robust, more reliable and require little maintenance. The induction motor is fed by a drive that provides an instantaneously controlled set of phase currents that form the stator space vector current which consists of two components: the first is the magnetizing current which is controlled to have constant magnitude to maintain constant rotor flux linkage and the second is the torque current which is instantaneously controlled to be proportional to the demand torque. Once the inverter can supply instantaneous stator currents meeting these two requirements, the motor is capable of responding without time delay to a demand for torque. This feature, along with the relatively low rotor inertia of induction motors, makes this drive system attractive for high-performance control systems.

One of the major markets for the MV drive is for retrofit applications. Researches show that 97% of the currently installed MV motors operate at a fixed speed and only 3% of them are controlled by variable speed drives. When fans or pumps are driven by a fixed-speed motor, the control of air or liquid flow is normally achieved by conventional mechanical methods such as throttling control, inlet dampers and flow control valves which result in a substantial amount of energy loss.

Depending on the system requirements and the type of the converters employed, the line- and motor-side filters are optional. A phase shifting transformer with multiple secondary windings is often used mainly for the reduction of line current distortion. The rectifier converts the AC utility supply to a DC level with a fixed or adjustable magnitude. The commonly used rectifier topologies include multipulse diode rectifiers, multipulse SCR rectifiers or pulse-width-modulated (PWM) rectifiers. The DC filter can simply be a capacitor that provides a stiff DC voltage in voltage source drives or an inductor that smoothes the DC current in current source drives.

The inverter can generally be classified into voltage source inverter (VSI) and current source inverter (CSI). The VSI converts the DC voltage to a three-phase AC voltage with adjustable magnitude and frequency whereas the CSI converts the DC current to an adjustable three-phase AC current. A deep treatment of High Power Converters and AC Drives is available in [1] which was the base for this introduction section.

Figure 1 shows a generic functional block of a MV VSD. In the next sections, the line side and motor side characteristics and requirements are discussed.

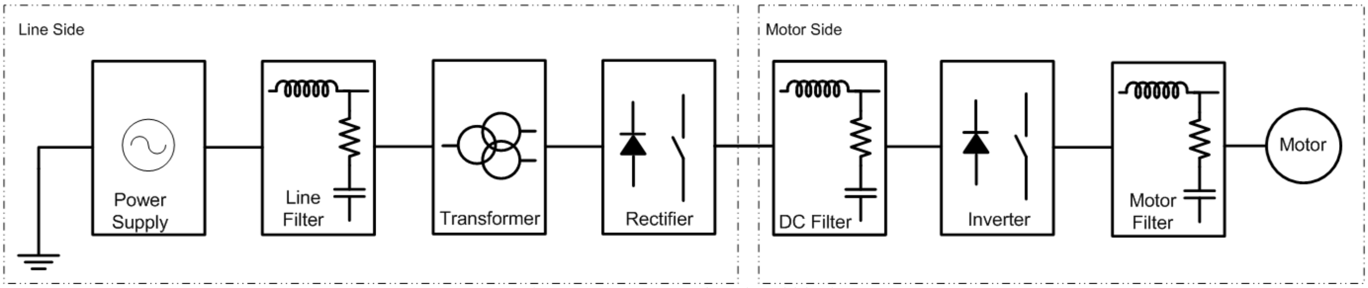


Figure 1 – MV VSD functional blocks

## II. LINE-SIDE

MV VSDs have a semiconductor-based bridge at input. This bridge may draw distorted current that can pollute the power supply and reduce the power factor due to the harmonics components.

There are several problems for the loads connected to a polluted utility supply:

- ***Capacitors***: increase in temperature, increase in losses, life time reduction, over-voltage, over-current and dielectric rupture;
- ***Motors*****:** increase in temperature, increase in noise, life time reduction, efficiency reduction, bearing and bushing damage and torque cogging;
- ***Fuses / Circuit Breakers / Disconnecting Switches:*** improper operation;
- ***Transformers*****:** increase in temperature, increase in iron and copper loss and life time reduction;
- ***Meters*****:** measurement errors;
- ***Installation*****:** neutral over-heating in installations and power factor reduction;
- ***Electronic Equipment***: operational fault;
- ***Cables*****:** increase in losses caused by the higher effective current value.

