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AC Motor Control Applications in High-Power Industrial Drives

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23.1 Introduction

The power ratings of large medium voltage (2.2–13.8 kV) industrial drives range between few hundred kilowatts to a few tens of megawatts and even 100 MW. The upper limit is decided by the requirements of the applications rather than by the technology of the converters and machines (Stemmler 1994). The available speed range lies from 10 rpm for low-speed machines (e.g. Cement mills), 1500/3000 rpm for normal-speed drives to even 18 000 rpm for very high power high speed drives (e.g., compressors). The limits for the dc motors such as cost, size, commutator problems and inability to operate satisfactorily in a dirty and explosive environment have called for ac motor drives for high power applications. Major technical breakthroughs have occurred both in the power conversion and in control areas of variable voltage variable frequency (VVVF) ac drives to meet the exacting requirements of ac drives using direct ac/ac cycloconverters or ac/dc/ac link inverters that feed either induction motors (IM) or synchronous motors (SM). The machine may be excited by a voltage source inverter (VSI) or a current source inverter (CSI). Synchronous motor drives have the advantages over the induction motor drives in that, with separate field excitation, these can be operated at any power factor-leading, lagging and unity. The operation near unity power factor reduces armature copper loss and permits inverter size reduction with simplicity of commutation (load commutation) with thyristors as switches. Further, a synchronous motor runs at a precisely set speed independent of load and voltage fluctuations unlike an induction motor.

The recent trends in high-power ac drives are to use pulse width modulated (PWM) VSI or CSI with self-commutated devices like insulated gate bipolar transistors (IGBTs), gate turn
off thyristors (GTOs), integrated gate commutated thyristors (IGCTs) and injection enhanced gate transistors (IEGTs) for efficient VVVF control with harmonic reduction. The development of new high-power semiconductors such as 3.3/4.5 kV, 1.7/1.2 kA IGBTs, 6 kV, 6 kA IGCTs and 4.5 kV, 5.5 kA IEGTs capable of snubberless operation and the introduction of three level topologies in contrast to earlier two level ones have led to an increased application of PWM controlled Voltage Source Converters (VSC) ranging from 0.5 MVA to about 30 MVA (Chattopadhyay 2010). CSI-fed drives with simplified regeneration control and microcomputer-controlled drives implementing evolutionary concepts like field orientation or vector control (VC), with either inverter or cycloconverter-fed induction or SM by which dc machine-like performance can be obtained and direct torque control (DTC) are now finding increasing acceptance in high-performance industrial ac drives for applications such as steel mills, ore-grinding mills, cement kilns, ship drives, mine winders, and electric traction (Chattopadhyay 1997a). The converters for such drives meeting the high performance requirements must:

- generate smoothly variable frequency and voltage;
- produce nearly sinusoidal current waveforms throughout the operating range to avoid undesirable torque oscillations;
- permit highly dynamic control both in forward and reverse motoring and braking applications;
- provide as nearly as possible or even better performance than that of the dual converter-fed dc drives as regards cost, service reliability and harmonic effects on the system.

Besides the application of field-oriented control (FOC) in PWM inverter-fed motor drives with various PWM schemes like carrier-based, hysteresis-band control and space vector modulation (SVM), the recent application of DTC to ac drives (Chattopadhyay 2010) has been claimed to achieve the highest torque and speed performance ever achieved with variable speed drives, making it possible to control the full torque within a few milliseconds, reducing the impacts of load shocks.

Thus, rapid and remarkable progress has been made over the years in the ac drive technology used in the high-power drives and their control. Figure 23.1 shows a block diagram of a typical high power ac drive system for a mill with its various components. The technology is vast and the objective of this chapter is to present a brief but comprehensive state-of-the-art overview of the development of each of the components such as high-power semiconductor devices, converter topologies, motors used and the control strategies employed together with their various application examples in the industry. The brief features of the industrial ac drives developed by the leading manufacturers worldwide are also provided as well as new developments and possible future trends.

### 23.2 High-Power Semiconductor Devices

Rapid advances in industrial ac drives and power conversion systems have been possible due to continuous and astonishing development of the rating and performance of the power semiconductor devices over the last 50 years. Two major types of high-power semiconductor devices are used in high power converters in the industry: the thyristor-based (current switched)
devices that include SCR (silicon-controlled rectifier), GTO, IGCT (or GCT), and the transistor based (voltage switched) devices that comprise IGBT and IEGT. The voltage and current ratings of these devices as commercially available today for high power converters are shown in Figure 23.2 (Wu 2006). Some typical high-power devices are shown in Figures 23.3 and 23.4 (Sato and Yamamoto 2001; Ichikawa et al. 2004).

### 23.2.1 High-Power SCR

Figure 23.3a shows a 12 kV / 1.5 kA SCR that is a high-power press-pack thyristor-based device with three terminals: gate, anode, and cathode. Its turn-on process is initiated by applying a pulse of positive gate current and it turns off when anode current becomes negative. The turn-on time is 14 μs and turn-off time is 1200 μs. The on-state voltage drop is about 4 V. This device blocks voltage in both forward and reverse directions. Originally, developed and marketed by GE, USA in 1958, it is the highest rated power device so far (specially with the light-triggered ones) for use with cycloconverter—and load-commutated inverter (LCI) fed motor drives besides High Voltage DC (HVDC) systems and Static VAR Compensators (SVC).

### 23.2.2 High-Power GTO

The GTO is a self-commutated thyristor-based device that can be turned off by a negative gate current. Figure 23.3b shows a 6 kV, 6 kA press-pack GTO (high-power GTOs being developed by Japanese since 1980s), which is turned on by a pulse of positive gate current and turned off by a negative gate current pulse. However, the turn-off current gain is typically 4–5 which means that a GTO with a 6000 A anode current rating may require −1500 A gate current pulse.
Figure 23.2  Voltage and current ratings of high-power semiconductor devices. Reprinted with permission from IEEE (Chattopadhyay 2010)

Figure 23.3  Thyristor-based (current switched) high-power semiconductor devices. Reprinted with permission from IEEE (Chattopadhyay 2010)
to turn off. GTOs need bulky and expensive turn-off snubbers and complex gate driver. The typical turn on time is $2.5 \mu s$ and turn-off time is $25 \mu s$. The on-state voltage drop is typically $4.4 \text{ V}$. The GTO switching frequency is lower than that of IGBTs and IGCTs (to be described later). So, the GTO converters operating in PWM (high-frequency) mode use energy recovery snubbers consisting of a capacitor, a diode and a resistor across each device in addition to a turn-on snubber consisting of an anode inductor in series with each device to reduce $di/dt$ of the anode current. The GTO can be fabricated with asymmetrical structures suitable for VSIs or symmetrical structures suitable for CSIs.

