

## Variable Speed Drive (VSD) – towards modern industry and electric power systems

**Abstract.** High-power motor drives play an important role in present-day power systems. Due to high requirements put on drive systems, particularly strong development has been observed in recent years in variable speed drives (VSD), with power converters as their key part. This article reviews topics related to VSD systems, with particular focus on VSD applications, converter configuration and the harmonics injected to the grid.

**Streszczenie.** We współczesnych systemach elektroenergetycznych istotną rolę odgrywają układy napędowe dużej mocy. Wysokie wymagania stawiane układom napędowym powodują, że w ostatnich latach szczególnie rozwijane są układy Variable Speed Drive (VSD), których kluczowym elementem jest przekształtnik mocy. W tym artykule przedstawiony został przegląd zagadnień dotyczących układów VSD, przy czym uwaga została skupiona na kwestiach zastosowań VSD, konfiguracji przekształtników oraz harmonicznym wprowadzanych do sieci elektroenergetycznej. (Przekształtnikowy układ napędowy – w kierunku nowoczesnego przemysłu i systemu elektroenergetycznego).

**Słowa kluczowe:** przekształtnikowy układ napędowy, system elektroenergetyczny, harmoniczne.

**Keywords:** variable speed drive, power system, harmonics.

### Introduction

Industry, services (including agriculture), transportation and households are the biggest consumers of electricity in Europe [1]. According to the Energy Regulatory Office in Poland [2] and the European Environment Agency [1], with approximately 25÷30% of overall power supply, the volume of power supplied to households is relatively low. The main consumer of electricity in Europe, including in Poland, is industry. More than 65% of the energy taken off in industry is consumed by motors [3], or, more broadly, by electrical motor drives.

Diverse applications of electrical motors in industry require speed control capabilities, not infrequently in a broad range [4]. Present-day motor drives used in various sectors of industry can reach significant rated powers, with several megawatts or more. This makes it even more important to use solutions that allows one to precisely control the speed of the system and to properly manage the industrial process.

Variety of speed control methods that are used in industry can be classified into three main categories: electrical, hydraulic, and mechanical drives [5]. This article is focused on electrical motor drives.

Traditional drives, which use asynchronous cage motors or DC motors, are unsuitable for sufficiently precise and energy-efficient control of motors in dynamic and static operating conditions [6]. Due to the development of new, highly efficient and characterized with short response Insulated Gate Bipolar Transistors (IGBT), a marked rise in the number of VariableSpeed Drives (VSD) can be observed in the recent years [7].

High interest in industrial applications of the VSD systems is due to their advantages which include [8]:

1. controlled starting current,
2. reduced harmful disturbances in the power grid,
3. lower power requirement of the drive at start-up,
4. controlled value and characteristics of accelerations,
5. smooth regulation of motor speed (measured in revolution per minute, rpm),
6. controlled torque,
7. fully controlled drive deceleration,
8. electricity savings,
9. power recuperation,
10. easy motor reverse,
11. elimination of additional mechanical parts.

### Drives type

There are several terms used to describe devices that control motor speed. While the acronyms are often used interchangeably, the terms have different meanings [9].

- **Variable Frequency Drive (VFD)** - This device uses power electronics to vary the frequency of input power to the motor, thereby controlling the motor speed.
- **Variable Speed Drive (VSD)** - This more generic term applies to devices that control the speed of either the motor or the equipment driven by the motor (fan, pump, compressor, etc.). This device can be either electronic or mechanical.
- **Adjustable Speed Drive (ASD)** - Again, a more generic term applying to both mechanical and electrical means of controlling speed.

According to the IEEE Std. 1566 [10], the term Adjustable Speed Drive is defined as an interconnected combination of equipment that provides means of adjusting the speed of a mechanical load coupled to a motor. A drive system consists of a drive and auxiliary electrical apparatus.

This article focuses on VSD systems.

### Applications of VSD

VSDs have a wide variety of potential applications in electric drives. This is due to the possibility to drive different types of load, including:

- constant power loads,
- constant torque loads,
- variable torque loads.

Examples of the loads in which significant energy savings can be achieved include [11] single pumps, staged pumping plants, fans, compressors, lifts, centrifugal machines and machine tools, conveyors. Table 1 shows typical power ranges of common VSD applications.

### General classification of variable speed drives

Basically, an electric Variable Speed Drive is a device that controls the speed of a motor by varying the magnitude of one of its controllable variables such as voltage, current, or frequency. Obviously, the technique used to vary the speed will largely depend on the drive's load type.