There are guidelines for harmonic regulation such as the IEEE STD 519 recommendations [4]. In several low voltage applications, the 6 pulse variable frequency drive with an input line reactor or a DC reactor may perfectly meet these recommendations. When it is not enough, some techniques can be used to reduce the harmonic currents such as:

- Passive tuned and active filters;
- Multipulse configuration: increasing the number of pulses of the input rectifier using 12, 18, 24 pulses or more;
- Active-front-end rectifier also called regenerative drive or PWM rectifier.

If passive filters are connected at the input of the MV drive the LC circuit may be excited by the harmonic voltages already present due to the other non-linear loads connected in the utility power supply. Because the utility power supply at the Medium Voltage level may have low line resistance, the LC resonant circuits may not be sufficiently damped and oscillations and overvoltages may occur. This may destroy the rectifier components. Active filters are not usual in MV applications because they need to operate in high switching frequency and the losses are prohibitive.

In the industry, the term *multipulse*, when related to VSDs, means the association, in series or in parallel, of 6 pulse three-phase rectifiers normally with diodes and the use of phase shifting transformers to feed the rectifiers [2,3,5]. The fundamental idea of the multipulse configuration can be understood as the interconnection of 6 pulse rectifiers so that the characteristic harmonics generated by these rectifiers are cancelled by the harmonics generated by other sets of rectifiers. This mitigation is performed by the appropriate design of the phase shifting transformer with multiple secondaries. The harmonics of the 6 pulse rectifier that are present on the secondary of the transformer will be cancelled and will not appear at the primary of the transformer that is connected to the utility. In a multipulse rectifier, the generated characteristic harmonics are given by:

$$h = P.n \pm 1 \tag{1}$$

Where:

n - is an integer (1, 2, 3, 4, ....∞).
h - is the harmonic order.
P - is the number of pulses of the rectifier.

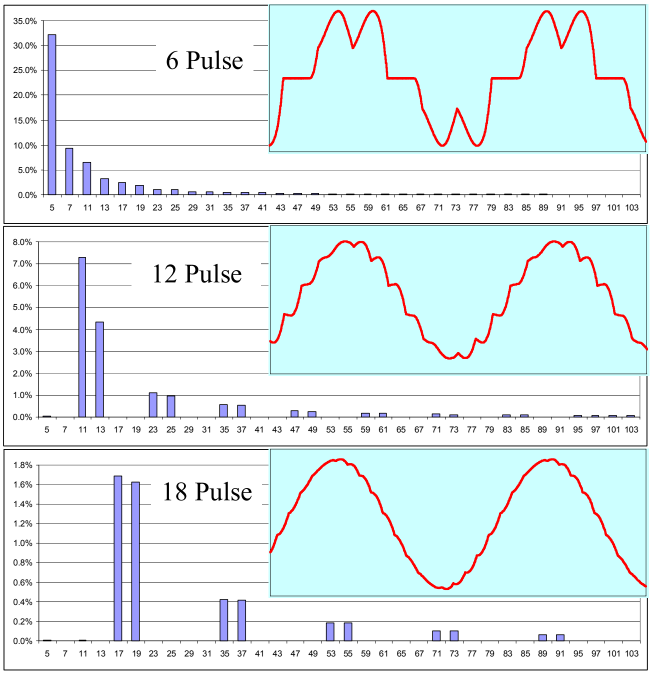
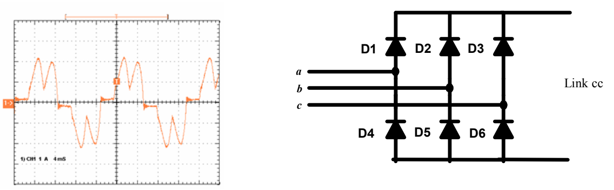


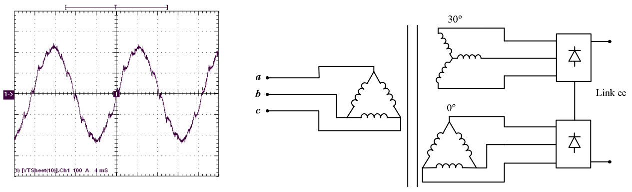
Figure 2 – Typical waveforms of currents at mains and characteristic harmonics for 6/12/18 pulse diode rectifiers.