23.2.3 IGCT/GCT

IGCT (also known as GCT) is a hard-driven GTO (developed by ABB in 1996) with unity current gain that means that a 6000 A (anode current) device is turned off by a $-6000 \text{ A}$ gate current (Sato and Yamamoto 2001). However, the current pulse should be very narrow with low energy for fast turn off. Figure 23.3c shows an ABB press-pack type 6.5 kV, 6 kA IGCT with a built-in integrated gate drive circuit (consisting of several MOSFETs in parallel) on the same module. The IGCTs have replaced the GTOs for the medium-voltage drives over the past few years due to their special features like snubberless operation and low switching loss. The snubberless operation is possible because of extremely low gate inductance (typically $< 3 \text{ nH}$ compared to $< 30 \text{ nH}$ for GTOs) by special construction. The rate of the gate current change at turn-off is normally greater than $3000 \text{ A}/\mu s$ compared to around $40 \text{ A}/\mu s$ for GTO. The turn-on and turn-off times are much faster than those of the GTO. Though the IGCT does not
require a turn-off snubber, it requires a simple turn-on snubber or a clamping circuit since the $di/dt$ capability of the device at turn-on is around 1000 $A/\mu s$ only. The on-state voltage of IGCT at 6000 $A$ is only 4 V compared to 4.4 V for a GTO at 4000 $A$. As the storage time of IGCT is reduced to 1/10th compared to GTO, a high switching speed is obtained. IGCTs have a higher switching frequency (typically 1.0 kHz) than GTOs (typically 0.5 kHz). Besides the asymmetrical IGCT (suitable for VSI as shown in the Figure 23.3c, marketed by ABB), symmetrical SGCTs (suitable for CSI) are available from Mitsubishi for smaller ratings. IGCTs are simple to use, easily available and have demonstrated their reliability in many applications that include rolling mill drives (e.g., ACS 6000 by ABB and SIMOVERT-ML2 by Siemens).

### 23.2.4 IGBT

After completely dominating the low-voltage converters, IGBTs are increasingly used for medium-voltage converters. It is a voltage controlled hybrid device (developed by Baliga of GE in 1983) combining the advantages of MOSFET’s high-gate circuit resistance and BJT’s small collector-emitter drop at saturated condition. The ratings of these devices have reached as high as 6.5 kV/0.6 kA or 3.3 kV or 4.5 kV/1.2 kA. It can be turned on with a 15 V gate voltage and turned off when the gate voltage is zero or negative. The majority of high-power IGBTs are of modular design as shown in Figure 23.4a and b. It can be turned on within 1 $\mu s$ and turned off within 2 $\mu s$. The main advantages of IGBT are simple gate driver, snubberless operation, high-switching speed, modular design, and controllability of switching behavior providing reliable short-circuit protection. Presspack devices are also available which are suitable for series operation. The device has only forward blocking capability and can be used in a VSI with a feedback diode. However, very recently, reverse-blocking IGBTs are also available. High-voltage IGBTs have a higher voltage drop (e.g., 4.3 V for a 3.3 kV/1.2 kA device) during conduction compared to thyristors or GTOs. IGBT devices can be available in intelligent power module (IPM or HVIPM in Figure 23.4a) form with gate drivers and built-in protection features to provide lower size and cost, improved reliability and fewer EMI problems.

### 23.2.5 IEGT

IEGT is basically an advanced high-voltage high-power IGBT with special gate construction commercially developed by Toshiba in 1999 (Ichikawa et al. 2004). It is designed in such a way that large numbers of electrons accumulate at its electrodes and it exhibits low on-state voltage (compared to IGBTs and GTOs of the same rating). Figure 23.4c shows a 4.5 kV/2.1 kA (turn-off current 5.5 kA) IEGT and its gate driver that is less than 1/200 in gate power compared with that of GTO/IGCT and more reliable. It can be turned on by the gate voltage of $+15$ V and turned off by that of $-15$ V. The transistor-based IEGT has the potential to achieve higher output frequencies than the IGCT/GCT. Another advantage over the IGCT is the power required to turn the device on and off. Figure 23.5 (Tessendorf and Hosoda 2004) shows the comparison of typical gate trigger pulses required for equivalent power devices. As a transistor-based device, the gating power of IEGT is low and approximately equal for both turn-on and turn-off. The on-state voltage drop across this device is of the order of 3.0 V (much less than that of IGBT or GTO of similar rating). In the IEGT-based system, neither turn-on nor turn-off snubber is required for each IEGT as in the case of GTO. However, each IEGT
Figure 23.5  Typical gate trigger pulses for IGCT/GCT and IEGT. Reprinted with permission from IEEE (Chattopadhyay 2010)

leg needs simple and efficient clamp circuits to eliminate the snubbers. As discussed later, Toshiba has supplied 8 MVA IEGT-based three-level inverter systems for rolling mill drives in 2000 with an efficiency of 98.5%, which is 2% more than that of an equivalent GTO-based system thus saving a lot of energy.

23.3 High-Power Converters for AC Drives and Control Methods

Figure 23.6 shows a classification of converters as used for the high-power drive applications. The direct topology connects the load directly to the source through power semiconductors and a suitable control logic, while the indirect topology transfers the power in two stages, rectification and inversion. For direct connection, the cycloconverter is the most used topology

Figure 23.6  Classification of converters for high-power drives
in high-power applications that uses an array of naturally commutated power semiconductor devices such as thyristors, to connect directly the power supply to the machine, converting a three-phase ac voltage with fixed magnitude and frequency to a three-phase ac voltage with variable magnitude and variable frequency (VVVF). Matrix converters (MC), belonging to this category using self-commutated bilateral devices have a limited application. Only very recently they have been used for medium-voltage, high-power drives with multilevel operation (Yamamoto et al. 2011). Indirect dc-link inverters may be current source (CSI) or voltage source (VSI) type depending on the dc-link energy-storage component which can 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. While the CSIs for high-power applications may be either PWM-CSI or LCI, the VSIs may be two-level PWM with switches in series or multi-level PWM. Inverter originally developed as the neutral-point clamped (NPC) three-level inverter in 1981 (Nabae et al. 1981). Other topologies of the multilevel inverters that have been commercialised are flying capacitor (Rodriguez et al. 2007) and cascaded H-Bridge (Rodriguez et al. 2007) for medium-voltage drives up to about 40 MVA.

23.3.1 Pulse Width Modulation for Converters

Pulse width modulation techniques to control the voltage output and improve the waveform of the converters may be carrier-based sinusoidal pulse width modulation (SPWM), PWM with selected harmonic elimination, hysteresis band current control PWM and SVM. These modulation techniques have become mature technology and implemented in power converters for high-performance drives as commercial products (Rodriguez et al. 2007). Out of these schemes, SVM is an advanced digital modulation technique preferred over the SPWM technique as it provides better utilisation of the dc bus voltage and lower harmonics. This method deals with the interactions among all the phases in contrast to the case of SPWM, where each phase is treated independently. The concept of rotating space vectors are involved here and it needs a microcomputer or digital signal processor (DSP) (Bose 2002) for its implementation.

23.3.2 Control Methods of High-Power Converter-Fed Drives

Converter-fed AC drives with, either induction or SM, are controlled with control of frequency and voltage (or current). To obtain high performance, closed loop control is preferred, while the open-loop control is popular for pump, fan- and compressor-type drives, because this control is simple and does not involve any complex feedback signal measurement or estimation as needed for closed loop control. In general, the control methods for converter-fed drives may be classified as scalar (volts/hertz or \( V/f \)) control, VC or FOC and DTC. DTC is an advanced scalar control with performance comparable with the VC method. The VC inherently provides high performance and permits to control the ac machine like a dc machine and most of the advanced control techniques like adaptive control, optimal control, intelligent control (with AI techniques) and fault-tolerant control can be applied to ac drives with the VC (Bose 2011a). Scalar control, unlike VC, means control of the magnitude of a variable, whereas in the latter, both magnitude as well as phase of the space vector variables are controlled.
23.4 Control of Induction Motor Drives

23.4.1 Induction Motor Drives with Scalar or Volts/Hz Control

The simplest type of scalar control is open-loop Volts/Hz (V/f) control with low performance compared to closed-loop VC. Machines are normally operated at rated flux so that the developed torque/Amp of stator current is high and transient response is fast.