Motor drives can be generally classified by the type of the motors, mainly in two categories: (i) DC drives, and (ii) AC drives. These two types can be branched into even more subtypes. For example, AC drives can be divided into synchronous motor drives and induction motor drives. A graphical approach to VSD drives classification is shown in Fig. 1 [13].

Table 1. Typical industrial applications of VSD [12]; P denotes rated power of the VSD system.

Application	P<10 [kW]	10<P<50 [kW]	50<P<500 [kW]	P>500 [kW]
Robotics	X			
Machine tools	X	X		
Material handling	X	X		
Small and medium process machines		X	X	
Large machines (e.g. mills, compressors)				X
Centrifugal machines (excluding large machines)	X	X	X	
Replacement of thermal engines				X

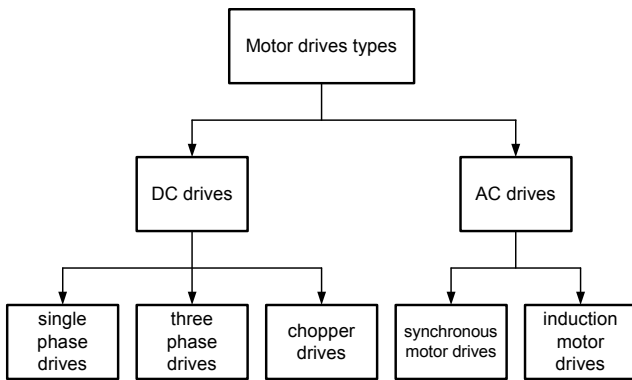


Fig.1. Main motor drive classification [13]

Another VSD classification can be made based on voltage and power ranges of the drive. The output voltage of a LV drive is typically less than 750 Volts. Low Voltage (LV) drives are typically used for powers lower than approximately 375 kW, or 500 HP (horsepower). Medium Voltage (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 (135,000 HP), where synchronous motor drives with load-commutated inverters are often used. However, the majority of the installed MV drives are in the 1-4 MW range, with the voltage ratings from 3.3 kV to 6.6 kV [14, 15].

This paper focuses on middle (high) voltage (MV) and high power drives. In the subsequent part, this paper addresses VSD equipped with AC motors.

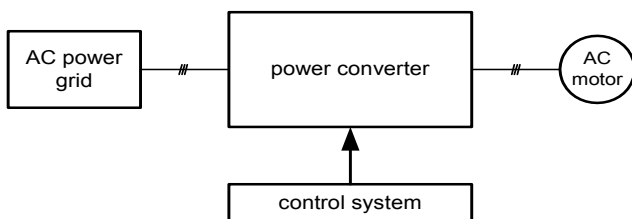


Fig.2. General configuration of VSD

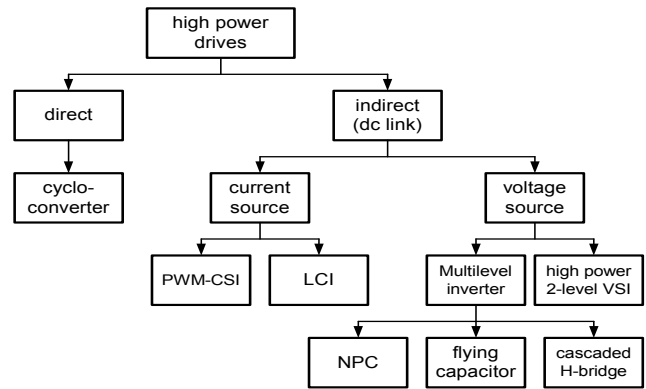


Fig.3. Classification of converters for high-power drives (>1 MW) [16]; NPC – Neutral Point Clamped, LCI – Load Commutated Converter, VCI/CSI – Voltage/Current Source Converter.

### VSD configuration

Typical electric VSD systems consist of three basic components: electrical motor, power converter, and control system. Fig. 2 shows the general configuration of VSDs.

Topologies of high-power converters for industrial medium-voltage drives fall within two major categories: indirect and direct ones. Fig. 3 presents a simplified classification of converter families used in high-power drive applications, which have a basic division into direct and indirect topologies.

### Direct AC/AC converters - cycloconverters

This type of VSD makes a direct power conversion from constant frequency and constant voltage to variable frequency and variable voltage. The conversion is performed in one step, without resorting to an intermediate DC link for energy storage [12]. There are various forms of cycloconversion such as ac-ac matrix converters and high frequency ac-ac (hfac-ac) converters and these use self-controlled switches.