Figure 2 shows the typical waveforms of currents at mains and characteristic harmonics for 6/12/18 pulse diode rectifiers. Experimental measurements were conducted on commercial drives according to the diagrams of figure 3 and the total harmonic distortion of the input current (THDi) measured was: 36 % for a 6-pulse rectifier with AC line reactance sized to produce around 4% of voltage drop, 8,5 % for a 12 pulse rectifier fed by a transformer with 2 secondaries in delta/wye connection and 4,5 % for a 18 pulse rectifier fed by a transformer with 3 secondaries in delta/delta, delta/+20° delta, delta/-20° delta connection. Both phase shifting transformers had around 6 % of per unit impedance.

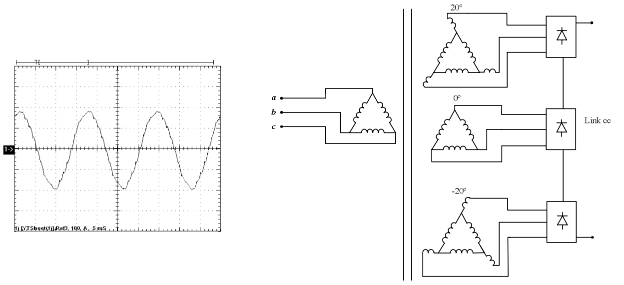
Some practical aspects related to the transformer should be considered: there are some residual non-characteristic harmonics like 5th and 7th in 12 and 18 pulse topologies. It is due to the non-ideal behavior of the transformer which causes angle phase errors. These harmonics are not perfectly canceled in the primary and this affects the expected result. Also, an already existing presence of voltage distortion on the power electric system may increase the values of these non-characteristic harmonics.



a) 6-pulse rectifier.



b) 12-pulse rectifier with delta/wye transformer.



c) 18-pulse rectifier with delta/delta, delta/+20° delta, delta/-20° delta transformer.

Figure 3 – Measured input current of different multipulse diode rectifiers at primary of the phase shifting transformers.
TEST SETUP: WEG

The number of pulses at the input rectifier defines the harmonic spectrum of the current at the primary of the phase shifting transformer. The total harmonic distortion of the current, the power capacity of the plant and its impedance will be the factors involved in the total harmonic distortion of the voltage (THDv) at the point of common coupling (PCC). Theoretically, the higher the number of pulses, the lower the harmonic content. It only works well if the system and the transformer are balanced. A transformer for 12 or 18 pulses is extremely easy to design and manufacture. For higher number of pulses the design becomes more complex and the results, in terms of harmonics, are not so perfect. In [3] a study case shows that it is possible to meet all IEEE STD 519 requirements with an 18 pulse diode rectifier.

Some industrial MV drives have 24/36/72 or more pulses at the input rectifier but the main reason for that is not related with the harmonics issues. The reason is that they are using low voltage power cells in series or cascade connection at the inverter section and they have to supply each power cell separately, so they use a transformer with more isolated secondaries. A disadvantage for this strategy is that the transformer must be located close to the VSD because the voltage drops and the excessive number of cables and connections. The costs involved for cooling and space requirements should be considered in this case.

The phase shifting transformer should be designed to allow the additional losses introduced by the input rectifier harmonic currents. Application related specifications should also be followed, as shown below:

*transformer type (oil filled, dry); installation site (indoor, outdoor); pollution degree, enclosure protection degree; altitude; ventilation (natural, forced); cable entry (top, bottom); primary/secondary connections (flanged, cable, bus bar, and position); primary protection system (fuse, relay); insulation class; temperature rise; ambient temperature; winding material (copper, aluminum); oil/winding temperature sensor/indication; over temperature protection, standards; noise level; maximum size/weight; lifting lugs; etc.*

*Transformer-less* MV-VSD topologies require: special insulation on the motor due to high common mode voltage stress or the use of an input inductor which has approximately the same impedance as an input transformer. Also, higher insulation and overvoltage capability is required for the VSD components because there is no galvanic separation from the network.

The SCR is a thyristor-based device with three terminals: gate, anode and cathode. It can be turned on by applying a pulse of positive gate current with a short duration provided that it is forward-biased. Once the SCR is turned on, it is latched on. The device can be turned off by applying a negative anode current produced by its power circuit. Multipulse diode rectifiers are normally used in voltage source inverter (VSI) fed drives while the multipulse SCR rectifiers are mainly for current source inverter (CSI) based drives. The SCR rectifier provides an adjustable DC current for the CSI which converts the DC current to a three-phase PWM AC current with variable frequencies. The power flow in the SCR rectifier is bidirectional which also enables the CSI drive to operate in four quadrants. SCR rectifiers have to use gatedriver circuits which increase the risk of fault in drive components. Another disadvantage is related to the input power factor which varies greatly with the firing angle which is a function of the load.