PWM Two-Level VSI Induction Motor Drive

The well-known two-level VSI as shown in Figure 23.7a with a line side PWM rectifier using either IGBTs or GTOs feeding a well-regulated dc voltage with little ripple and at a high-power factor to a load side PWM inverter also using IGBTs or GTOs is applied for medium- and high-power industrial drives. To increase the converter voltage, a series connection of these switches is applied. The capacitor used as a dc-link filter provides the voltage source. A simple and most common SPWM method of 2-level voltage control is shown in Figure 23.7b. An isosceles triangle carrier is compared with the sine wave reference signal and the crossover points determine the points of switching. Except at low-frequency range, the carrier

![Diagram of PWM Two-Level VSI Induction Motor Drive](image-url)
Figure 23.8 Constant $V/f$ or scalar control of a rectifier-inverter induction motor drive with slip regulation

is synchronised with the signal and an integral ratio (multiple of 3) is maintained to improve harmonic content. The fundamental output voltage can be varied by variation of the modulation index (the ratio $A_r/A_c$, where $A_r$ and $A_c$ are the amplitudes of reference and carrier waves, respectively).

The classical flux regulation control scheme for an SCR-rectifier-inverter fed drive with simple constant $V/f$ ratio or scalar control for the constant torque region with slip regulation is shown in Figure 23.8 (Bose 1982). The slip frequency $\omega_{sl}$ which is proportional to torque is regulated by the speed loop error. The $\omega_{sl}$ signal is added to $\omega_r$ to generate the inverter frequency $\omega_e$. The voltage control signal $V_e$ is generated from $\omega_e$ through a function generator so as to maintain the airgap flux nearly constant. A small boost voltage is added with the estimated voltage to overcome the machine resistance drop that becomes dominant at very low frequency. The drive accelerates with the clamped value of slip corresponding to the maximum torque and then settles down to a value as dictated by the load torque. If the commanded speed $\omega_r^*$ is reduced at steady state, the slip becomes negative and the drive system goes into the dynamic or regenerative braking mode. Instead of regulating the slip, it can be maintained constant and the speed loop error may control the dc-link voltage. The variation of $V/f$ ratio causes the variation of air-gap flux and correspondingly the developed torque is regulated. The open-loop scalar control is popular in the industry when a small drift in speed and air-gap flux due to fluctuation are of no significance. Commercial drives with $V/f$ control are also available with efficiency optimisation control (Bose 2011a).

PWM Three-Level VSI-Induction Motor Drive

Figure 23.9 shows a three-phase three-level PWM inverter (also known as neutral-clamped converter (NPC) using IGBTs / GTOs). In two-level inverters, the output voltages consist of
pulses of either $+V_d/2$ or $-V_d/2$, whereas with a three-level inverter, these may be $+V_d/2$, 0, and $-V_d/2$. For high-power high-speed drives, three-level inverters have been preferred as they can be operated with twice the rated voltage without any series connection and therefore with twice the rated power with significantly improved output voltage waveform when compared to a two-level inverter. However, a three-level inverter consists of 12 IGBTs/GTOs—4 IGBTs/GTOs per phase. Here, the connection in each phase may be represented by a three-point changeover switch, the output of which can be connected to the positive pole, zero or the negative pole of the dc supply. One three-level inverter can be regarded as an inverter that can be operated with two independent pulse patterns. Till 1993, the rated power and frequency of GTO-VSIs were limited to about 2 MW/60 Hz for two-level VSIs and 4 MW/130 Hz for three-level VSIs but now with IGCTs (developed by ABB in 1996) and IEGTs (developed by...
Toshiba in 1999) and breakthrough in series connection, the rating of the converters has gone above 10 MVA. Siemens has introduced SIMOVERT-ML drive with three-level converters of MW range with VC for application to synchronous or induction motor drives.

Hitachi Ltd., Japan, also developed three-level GTO-based 6.4 MW inverter induction motor drive for steel rolling mills in 1996. The synchronous motor is often the most cost-effective solution for applications with a wide field weakening range and for high surge load requirements. Several recent applications of three-level inverters for large drives with regenerative front end includes a 20 MW downhill conveyer system with GTOs. Figure 23.10 (Okayama et al. 1996) shows a three-level GTO converter-inverter system used for steel rolling mills with VC (to be discussed later). The same configuration has been used with IGBTs, IGCTs or IEGTs as switches replacing GTOs with improvement in efficiency and reduced volume and weight.

**Current Source Inverter-Induction Motor (CSI-IM) Drive**

A schematic diagram of a dual PWM CSI-fed drive using GTOs is shown in Figure 23.11 (Chattopadhyay 2002). The system is a dual of the PWM-VSI rectifier-inverter system in Figure 23.7a. The PWM rectifier provides sinusoidal input current at unity power factor. This scheme has replaced the earlier phase-controlled rectifier-fed auto-sequentially commutated inverter (ASCI) using SCRs with capacitors and series diodes as commutation elements, Figure 23.12 (Chattopadhyay 2002). The variable dc voltage is converted to a current source by connecting a large inductor in series eliminating the filter capacitor of the VSI. The freewheeling diodes, typical of VSI, are absent in CSI as when supplied by a current source, current in any half-leg of the inverter cannot change in polarity and can only flow through the power switches. A method of speed control with CSI in which the slip \( \omega_s \) is varied as a function of the \( I_d \)
Figure 23.11 CSI-PWM rectifier PWM-inverter fed induction motor drive

(pre-computed for given parameters of the machine) to maintain constant air-gap flux (as in the \(V/f\) control of the VSI-fed drive) is shown in Figure 23.13 (Chattopadhyay 2002). The full four-quadrant capability of the drive can be obtained.

**Cycloconverter-AC Motor Drive**

A cycloconverter converts ac line power from one frequency to that in another directly (AC/AC) in contrast to the dc link inverter (AC/DC/AC). For large drives, 6 or 12 pulse converter
bridges are used requiring 36 or 72 thyristors in total, respectively. Like dual converters, the cycloconverters can be operated in the circulating current-free mode where no circulating current is permitted between the $P$- and $N$-groups by appropriate logic control. The circuit operates in phase control line commutation mode and the firing angles are modulated to synthesise a mean sine wave voltage. Basic cycloconverter configurations (both for non-circulating and circulating current type) are shown in Figure 23.14 (Chattopadhyay 2010) with voltage and current waveforms for the non-circulating current one. The bridge that

\begin{figure}[h]
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\includegraphics[width=\textwidth]{figure2313.png}
\caption{CSI-drive with slip-frequency control}
\end{figure}

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\includegraphics[width=\textwidth]{figure2314.png}
\caption{(a) Non-circulating current-type cycloconverter, (b) circulating current-type cycloconverter, (c) voltage and current waveforms for (a). Reprinted with permission from IEEE (Chattopadhyay 2010)}
\end{figure}
conducts the current generates the voltage. Due to line commutation, its output frequency is limited to, typically, 1/3 to 1/2 of the line frequency and is suitable for low-speed high-power drives, with easy four quadrant operation. The circulating current type, though expensive, is commonly employed for its simplicity, less torque ripple, higher maximum output frequency compared to the noncirculating current type, which though more efficient has a dead time of 1 to 3 ns for switching between forward and reverse current resulting in a higher torque ripple.

The output voltage of a cycloconverter contains a complex harmonic pattern given by $k_1 f_i \pm k_2 f_0$, where $f_i$ is the input frequency, $f_o$ is the output frequency, $n$ is the pulse number and $k_1, k_2$ are integers. A cycloconverter output may contain sub-harmonics of lower frequency than the output frequency that may be reduced by modifying the cosine firing control technique and feedback method to improve power quality and operating output frequency range. Because of the phase control principle, the cycloconverter presents lagging reactive power at the input irrespective of the power factor of the load and various schemes to improve this power factor have been developed including fast current control loop or trapezoidal modulation. The control method concepts discussed with VSI and CSI can be extended to cycloconverter drives. The cycloconverter-fed induction/synchronous motor drives have been used with scalar control for low-speed multi-motor-driven steel mill roller tables and with VC, in cement mills and rolling mill drives as discussed later.