Main advantages of the matrix converters come from their compact design (due to elimination of the DC-link reactive element), possibility of simultaneous power factor correction at the input and vector control at the output, and high-quality waveforms on both sides. The main disadvantages of the matrix converters are: high switching losses, complexity of control, lack of energy storage (leading to practically no ride-through capacity), and direct transfer of harmonic distortion and imbalance in the side-1 voltage and side-2 current to the side-2 voltage and side-1 current [17].

### Indirect AC/AC converters

#### Main components

Indirect converters are classified into current-source (CSC) and voltage-source (VSC) topologies, depending on the dc-link energy-storage component. Fig. 4. shows a general block diagram of an indirect MV drive. Depending on system requirements and the type of the converters employed, the line- and the motor-side filters are optional. A phase-shifting transformer with multiple secondary windings is often used, mainly for reduction of line-current distortion [16].

Medium-voltage VSD systems are connected to the grid via 2- or 3-winding transformers. For the 3-winding transformers, two lower windings are used for connecting the rectifier system. To reduce unfavourable effects of the converters (rectifier and inverter), filter systems can be used on the AC system or on the AC motor (the Line-side AC filter and the Motor-side AC filter respectively).

Some VSD systems can have a regeneration capability. In that case, depending on the mode of operation being “motoring” or “regenerative braking”, one of the two back-to-back converters assumes the role of a “rectifier”, and the other converter acts as an inverter [17].

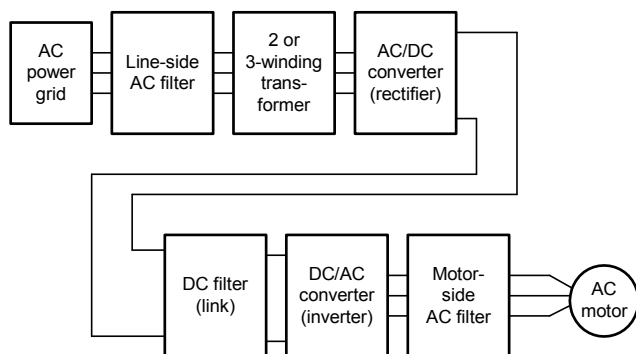


Fig.4. General block diagram of the MV drive [16]

### Rectifier converters

The rectifier converts the utility supply voltage to a DC voltage with a fixed or adjustable magnitude. The commonly used rectifier topologies include multipulse diode rectifiers, thyristor rectifiers, and pulse-width modulated (PWM) rectifiers. [16].

As shown in Fig. 5, rectifier (AC/DC) converters can be classified by topology as working with low switching frequency (line commutated) and other circuits which operate with high switching frequency (internally commutated) [18].

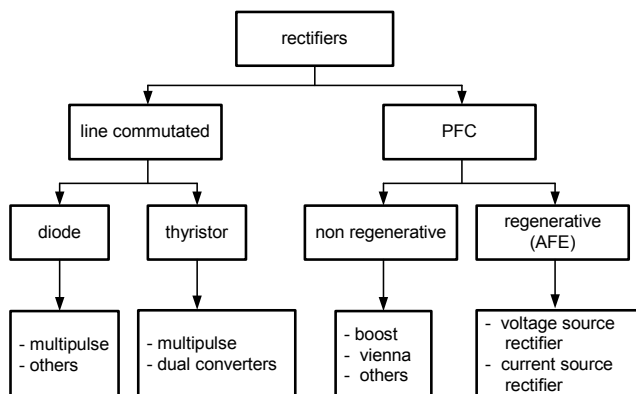


Fig.5. General classification of rectifiers [18]; PFC – Power Factor Correction, AFE – Active Front End

In power-factor correction (PFC) converters, by applying semiconductors such as IGBT, Gate-turn-off Thyristors (GTO), Integrated Gate Commutated Thyristors (IGCT), a Silicon Controlled Rectifiers (SCR) allows to reduce harmonics and to improve power factor.

Rectifiers of active front end (AFE) type (as shown in Fig. 5) can operate with high power factor or any active–reactive power combination. These rectifiers can be classified as voltage-source rectifiers (VSRs) and current-source rectifiers (CSRs). AFE drives are inherently “four quadrant” ones (i.e. they can drive and brake in both directions of rotation with any excess of kinetic energy during braking returned to the supply).

### Inverter converters

To meet the motor-side challenges, a variety of inverter topologies can be adopted for the MV drive. The most used inverters are as follows:

1. conventional two-level inverter,
2. three-level neutral-point clamped (NPC) inverter,
3. seven-level cascaded H-bridge inverter,
4. four-level flying-capacitor inverter.