Diodes, SCRs and others switching devices are often connected in series with the intention of achieving the required medium voltage levels. Series connected devices may not have identical static and dynamic behavior so they may not share the total voltage in steady-state or switching-state. Sometimes RC snubber networks are necessary to enable proper voltage equalization. This solution may affect the reliability and the global efficiency of the system.

Replacing the diode or SCR rectifier bridge for turn-on / turn-off controlled switches it is possible to implement an active-front-end (AFE) converter also called regenerative converter, which can also be used to reduce the harmonic components of the input current. However, the obtained THD with these converters is close to an 18 pulse solution. Active front-end converters are more suitable for applications where motor repetitive braking is needed and the economy obtained, regenerating the energy back to the power supply, justifies the investment of this solution.

## III. MOTOR-SIDE

In the same way that the best current waveform drained from the network by any equipment should be sinusoidal, the best voltage and current provided by the VSD to the motor is always the sine wave.

After the rectification process the energy is available in the DC link capacitors for voltage source inverters or in the DC link inductors for current source inverters. The semiconductor devices of the inverter bridge have the function to take this energy in DC mode and deliver it to the induction motor in an AC mode, as sinusoidal as possible. The control of the speed is made by controlling the frequency of the fundamental component of this AC waveform.

In voltage source inverters (VSIs), semiconductor devices switching at fast frequency may produce high *dv/dt* levels at the motor terminals. The cables to connect VFD output to motor terminals have their own inductance, capacitance and resistance. These parameters are variable depending on the length and geometry of the cable. Due to this RLC circuit characteristic, each edge of these rectangular pulses will produce a voltage overshoot at the motor terminals. This overshoot will settle down at the DC link level after some ringing cycles. The VFD switching frequency and topology, which means the power devices arrangement, also affect the behavior of the motor voltage. The effects of this repetitive overshoot combined with the *dv/dt* rates and the common mode voltage can cause insulation stress in the motor winding and shaft / bearing currents that can reduce the motor life expectancy.

The switching action of the rectifier and inverter normally generates common-mode voltages. The common-mode voltages are essentially zero-sequence voltages superimposed with switching noise. If not mitigated, they will appear on the neutral of the stator winding with respect to ground which should be zero when the motor is powered by a three-phase balanced utility supply. Furthermore, the motor line-to-ground voltage, which should be equal to the motor line-to-neutral (phase) voltage, can be substantially increased due to the common-mode voltages. This leads to the premature failure of the motor winding insulation system. As a consequence, the motor life expectancy is shortened. It is worth noting that the common-mode voltages are generated by the rectification and inversion process of the converters. This phenomenon is different from the high *dv*/*dt* caused by the switching transients of the high speed switches. It should be further noted that the common-mode voltage issue is often ignored in the low-voltage drives. This is partially due to the conservative design of the insulation system for low-voltage motors. In the MV drives, the motor should not be subject to any common-mode voltages. Otherwise, the replacement of the damaged motor would be very costly in addition to the loss of production.

For the MV drives with a motor-side filter capacitor, the capacitor forms an LC resonant circuit with the motor inductances. The resonant mode of the LC circuit may be excited by the harmonic voltages or currents produced by the inverter. Although the motor winding resistances may provide some damping, this problem should be addressed at the design stage of the drive

Torsional vibrations may occur in the MV drive due to the large inertias of the motor and its mechanical load. The drive system may vary from a simple two-inertia system consisting of only the motor and the load inertias to very complex systems such as a steel rolling-mill drive with more than 20 inertias. The torsional vibrations may be excited when the natural frequency of the mechanical system is coincident with the frequency of torque pulsations caused by distorted motor currents. Excessive torsional vibrations can result in broken shafts and couplings and also cause damages to the other mechanical components in the system.

The device switching loss accounts for a significant amount of the total power loss in the MV drive. The switching loss minimization can lead to a reduction in the operating cost when the drive is commissioned. The physical size and manufacturing cost of the drive can also be reduced due to the reduced cooling requirements for the switching devices. The other reason for limiting the switching frequency is related to the device thermal resistance that may prevent efficient heat transfer from the device to its heatsink. In practice, the device switching frequency is normally around 200 Hz for GTOs and 500 Hz for IGBTs and SGCTs. The reduction of switching frequency generally causes an increase in harmonic distortion of the line-side and motor-side waveforms of the drive. Efforts should be made to minimize the waveform distortion with limited switching frequencies.