Matrix Converter-Fed AC Motor Drive

The MC is a development of the force-commutated cycloconverter (Gyugi and Pelly 1976) based on bi-directional fully controlled switches, incorporating PWM voltage control, as mentioned earlier. With the initial progress made by Venturini (1980), it has received considerable attention in recent years as it provides a good alternative to the double-sided PWM voltage source rectifier-inverters having the advantages of being a single-stage converter with only nine switches for three-phase to three phase conversion and inherent bi-directional power flow, sinusoidal input/output waveforms with moderate switching frequency, possibility of a compact design due to absence of dc link reactive components and controllable input power factor independent of the output load current. The main disadvantages of the MCs developed so far are the inherent restriction of the voltage transfer ratio (0.866), complex control, commutation and protection strategy and above all the non-availability of a fully controlled bi-directional high-frequency switch integrated in a silicon chip. The power circuit diagram of the most practical three-phase to three-phase MC is shown in Figure 23.15a that uses nine bi-directional switches so arranged that any of three input phases can be connected to any output phase or terminals while the current in any phase of the load may be drawn from any phase or phases of the input supply. For the switches, the inverse-parallel combination of reverse-blocking self-controlled devices like Power MOSFETs or IGBTs or transistor embedded diode bridge as shown have been used so far. New perspective configuration of the bi-directional switch is to use two RB-IGBTs with reverse blocking capability in anti-parallel eliminating the diodes reducing the conducting losses in the converter significantly. The circuit is called a MC as it provides exactly one switch for each of the possible connections between the input and the output. The switches should be controlled in such a way that, at any time, one and only one of the three switches...
connected to an output phase must be closed to prevent “short circuiting” of the supply lines or interrupting the load.

The control methods adopted so far for the MC are quite complex and are subjects of continuing research (Zhang et al. 1998). Out of the several methods proposed for independent control of the output voltages and input currents, two methods are of wide use: (i) the Venturini method based on a mathematical approach of transfer function analysis and (ii) the SVM approach (as has been standardised now in the case of PWM control of the dc link inverter). These are discussed in Zhang et al. (1998).
A vector controlled high-performance MC-induction motor is described in Ishii et al. (2000). A multilevel MC with four-quadrant dc link \( H \)-bridge switching cells suitable as shown in Figure 23.16 for medium or high voltage ac-to-ac power conversion was introduced in 2001 (Erickson and Al-Naseem 2001). The use of four transistors in the switch cell of Figure 23.16c allows the average current to be doubled relative to the conventional MC whose four-quadrant switches are realized using two transistors and two diodes. With dc capacitor, the switch cell is capable of producing instantaneous voltages \( +V, 0, -V \).

The Yaskawa medium voltage MC (Yamamoto et al. 2011) utilizes a series connected multi-level topology shown in Figure 23.17, where a three-phase input/single phase output MC is a basic component called the cell. Connecting three cells in series, each designed for 635V yields a line-neutral voltage of 1905 V, corresponding to a line-line voltage of 3300 V. These multi-cell medium voltage MCs (FS Drive-MXIS) of rating 3 kV, 200–3000 kVA or 6 kV, 400–6000 kVA have been built by Yaskawa and applied to 200 V, 22 kW wind turbine generator system, 400 V, 16 kW elevator system and 3.3 kV, 3 MVA skin-pass mills (Yamamoto et al. 2011). Compared to PWM converter-inverter system, the MC scheme has higher reliability, improved efficiency from 92.7% to 96.9% and weight about 62% (Yamamoto et al. 2011).

**Figure 23.16** Multi-level MC: (a) configuration, (b) switch symbol, (c) switch realization (Erickson and Al-Naseem 2001)

**Slip-Power Controlled Induction Motor Drive**

With wound rotor IM, while the stator is connected to the ac system, the rotor side slip power can be controlled by a converter cascade, either a rectifier-inverter or a cycloconverter, via slip rings as described in (Akagi 1998). New applications for high power ratings of some hundred megawatts involving cycloconverters or GTO inverters are in the fixed-frequency variable speed motor generators in pumped-storage plants in Japan. Figure 23.18 shows the
Figure 23.17  Schematic of multicell MC with three cells in series in each phase (Yamamoto et al. 2011). (a) One cell, (b) Single-phase and line-to-line voltage

Figure 23.18  400 MW Adjustable speed pumped storage system (Akagi 1998)
arrangement of a 400 MW adjustable-speed pumped-storage system in Japan where a 72 MVA, 3-phase, 12-pulse line-commutated cycloconverter feeds the slip rings of the Scherbius drive. The armature terminals, rated at 18 kV, of the 20-pole induction machine are connected to a 500 kV utility grid through a step-up transformer. The output frequency of the circulating current-free cycloconverter is controlled within ±5 Hz, and the line frequency is 60 Hz. With a synchronous speed of 360 rpm the speed can be controlled from 330 rpm to 390 rpm. The total operational efficiency of the system increases by 3% when compared to the conventional constant-speed version of the system.

23.4.2 Induction Motor Drives with Vector Control

The vector or FOC, introduced in the beginning of 1970s (Blaschke 1972), has revolutionised the control of high-performance ac drives when, with this control, an induction motor drive can be operated like a separately excited dc motor drive. The stability and sluggish response problems of the higher order and complex coupling model of ac machine under scalar control vanishes with VC. In a separately excited dc machine, use of power electronic converters with current feedback provides a direct control of the magnitude of the armature current and in proportion, the torque. For ac machine, however, this control is to be achieved in terms of both amplitude and phase that has led to the generic term VC. In addition, unlike the dc machine, where the orientation of the field flux and the armature MMF is fixed by commutator and brushes, ac machine requires external control to fix this orientation without which the space angle between various fields vary with load (and during transients), giving rise to oscillatory dynamic response. Field orientation control (FOC) directly controls this space angle and, in particular, attempts to make it 90◦ between the specifically chosen field components so as to emulate a dc machine and provide de-coupling control. The technique can be applied to either induction or synchronous motor fed from either CSI/ CRPWM (current regulated PWM VSI) / VSI or cycloconverter (Chattopadhyay 1997a). Early conceptual works on VC were developed in Germany in the beginning of seventies and its implementation progressed with the development of microprocessors in early eighties. In VC, the currents \(i_{ds}^e\) and \(i_{qs}^e\), the \(d\)-axis and \(q\)-axis components, respectively, of the stator current in synchronously rotating reference frame are analogous to the field current \(I_f\) and to the armature current \(I_a\) of the dc machine and therefore the torque can be expressed as \(T_e = K_t \Psi_m i_{qs}^e = K'_t I_f I_a = K''_t i_{qs}^e i_{ds}^e\). These two components can be independently controlled. For normal operation as in the dc machine, the current \(i_{qs}^e\) remains constant and the torque is varied by varying the \(i_{ds}^e\) component. There are two basic methods of VC based on the acquisition of the flux vector angle \(\theta_e (= \omega_r t)\) that assures the alignment of \(i_{ds}^e\) with \(\Psi_m\) and \(i_{qs}^e\) with the airgap voltage (Bose 2002). The direct method is based on the measurement or computation of the magnitude as well as the position of the flux vector and the indirect method uses a slip relation to compute \(\theta_e\) as a sum of \(\theta_r\) and \(\theta_{sl}\) (corresponds to \(\omega_r\) and \(\omega_{sl}\), respectively).