Either IGBT or IGCT can be employed in these inverters as switching devices.

Current-source inverter (CSI) technology has been widely accepted in the drive industry [14]. The most frequently used inverters are as follows:

1. load-commutated inverter (LCI),
2. Pulse Width Modulation (PWM) SCI,
3. parallel PWM CSI.

The SCR-based load-commutated inverter (LCI) is particularly suitable for very large synchronous motor drives, while the PWM current source inverter is a preferred choice for most industrial applications. The parallel PWM CSI is composed of two or more single-bridge inverters connected in parallel for super-high-power applications. Symmetrical IGCTs are typically used in the PWM current source inverters [14].

Current-source inverter (CSI) technology is well suited for high-power drives. The current-source converters feature a simple converter structure, low switch count, low switching dv/dt, and reliable overcurrent/short-circuit protection. The main drawback lies in its limited dynamic performance due to the use of a large DC choke [19].

Traditional two-level voltage-source inverters (VSIs) (2L-VSIs) have been limited to low- or medium-power applications due to the power-semiconductor voltage limits. Series connection of switching devices has enabled high-power 2L-VSIs. The well-known 2L-VSI is also used in medium- and high-power traction and industrial high-power drives [16]. The 2L-VSI inverter is a simple converter topology and has an easy PWM modulation pattern. However, the inverter produces high dv/dt and high THD in its output voltage and, therefore, often requires a large-size LC filter installed at its output terminals [20].

The three-level NPC-VSI (3L-VSI) has been successfully used in the industry in past years. The main features of the NPC inverters include reduced dv/dt and low THD in its AC output voltages in comparison to the 2L-VSI topology. The 3L-VSI can be used in MV drives to reach a certain voltage level without switching devices in a series connection. Thus, the efficiency levels can reach 99% [20].

It should be noted that, in terms of efficiency, the VSIs and CSIs are attractive for non-regenerative low dynamic requirement drives. For regenerative applications, the three-level NPC VSI achieves higher efficiency in comparison to the CSI converter. For very high power applications, the thyristor-based current-source topology offers significantly higher performance due to the low-voltage drop of the semiconductors used [21].

### Harmonics

The primary adverse outcome of an VSD for a power system is the effect of harmonics generated by the VSD. There are two mechanisms by which the VSD generates harmonic currents. The first mechanism is the converter operation which injects harmonic currents into the supply system by an electronic switching process. The second mechanism is the inverter operation [22].

The magnitude of the harmonics generated by the VSD is determined by [15]:

1. topology of the drive (number of pulses, rectifier type),
2. percentage of the total power system capacity that the VSD represents,
3. stiffness or short circuit capacity of the power system supplying the VSD,

4. whether or not the VSD is electrically isolated from other sources of harmonics,
5. installation practices for the VSD,
6. rating of electrical load of the VSD.

When planning the installation of variable speed drives in a power supply system, a choice has to be made between designing nonlinear devices for low levels of waveform distortion or installing harmonic compensation equipment at the terminals. The first solution is often possible by phase-shifting of the transformers and/or the control of converter bridges or by the use of switching devices with turn-off capability. Second solution of harmonic elimination is achieved by means of filters [23] (external harmonic compensation). Passive filters comprise inductance, capacitance, and resistance elements configured and tuned to control harmonics characterizing operation of particular VSD system. They are commonly used and are relatively inexpensive compared with other means for eliminating harmonic distortion. As they have disadvantage of potential adverse interaction with the power system, it is important to verify all possible system interactions in the system planning and design stage [24].

### Conclusions

Development of power electronics systems has provided the tools to build high-power motor drives which have high efficiency, versatile operational capabilities and no adverse effects on the power system. These systems, called variable-speed drives, can reach rated power of several megawatts or more. The advantages of the VSD systems made them a popular choice in different industry sectors, such as: petroleum, chemical, power and mining.

Due to diverse range of the VSD components (i.e. various types of motors, power converter devices, rectifier and inverter topologies), the VSD defines a family of solutions. Matching the topology and parameters of the VSD system to a particular application requires detailed analysis, in which particular attention should be focused on harmonics.

From the point of view of the power system, the VSD systems equipped with an active front-end rectifier are untypical power load components. On the the important features characterizing VSD systems is the operation in regenerative braking mode, in which the VSD system generates power instead of consuming it. Proper components selection should ensure that the overall system reliability is not affected.

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