To meet the motor-side challenges, a variety of inverter topologies can be adopted for the MV drive. Figure 4 summarizes the main industrial medium voltage topologies and their characteristics. Four per-phase VSI diagrams are presented: the conventional 2-level inverter; the 3/5-level neutral-point clamped (NPC) inverter; the 7-level cascaded H-bridge inverter and the 7-level flying-capacitor inverter. One current source inverter (CSI) topology diagram is also presented. The VSI inverter topologies normally use IGBTs or IGCT as switching device while CSIs use SGCTs or thyristors.

These different arrangements and combinations of the switching devices define the topology of the inverter bridge. The challenge is to bring the best waveform to the motor with reduced number of components guarantying high reliability and efficiency complying with the medium voltage requirements.

Figure 4a shows a topology known as ***2-level-VSI*** with components in series connection aiming to meet the adequate voltage balancing for each component. Due to the inherent characteristics of the components, the voltage equalization must be guarantied with special gatedrivers and passive voltage equalization techniques. The drawbacks of this topology are associated with the reliability because the higher number of electronic components used by the gatedrivers and with the efficiency because the passive components used for the voltage equalization are power resistors and have energy losses. The *2-level-VSI* inverter is a simple converter topology and has an easy PWM modulation scheme. However, the inverter produces high $dv/dt$ and THD in its output voltage and, therefore, often requires a large-size LC filter installed at its output terminals. Figure 4a1 shows its typical voltage waveform. With a 2-level inverter topology the motor voltage has 3 level steps.

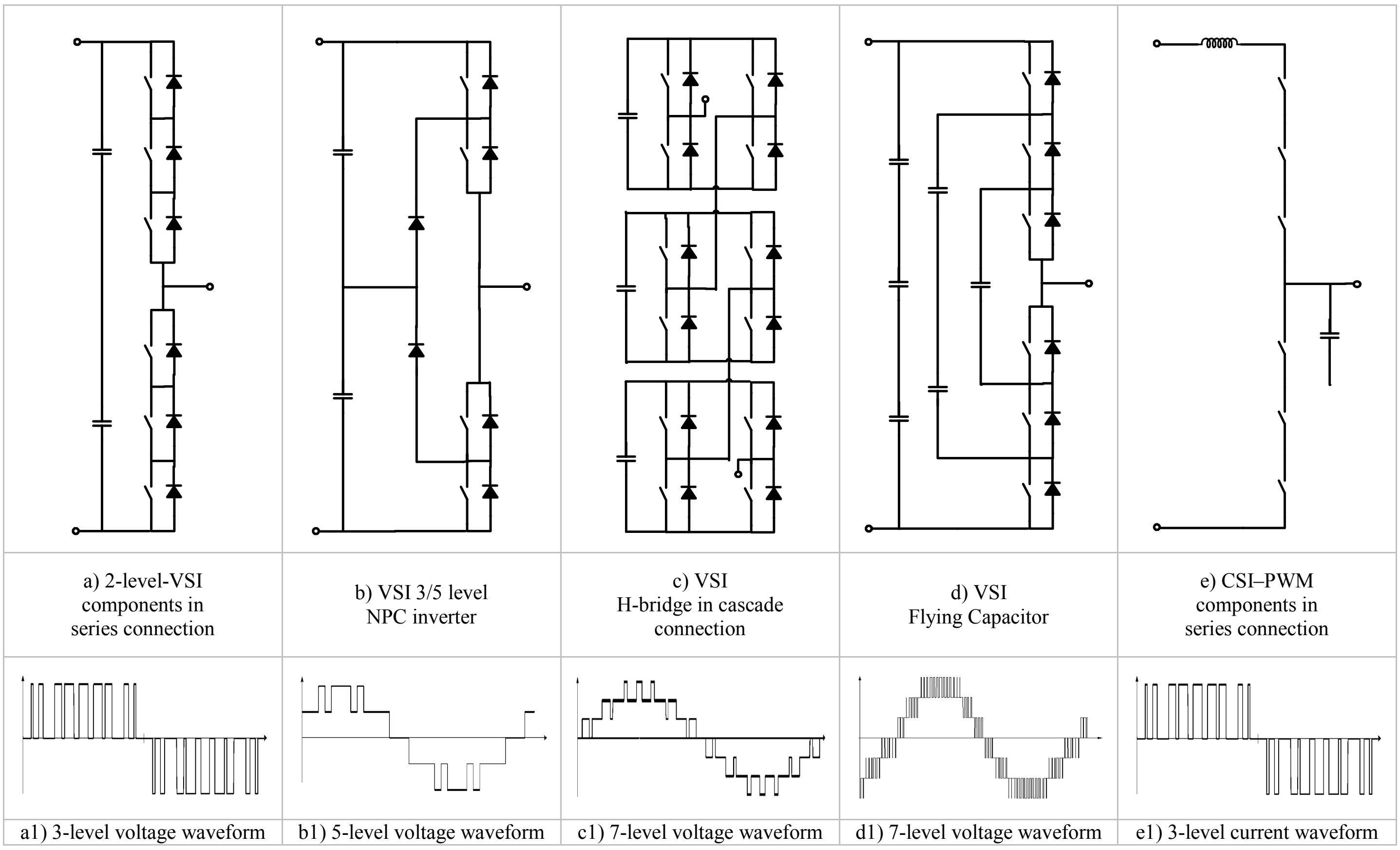
A ***Neutral Point Clamped (NPC)*** multilevel topology is shown in figure 4b. It employs clamping diodes and cascaded DC capacitors connected to the floating neutral point. It produces AC voltage waveforms with multiple levels as shown in figure 4b1. The inverter can be configured as three, four or five-level topology. The higher the level steps, the higher the number of switching devices. The NPC inverter shown in figure 4b produces three level voltages between each phase to neutral point and five level voltages between phase to phase at motor terminals. This topology is suitable for motors rated up to 4.16 kV with standard 6.5 kV semiconductors. It is possible to increase the voltage to 6.9 kV connecting two NPC legs in an H-bridge form. In this configuration the phase to neutral voltage contains five voltage levels and nine levels at motor terminals. The main features of the NPC inverter include reduced $dv/dt$ and THD in its AC output voltages in comparison to the *2-level-VSI* topology. This inverter can be used in MV drives to reach a certain voltage level without switching devices in series connection. Thus, the efficiency levels can reach 99%. The switching frequency should be as low as possible due to the power losses and it is usually limited to a few hundred hertz. Normally, special modulation techniques are needed to produce the minimum harmonic distortion in the motor current in all range of speed and torque. In some applications the floating neutral point requires control of voltage deviation.