Direct Vector Control (Flux Feedback)

Figure 23.19 shows the block diagram of a direct VC scheme for a Current-regulated PWM (CRPWM) inverter-fed induction motor drive (Chattopadhyay 1997a). The reference control signals \(i_{ds}^{es}\) and \(i_{qs}^{es}\), which are dc quantities, are converted to a stationary reference frame by
a vector rotator with the \( \cos \theta_e \) and \( \sin \theta_e \) signals generated from the flux signals followed by 2/3 phase transformation as shown. A flux feedback loop provides precision flux control. The speed control loop provides the torque command that generates the current reference. The air-gap fluxes \( \Psi^{s}_{dm} \) and \( \Psi^{s}_{qm} \) can be measured directly by search coils /Hall probes or estimated (observed) from stator voltage and current signals. Though the air-gap or the stator flux orientation is attractive due to ease of flux measurement or computation, it has been shown that they lead to instability and not a perfect de-coupling and the orientation to rotor flux is resorted to by synthesising the rotor flux \( \Psi^{s}_r \) from the directly sensed air-gap flux.

**Indirect Vector Control (Flux Feed-Forward)**

An alternative to direct measurement or estimation of the flux position for application of VC is to employ a slip relation derived from rotor voltage equations in a synchronously rotating reference system with rotor flux entirely in the \( d \)-axis (Bose 2002),

\[
\omega_{sl} = \frac{L_m}{\Psi^{s}_r} \left( \frac{R'_r}{L'_r} \right) i^{s}_{qs}
\]  

(23.1)
Figure 23.20  Rotor flux oriented indirect vector control for an induction motor with a CRPWM inverter (Chattopadhyay 1997a)

to compute the flux position relative to the rotor by summing a sensed rotor position signal with a commanded slip position signal

\[ \theta_e^* = \theta_{sl}^* + \theta_r. \]  

(23.2)

Figure 23.20 shows the block diagram of the indirect vector-controlled induction motor drive (Chattopadhyay 1997a). The commanded currents \( i_{qs}^* \) and \( i_{ds}^* \) are converted to stator referred reference currents by transformation as in the case of the direct field orientation. \( i_{qs}^* \) is controlled according to the desired torque and constant rotor flux. \( i_{ds}^* \) is obtained as \( \Psi_d' / L_m \) at the steady state. Indirect VC, also known as flux feedforward control, has the limitation in the slip calculation that depends on the commanded machine parameters that may differ from the actual values during the running condition of the drive. Several methods of parameter adaptation have been attempted as discussed in Bose (2002). A universal field oriented controller applicable to both direct and indirect field orientation was reported in DeDoncker and Novotny (1994).

Few typical simulation results as obtained and experimentally verified (Chattopadhyay 1997a) are shown in Figure 23.21 for both indirect and direct VC.

**Sensorless Vector Control of Induction Motors**

Sensorless VC essentially means VC without any speed and flux sensor (Figure 23.22). A mechanical speed encoder is undesirable in a drive as it adds to the cost and reliability
problems, besides the need for shaft extension and mounting arrangement. The speed signal can be estimated from machine terminal voltages and currents by a number of methods (Rajashekara et al. 1996; Bose 2002) such as slip calculation, direct synthesis from machine state equations, model referencing adaptive systems, speed adaptive flux observer, extended Kalman filter and slot harmonics. These estimation methods are complex and dependent on
machine parameters. Further the estimation near zero speed imposes a challenge. Attempts have been made to inject auxiliary signal at a carrier frequency from the stator side for a machine designed with saliency and processing the response but with limited success (Holtz 2002). Several speed-sensorless vector-controlled induction motor drives have been implemented by Toyo Electric Company of Japan in newspaper printing machines, coating machine, textile machines and so on. with a wide range of speed control with speed control accuracy of ±0.5% and speed response of 90 rad/s (Akagi 1998).

Two commonly used methods for flux estimation by sensing the machine terminal voltages and currents are the voltage model and current model as described in Bose (2002). Voltage model flux estimation is better at higher speed ranges, whereas the current model estimation can be made at any speed. A hybrid model (Jansen and Lorenz 1992) is possible where the voltage model is effective at higher speed ranges but transitions smoothly to the current model at lower speed ranges.

Speed-sensorless vector-controlled system requires information on motor parameters to realise high performance. A speed-sensorless vector-controlled inverter equipped with auto-measuring of the parameters is reported in Ohmori et al. (1995). A DSP-based speed adaptive flux observer is described in Kubota et al. (1993).

23.4.3 Induction Motor Drives with Direct Torque Control (DTC)

A new concept to control the torque and flux in induction motor drives, popularly known as DTC, which is basically a performance-enhanced scalar control was developed in the late eighties and commercialised in the late nineties by the ABB with IGCT inverters. It can be shown that the developed torque of the machine is proportional to the product of synchronously rotating stator flux $\Psi_s$, rotor flux $\Psi_r$ and the angle $\theta_{sr}$ between them. The main variable to be controlled in the DTC scheme is $\Psi_s$ that can be directly controlled by the stator voltage $v_s$ (neglecting stator resistance). With this scheme it is possible to obtain a good dynamic control
of the torque without any mechanical sensor on the shaft (sensorless). The scheme is shown in Figure 23.23 (Wu 2006), where both the flux $\Psi_s$ and the torque $T_e$ are controlled by the hysteresis controllers in the outer loops as indicated. The machine voltages and currents are sensed to estimate the torque and the flux vector that gives information about the angle $\theta_s$ in one of the 60° sectors as shown in Figure 23.24 (Bose 2006). The vector $\Psi_s$ rotates in a circular orbit within a hysteresis band covering six sectors as shown. Figure 23.24 (Bose 2006) shows the six active voltage vectors and two zero vectors of the two-level inverter (relevant to the Space Vector PWM control) controlled by the voltage switch logic unit (SLU) of Figure 23.23. If a voltage vector is applied for time $\Delta t$, the corresponding flux vector increment is given by the relation $\Delta \Psi_s = V_s \Delta t$. The flux increment vector contributed by each voltage vector is indicated in the same figure. The flux is initially established at zero frequency in the radial

Figure 23.23 DTC control of induction motor (Wu 2006). Reprinted with permission from IEEE (Chattopadhyay 2010)

Figure 23.24 Stator flux trajectory and voltage vectors (Bose 2006) for a two-level VSI
direction aA, as shown in Figure 23.24a. With the rated flux, the command torque is applied and the flux vector starts rotating in the usual counterclockwise direction within the hysteresis band depending on the selected voltage vector. The motor state calculations are updated in each sampling period $\Delta t$ (e.g., $25 \mu s$) in the software model by a DSP. The control loop errors generate the digital signals $\varepsilon_Q$ and $\varepsilon_T$ through the respective hysteresis-band comparators. The delays associated with the PWM stage are replaced by an optimal switching flux vector selection table SLU (can be realised by an ASIC hardware or through a DSP software) or a look-up table which selects the most appropriate voltage vector to satisfy the flux and the torque demands. The drive has a faster response than the field oriented/VC and the absence of the closed loop current control, PI regulators, vector transformation and conventional PWM algorithm simplifies the scheme. However, as the feedback signals are estimated from the machine terminals, the low speed limitation and the parameter variation problems are similar to those of the stator flux oriented direct VC. In contrast to FOC, which is a linear control where the PWM and the static converter are modeled as a linear actuator, DTC is nonlinear, which in turn exploits the discrete nature of the static converter for the sake of robustness and dynamics. Recently, a number of solutions of the inherent problems have been developed with the use of improved switching logic, discrete SVM techniques, three-level inverters, adaptive hysteresis-band control (Okumas and Aktas 2007) and introduction of fuzzy and neuro-fuzzy techniques involving more computer power. Figure 23.25 (Malik and Khage 1998) shows a circuit configuration of a compact 5 MW three-level IGCT converter motor system ACS 1000 with front-end rectifier and DTC control where the static speed control error is in the range of 0.1%. Typical torque response of a DTC drive is $<10$ ms compared with $10–20$ ms for a vector-controlled drive and $>100$ ms for an open-loop PWM drive. This has been used for pumps, compressors, conveyors and other auxiliary processes in a steel or process industry. ABB has supplied IGCT-based ACS 6000 (3–27 MVA) with front-end controlled rectifier (Active Rectifier Unit) designed to meet specific challenges faced by plate mills and reversing cold mills—one in the new 5 m wide plate mill in China in 2005 where 10 MW synchronous motors are used.

**Figure 23.25** Three-level IGCT Inverter topology for ACS1000 (ABB) (Malik and Khage 1998). Reprinted with permission from IEEE (Chattopadhyay 2010)
23.5 Control of Synchronous Motor Drives

23.5.1 Synchronous Motor Drives with Scalar Control

Self-Synchronous or Commutator-Less Motor

The synchronous motor drives have essentially two different modes of operation. One is the true synchronous mode in which the machine is controlled by inverter or cycloconverter through an independent oscillator just like the \( V/f \) control of an induction motor drive. The other mode is the self-synchronous mode which is known as commutator-less motor (CLM) mode (Figure 23.26) where the inverter or cycloconverter firing signals are derived from a rotor shaft position sensor; dc-CLM, when supplied from an inverter and ac-CLM when supplied from a cycloconverter. In the self-synchronous mode, the synchronous motor acts exactly like a dc motor—the mechanical brush system being replaced by the shaft position sensitive converter. Here, the frequency is slaved to the speed and not vice versa. Therefore, there is no risk of pull out. Any slow down of the motor, no matter sudden, causes a corresponding drop in frequency. The magnitude of the dc current supplied to the static commutator (for dc CLM) determines the torque and the speed.

LCI Synchronous Motor Drive

An important feature of the synchronous machine is that it can be operated at leading power factor and when supplied by a CSI, load commutation can be used. Figure 23.27 shows the power circuit for such a drive. With a normal synchronous motor, the inverter is not capable of load commutation below a certain speed (typically 10%) because of inadequate counter EMF. Special starting arrangements with forced commutation through fourth leg or ‘current pulsing’ are to be made at starting/low speed running. In 1997, an SCR-based inverter based load-commutated commutator-less series motor (CLSM) (SenGupta et al. 2000) with unaided start-up capability, having the field winding in the dc link (Figure 23.28), suitable for a vehicle drive as developed at IIT Kharagpur, India, has been reported. LCI-fed drives in CLM mode are widely used in high-power drives such as pumps, compressors, pumped storage hydro- and gas turbine start-up applications besides continuous rolling mills and traction drives. The

![Diagram of Commutator-less dc motor](image-url)
power rating for this drive has gone up to 100 MW for a NASA wind tunnel drive with a single synchronous motor as discussed later.

**Cycloconverter-Synchronous Motor (ac-CLM) Drive**

Four quadrant torque-speed operation at a high power level with high torque at low speed is the drive requirement for which the cycloconverter-fed synchronous motor as ac-commutatorless (ac-CLM) drive (Figure 23.29) is best suited (Das and Chattopadhyay 1996). Some of the applications are:

- Gear-less cement mill drives; the mill tube is driven from a low-speed wrap-around motor with higher number of poles (Richlen 1971; Salzmann 1978);
- Reversing rolling mill drives with high dynamic requirements for torque and speed reversal employing VC (Timpe 1982; Sugi et al. 1983; Nakano et al. 1984; Ichihara et al. 1986);

![Figure 23.27](image1)

**Figure 23.27** LCI-fed synchronous motor drive

![Figure 23.28](image2)

**Figure 23.28** Power circuit diagram of an SCR-based CLSM (SenGupta et al. 2000)
Drives for mine hoists with high power ratings (Madiseti and Ramlu 1986);

Icebreakers and other ships equipped with diesel generator-fed cycloconverter-fed SM with power rating up to about 20 MW rating per unit (Hill et al. 1987).

The cycloconverter is normally operated with line commutation but can have load commutation if the output frequency approaches or exceeds the line frequency. The firing pulses are derived from shaft position sensors and the machine terminal power factor is maintained at unity by field excitation control. The method of driving the motor from a cycloconverter with the transvector control principle involving FOC was patented and used by Siemens in Germany, for years, in very high capacity cement Mills (>8 MW) and also for rolling mills rated above 3 MW since 1978. A 4 MW (peak loading 10 MW) blooming mill with a cycloconverter-synchronous motor drive having a speed of 60–120 rpm was commissioned in 1981 together with a 4 MW roughing stand of a strip mill (Timpe 1982). The control concept and relevant vector diagrams for field oriented operation is detailed in Salzmann (1978) and Sugi et al. (1983) and discussed briefly in the next sub-section.
23.5.2 Synchronous Motor Drives with Vector Control

The VC of SM is different from that of induction motors primarily due to the fact that, in the latter, the magnetising current can be supplied from the field side independently of the armature current and the space position of the field is located by the position of the rotor. Additionally, the steady-state slip between the rotor (field winding) and the controlled flux vector vanishes in the steady state. Therefore, the indirect or feed-forward type of VC as used extensively for the induction motor does not seem obvious for a synchronous machine. For a self-synchronous or CLM with rotor position feedback and VC, the implementation calls for control of the magnitude and the phase of the stator current with respect to the location of the field winding axis. The response of the field current is sluggish because of the large time constant and as a result, the response of a self-controlled synchronous machine is slow. The response can be improved considerably by using VC, where the transient magnetising current demand to maintain the rated flux can be temporarily supplied from the stator side.

Vector Control of a Cycloconverter-Fed Synchronous Motor Drive

Figure 23.30 (Trantner and Wick 1988; Rodriguez et al. 2005) shows the vector diagram of the synchronous machine (as preferred for a high-capacity steel mill), used to develop FOC required to adjust speed and torque, where $e_s$ is the air-gap emf, $i_q$ (torque-producing component) is the quadrature axis component of the current $i_s$, $i_d$ (flux-producing component) is the direct axis component of current $i_s$, $\Psi$ the magnetic flux, $i_\mu$ is the magnetizing current, $\phi_L$ is the load angle, $\phi_s$ is the flux axis angle and $\lambda$ is the rotor axis angle. The currents $i_q$ and $i_d$ of the stator current in synchronously rotating reference frame are analogous to the field current $I_f$ and to the armature current $I_a$ of the dc machine and the torque can be expressed as $T_e = K_i i_q = K_f^d I_f I_a = K_{i_d}^\prime i_d i_q$. These two components can be independently controlled with VC. Figure 23.31 shows the simplified block diagram (Rodriguez et al. 2005) of the speed and torque control system adopted by Siemens (Trantner and Wick 1988) that includes a PI controller for the speed $n$ and another PI controller for the flux $\Psi$. The speed controller delivers the reference value of the torque-producing current $i_q^*$, while the flux controller delivers the reference value of the field-controlling current $i_d^*$. The stator currents $i_{L1}$, $i_{L2}$ and $i_{L3}$ and the