A ***7–level VSI H-bridge*** in cascade connection is shown in figure 4c. It is composed of multiple units of single-phase H-bridge power cells. The H-bridge cells are normally connected in cascade on their AC side to achieve medium voltage level and low harmonic distortion as shown in figure 4c1. The number of power cells is determined by its operating voltage. Some industrial MV drives use this topology implemented with low voltage semiconductors and electrolytic capacitors. In this case, because of low reliability, redundant power cells should be installed. In case of failure, the faulty power cells can be bypassed and the drive can resume operation at reduced capacity with the remaining cells. The repair work must be fast once the bypass of defective cells may cause three-phase unbalanced operation for the motor. The power cells require isolated DC supplies that are obtained from a multipulse diode rectifier employing a phase shifting transformer which is normally complex and expensive. In most cases, this transformer should be installed close to the drive and the losses of this transformer will go into the electrical room which needs extra air conditioning.

Figures 4d and 4d1 show a typical configuration of a ***7-level flying-capacitor*** inverter and its waveform. It is also a VSI topology which produces the voltage waveforms with reduced $dv/dt$ and THD. However, this topology has the drawback of the large number of DC capacitors with separate pre-charge circuits and the complex capacitor voltage balancing control. The DC capacitor voltages in the inverter vary with the operating conditions. To avoid the problems caused by the DC voltage deviation, the voltages on the flying capacitors should be strongly controlled and this has impact on the complexity of the modulation and control technique.