![Figure 23.30 Vector diagram of the synchronous machine. Reprinted with permission from IEEE (Chattopadhyay 2010)](image-url)
voltages $v_{L1}$, $v_{L2}$ and $v_{L3}$ are measured and used in voltage model block M1 to calculate the magnitude $|\Psi|$ and the position $(\sin \varphi_S, \cos \varphi_S)$ of the flux. The position of the flux is used to transform from $d-q$ to $\alpha-\beta$ reference axis in block 2. Block 4 transforms the two-phase currents $i_{La}$ and $i_{Lb}$ into three-phase reference currents $i^*_{L1}$, $i^*_{L2}$ and $i^*_{L3}$, which are delivered to the current controllers of the cycloconverter. M2 in block 6 is the current model that uses the current components in field coordinates ($i_d$, $i_q$) to determine the flux position with respect to the rotor axis. Then, the field position with respect to the stator axis is obtained by adding $\varphi_L$ to the rotor position $\lambda$. The current model is useful during low-operating speeds as needed at starting and positioning of the mill when the machine voltage terminals are very noisy for using voltage model. Block 2 is the field flux controller used to generate the reference value of the rotor current $i^*_e$ fed to the controlled rectifier of block 8. Nakano et al. (1984) reported the development of a high-performance synchronous motor drive for a rolling mill by Fuji in Japan, with an open-loop flux estimator and PI current controller. Here, the flux linkage was kept constant by feeding part of the field current to the armature windings transiently and the power factor could be controlled to unity. An improved PC (personal computer)-based VC scheme for a 6-pulse non-circulating current cycloconverter-fed synchronous motor with a closed-loop flux observer and operating with unity power factor for a rolling mill drive as...
developed in IIT Kharagpur, India, in 1996 and a prototype made by C-DAC, Trivundrum, India, is reported in Das and Chattopadhyay (1997) and Chattopadhyay (1997b). It is briefly described in the following sub-section.

Observer-Based Vector Control of a Cycloconverter-Fed Synchronous Motor Drive

Figure 23.32 shows the block diagram of an observer-based stator flux oriented vector controlled six-pulse cycloconverter drive as applicable to rolling mills (Das and Chattopadhyay 1997) and the corresponding phasor diagram. This is an improvement on the Siemens’ drives (Bayer et al. 1972; Trantner and Wick 1988) as well as the Japanese one (Nakano et al. 1984). The implementation aims at a control that maintains a spatial orthogonality between the flux vector $\Psi_s$ and the armature current vector $i_a$ as shown in the space phasor diagram. The reference speed and reference flux commands are given to the vector rotator that generates the reference analog voltages for the cyclocoverter (through the current controller) and the field converter. The stator flux is estimated by a closed loop reduced order observer. $C_1$ is the speed controller (PI) that generates the torque command that is divided by the stator flux to generate the torque component of current $i_{sT}$. The magnetisation current along the flux axis $i'_m$ is obtained from a flux controller (PI) $C_2$. The transient stator flux component of current $i_{sm}$ is obtained from the relationship, $I_{sm}^* = i'_m - i_{fd}\cos\delta$, which decays down to zero in the steady-state. The steady state displacement angle is decided by the displacement angle controller and the power factor can be maintained at unity. The set value of the field current is obtained from the relation, $i_{fd} = i'_m/\cos\delta$. $C_3$ is the field current controller (PI) that generates the control voltage for triggering the field converter. The vector rotator (VR) transforms the vector from two-axes flux-torque reference frame to abc stationary reference frame. The observer and the control circuit design aspects together with the PC-based implementation are detailed in (Das and Chattopadhyay 1997). The observer is closed loop in nature, having constant gain matrix, and is robust to speed variation. It is easier for digital computer implementation as it does not contain any derivative term. The synchronous motor model with state variables comprising stator fluxes and stator as well as field currents is utilised to estimate the stator fluxes using the current measurements (Das and Chattopadhyay 1997).

Figure 23.33 shows the simulated and experimental current waveform of a phase following a speed reversal from $+200$ to $-200$ rpm, a range appropriate for reversing rolling mill applications.

23.6 Application Examples of Control of High-Power AC Drives

23.6.1 Steel Mills

While motors used in the primary area of steel making like Coke Oven, Blast Furnace, Steel Melting Shop do not need very accurate speed or torque regulation, the motors used in Roughing mills, Finishing mills, Plate mills, Tube mills, Run-out Tables, Coilers/Un-Coilers, Pinch roles and so on need speed and torque regulation of higher accuracy. Since 1970s, AC motor drives having either IM or SM fed from either direct ac/ac cycloconverters or ac/dc/ac link inverters have replaced the earlier Thyristor-Leonard DC motor drives. The AC Drive realises higher efficiency, less maintenance and a smaller motor. Synchronous motor drives
Figure 23.32  Stator-flux oriented flux-observer based vector-controlled cycloconverter synchronous motor drive. Reprinted with permission from IEEE (Das and Chattopadhyay 1997)
Figure 23.33  Speed and current response to step speed reversal: (a) simulation results, (b) experimental results. The entire experiment lasts 5 seconds. Reprinted with permission from IEEE (Das and Chattopadhyay 1997).

have the advantages over the induction motor drives in that these can be operated in near unity or even leading power factor with excitation control, reducing armature copper loss and permitting simplicity of commutation with thyristors or SCRs (silicon-controlled rectifiers) as switches (as in a LCI-fed drive) and it runs at a precisely set speed independent of load and voltage fluctuations. Thyristor or SCR-based cycloconverter-fed with FOC or VC (Chattopadhyay 1997b) have been extensively used in main rolling mill drives and cycloconverter-fed induction motor drives with scalar V/Hz control have been utilised in roller / run-out table drives.

With the introduction of FOC, a high performance 4 MW Blooming Mill with a cycloconverter-synchronous motor drive having a speed of 60–120 rpm was commissioned by Siemens in 1981 together with a 4 MW roughing stand of a strip mill (Chattopadhyay...
Major manufacturers of cycloconverter drives above 10 MVA are Siemens (Simovert D), Toshiba (Tosvert-μ /S850), ABB (ACS6000C) and Alstom (ALSPA CL9000). Cold rolling mills such as tandem mills require high dynamic response, accurate speed and torque control of main and auxiliary drives while hot rolling mills, such as roughers, and hot strip mills require good torque control and momentary overloadability; all such performance criteria are met by these drives.

Because of the limitations of cycloconverters such as low-power factor, presence of low-frequency inter-harmonics, less maximum output frequency, advances in IGBT and GTO technology cleared the way for their application to the steel mill drives with PWM two-level and later three-level NPC-inverters with high switching frequency, since 1990s. Hitachi and Mitsubishi of Japan reported the development of high-performance three-level GTO-based 6.4 MW and 10 MVA inverters for induction and synchronous motors, respectively, for steel main rolling mill drives in 1996. One such configuration developed by Mitsubishi is shown earlier (Figure 23.10). Regenerative snubber circuit developed to have high efficiency and a SVM method to minimise harmonic distortion are discussed in Okayama et al. (1996). Hitachi (Tobise et al. 1996) developed similar GTO-based three-level inverters 5–6.4 MW and 2 MW IGBT-based three-level inverters for steel rolling mills at the same time. Siemens introduced SIMOVERT-ML drive with three-level GTO converters of MW range with VC for application to synchronous and induction motors. These converters compete with cycloconverters in the capacity region of 10 MVA or less. Three-level IGBT inverters with the same configuration as the three-level GTO inverters in Figure 23.10 were introduced in many steel plants up to 3 MW of medium capacity, for example 1.5 MVA IGBT inverter as in Tobise et al. (1996), where three inverters were driven by a common converter. Group-drive applications like Approach Tables, Run-Out Tables are configured with one inverter supplying several motors in a simple V/f mode. Mitsubishi MELVEC 2000 N three-level IGBT inverter (1.5–3 MVA) is claimed to be 40% smaller than the conventional equipment (Masuda and Toyoda 2000).