The voltage source inverter produces a defined three-phase PWM voltage waveform for the load while the current source inverter ***(CSI)*** outputs a defined PWM current waveform. The current source inverter features simple converter topology with motor-friendly waveforms. There are two types of current source inverters commonly used in the MV drive: PWM inverters and load-commutated inverter (LCI). The PWM inverter uses switching devices with self-extinguishable capability like SGCTs. The load-commutated inverter employs SCR thyristors whose commutation is assisted by the load with a leading power factor. The LCI topology is particularly suitable for very large synchronous motor drives with a power rating up to 100 MW. The PWM current waveform supplied by the inverter (Figure 4e1) is filtered by the capacitors installed at the inverter output, as shown in figure 4e, and the load current and voltage waveforms are close to sinusoidal. Thus, the high $dv/dt$ problem associated with the VSI does not exist in the CSI. This topology uses an inductor in the DC link instead of capacitors, therefore the output current cannot be changed instantaneously during transients. This reduces the system dynamic performance. The CSI needs an adjustable DC current which is normally provided by a SCR rectifier which makes the input power factor dependant of the motor current. Another possibility is the use of a PWM current source rectifier which enables the regenerative operation. However, it also needs an input capacitor filter that may cause LC resonances and affect the input power factor of the rectifier as well.

The inverter topologies presented in this section are deeply studied in ref [1]. The user should take into consideration the advantages and disadvantages of each topology depending on the application, motor requirements and system efficiency. Some experimental tests with a 3/5-level Neutral Point Clamped (3/5 level NPC) topology are presented in the next section



a) 2-level-VSI components in series connection

b) VSI 3/5 level NPC inverter

c) VSI H-bridge in cascade connection

d) VSI Flying Capacitor

e) CSI–PWM components in series connection

a1) 3-level voltage waveform

b1) 5-level voltage waveform

c1) 7-level voltage waveform

d1) 7-level voltage waveform

e1) 3-level current waveform

Figure 4 – MV industrial VSI and CSI topologies (per-phase diagrams) and output waveforms

## IV. EXPERIMENTAL TESTS

The performance of a 3/5-level Neutral Point Clamped (3/5 level NPC) inverter was tested with a 4 pole, 1.8 MW, 4.16 kV medium voltage motor which was coupled to a dynamometer. The test setup is shown in figure 5 and some experimental results obtained are presented in this section. Figure 6 shows the measured phase to inverter neutral point voltages and the phase to phase voltage applied to the motor terminals. The drive was operating in the Volts/Hertz mode control [7] and the motor was under rated load. Despite the few number of pulses, which means low switching frequency, the motor current is almost sinusoidal due to the optimal pulse pattern strategy.

Some specific applications such as steel mills and conveyors require high dynamic performance and closed loop vector sensorless or closed loop vector with encoder control strategies are necessary [7]. The 3/5 level NPC inverter can provide this performance. Figure 7a shows the response of the drive to a speed reference step. The red curve is the torque signal, the blue and pink curves are the signals of the motor currents and the green curve is the speed signal. The system formed by the 1.8 MW motor coupled to the dynamometer was accelerated from zero to 1800 rpm in 4 seconds with an instantaneous torque response.

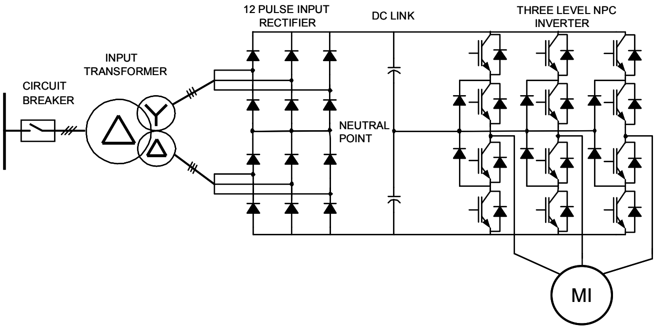
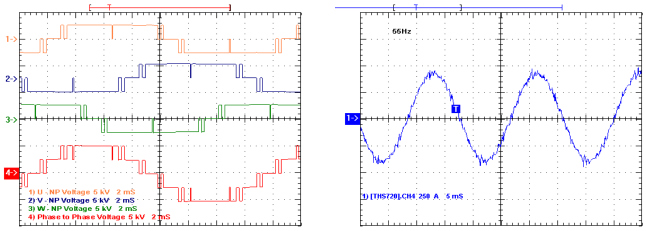


Figure 5 – MV VSD test setup: circuit breaker, 12 pulse phase shifting transformer and rectifier, 3/5 level NPC inverter, 1.8 MW / 4.16 kV motor coupled to a dynamometer (TEST SETUP: WEG)

Another challenge is the load step behavior which is required when the motor is running at a fixed speed and there is an instantaneous variation of the load. The green curve in figure 7b is the speed signal and shows a variation lower than 4% in a time shorter than 0.4 seconds when full load (red signal) is applied and removed. This high performance behavior is possible if there are no filters between the drive and the motor which means short motor cable lengths and motors able to operate with variable speed drives.

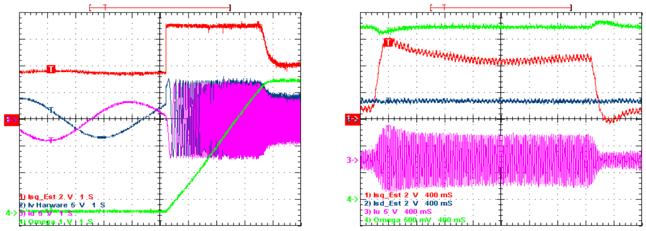
A sine filter is recommended for applications where the cable length between the VSD and the motor is higher than 500 meters or the motor is not able to operate with a PWM voltage waveform and a good/high dynamic performance is not required. Figure 8a shows the line-to-line voltage at the output of the 3/5 level NPC with a sine filter.

The 3/5 level NPC inverter needs a point at half potential of the full dc-link voltage (neutral point). A practical implementation of this neutral point is to use two capacitor banks in series connection. Normally, at steady-state operation, this inverter topology produces a natural balancing of the two capacitor voltages. However, in some operation conditions, voltage differences may appear and must be controlled to keep the operation safe and correct. A balancing strategy is described in [6] and figure 8b shows the action of this technique. The red and blue curves are the positive and negative DC link signals, the pink curve is the signal that indicates when the control action is ON and the green curve is the motor current signal. As shown, when the balancing strategy is enabled the capacitor voltages return quickly to a balanced condition without disturbance on the motor current.



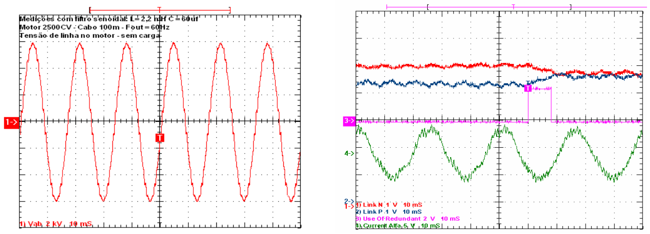
a) b)

Figure 6 – Phase to inverter neutral point voltages, phase to phase inverter output voltage (a) and motor current (b)



a) b)

Figure 7 – Speed reference step: 0 to 1800RPM (a) and Load step (b)



a) b)

Figure 8 – Line-to-line voltage at motor terminal with a sine filter (a) and action of the DC link balancing technique (b)

## V. CONCLUSION

This paper presented a study about the most common medium voltage industrial variable speed drives. The challenges of line and motor sides were presented. Different topologies and their vantages and advantages were analyzed.

Experimental measurements were performed in a 3/5 level NPC medium voltage high power drive and they show the open and close loop performance results as well as the operation with sine filter and the action of a DC-link balancing control which is needed in vector controlled drives due to the fast dynamic required.

The 3/5 level NPC is, among others, a topology with a good relation between the number of power components, reliability, efficiency, motor waveform quality and dynamic performance.

## ACKNOWLEDGEMENT

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## REFERENCES

[1] Wu, Bin, *High-Power Converters and AC Drives*, IEEE Press, USA, 2006

[2] Paice, Derek A, *Power Electronic Converter Harmonics – Multipulse Methods for Clean Power*, IEEE Press, USA, 1996.

[3] Alves, Joable and Torri, P, "IEEE Std 519 Recommended Practices for Applications with Variable Frequency Drives", In: 9º Congresso Brasileiro de Eletrônica de Potência (COBEP 2007), Blumenau / BRAZIL, 2007

[4] IEEE, *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems – IEEE 519*, IEEE Press, USA, 1993.

[5] Alves, Joable, and Hornburg, Edson, "High and Low Order Harmonics for Frequency Inverters" (portuguese), in: VI Conferência Internacional de Aplicações Industriais (Induscon 2004), Joinville / BRAZIL , 2004.

[6] Cunha, G. and Torri, P, "Neutral Point Potential Balancing Algorithm at High Modulation Index for Three-Level Medium Voltage Inverter*"*,In: 9º Congresso Brasileiro de Eletrônica de Potência (COBEP 2007), Blumenau / BRAZIL, 2007.

[7] MVW01 Medium Voltage Frequency Inverter Manual, WEG Automation, BRAZIL, 2009.