Figure 23.34 (Yullang et al. 2008) shows the application of DTC controlled IGCT-based ACS 6000 as supplied by ABB to a cold reversing mill and plate mill, respectively. These schemes result in higher switching frequency (1 kHz) compared with GTO-based schemes (0.5 kHz), higher efficiency (98%) and higher input power factor (0.97) and less space because of snubberless operation. The DTC method employed allows accurate control of both rotor speed and torque without pulse encoder feedback from the motor shaft.

High-performance three-level IEGT inverters have been introduced by Toshiba for main drives in the steel industry since 2000 (Ichikawa et al. 2000, 2004; Suzuki et al. 2001), replacing the GTOs in the same converter-inverter configuration as shown in Figure 23.10, resulting in higher efficiency and less size of the equipments. 4.5 kV, 5.5 kA press-packaged IEGTs have been used in an 8 MVA converter-inverter with 99% efficiency, 50% reduction in converter volume and weight (Ichikawa et al. 2000). The 8 MVA IEGT inverter supplied by TMEIC, Japan (Hosada et al. 2005), for a hot strip mill of Hunan Valin Liangang Steel Co. of China is working since 2003. A new method of PWM control named as fixed pulse pattern PWM to reduce the harmonics in the source input currents without increasing the switching frequency for use with these inverters has been reported in Tsukakoshi et al. (2005). GE-Toshiba has developed 6–26 MVA Dura-bilt5 MV drives with IEGT-based NPC inverters (GE Toshiba 2003). Figure 23.35 shows one phase leg of a three-level 10 MVA IEGT Inverter with its packaging unit (Tessendorf et al. 2008) for rolling mills.
Figure 23.34  (a) Cold reversing mill with ACS6000 and (b) plate mill with ACS 6000 ABB Reprinted with permission from IEEE (Chattopadhyay 2010). (For a color version of this figure, please see color plates.)
23.6.2 Cement and Ore Grinding Mills

By the end of 1960s, the advent of thyristors and control equipment made it possible to design gearless drives via a cycloconverter and a synchronous motor for cement and ore-grinding mills. The world’s first gearless Tube/Ball mill drive with motor rating of 8700 hp (6400 kW) at 15 rpm (44 poles, 5.5 Hz) in Le Havre, France, was reported in 1970 (Wurgler 1970). The electrical aspects of the first large gearless ball mill installed at St. Lawrence Cement company in Ontario, Canada, were reported in Allan et al. (1975) with a motor rating 8750 hp (6500 kW) at 14.5 rpm (4.84 Hz). The motor is in the self-controlled mode with the stator frequency directly controlled by rotor speed (ac-commutatorless motor) with a rotor position sensor. The motor thus cannot fall out of step and the characteristics are similar to dc machine. However, control of these cycloconverter-fed drives was scalar. First gearless drive with the ring motor (rotor of the synchronous machine wrapped directly around the mill cylinder) and FOC is reported by Siemens in 1978 (Salzmann 1978) and later an improved version in Trantner and Wick (1988). The VC system of the cycloconverter-fed synchronous motor used is described under Section 23.5.2. ABB developed world’s largest gearless ball mill drive in cement rated 15000 hp (11200 kW) installed in the United States for a mineral grinding process (Errath 1996). A view of the the “wrap-around” gearless ring motor without shaft and bearings is shown in Figure 23.36. The rotor is divided into a number of segments equaling the number of poles that are mounted directly on the mill tube flange. The flange is bolted on to the mill drum. A typical gearless ore grinding mill for mining applications looks the same (Rodriguez et al. 2005). The grinding circuit of a typical variable speed SAG mill of 12 MW with two fixed ball mills with SM of 5.5 MW for a copper mine is reported in (Pontt et al. 2003; Rodriguez et al. 2005; Bose 2011b). Cycloconverters were preferred instead of LCIs to improve the quality and global performance of the grinding process.

23.6.3 Ship Drive and Marine Electric Propulsion

Electric propulsion is now well-established in large ship drives and in the merchant marine, particularly, in cruise liners, icebreakers, shuttle tankers, and so on, as well as in warships. The schemes include power electronic converters located between the generators and the propulsion
motors to facilitate variable motor speed and thrust from fixed or controllable pitch propellers. The power electronic converters mostly used in modern marine electrical propulsion are ac cycloconverter, LCI and the PWM VSI. The feasibility of a practical marine MC for electrical propulsion system has been studied recently (Bucknall and Ciaramella 2010).

Cycloconverter drive technology is ideally suited to the extreme requirements (large powers at low speeds and high dynamic performance) of the icebreaker. For example, US Coast Guard Icebreaker Healy is equipped with $2 \times 11.2$ MW, $0–130/160$ rpm dual wound motors driving twin shafts, each motor being powered by two $5.6$ MW 12-pulse ALSTOM Alspa CL9000 Cycloconverters capable of providing $175\%$ full load torque for $30$ s at zero speed (English 2001; Radan 2004). A shuttle tanker equipped with ABB made cycloconverter propeller drives is also mentioned in Radan (2004). A vector-controlled cycloconverter-fed drive designed for icebreaker to deliver $16000$ hp to the twin propeller shafts of a Canadian Coast Guard icebreaker is reported in (Hill et al. 1987).

LCI-fed synchronous motor drives (also known as Synchroconverter-CSI drives) are ideally suited to normal high-power ship propulsion applications such as the cruise liners, for example, RCI Cruise Liner INFINITY with two $19$ MW Mermaid podded propulsers which use $2 \times 7$ MW, $0–118/135$ rpm motors with $2 \times 12$-pulse synchroconverters (English 2001; Radan 2004). Another interesting application of LCIs is in a container ship (Clegg et al. 1999), where a 24-pulse SCR-rectifier-inverter system serves as a frequency converter to convert a voltage of $14–25.7$ Hz generated by the shaft generator to a bus voltage of $6.6$ kV, $60$ Hz for the ship’s main distribution system.

Medium voltage source two-level inverters with water-cooled series IGBTs with ratings typically up to $20$ MW, $2000$ rpm, $6.6$ kV have been used in drill ships. The ship Pride
Africa is fitted with 7 medium voltage ALSTOM VDM5000 IGBT variable speed thruster drives up to 4.5 MW (English 2001). World’s first electric warship-UK’s “daring class” Type-45 Destroyer, in service from 2007 is fitted with two 15-phase 20 MW, 4.16 kV ALSTOM VDM25000 PWM drives with advanced induction motors for main propulsion. An integrated power system for all electric ship in a full-scale main propulsion drive for US navy (Crane and McCoy 1999) consists of a main propulsion 19 MW induction motor drive system. The PWM converter (Figure 23.37) consists of three 6-pulse rectifier bridges, three 6 kV dc links and 15 IGBT-based H bridges feeding a 15-phase induction motor.

23.6.4 Mine Hoists, Winders, and Draglines

The trends in the electronic control of mine hoists and winders in the 1970s and 1980s were reviewed in Madiseti and Ramlu, (1986), where it was mentioned that SM supplied by cycloconverter control are ideally suited for hoisting applications that are directly coupled. Torques of about six times the rated torque at low speed are possible and with digital monitoring the winding cycle can be optimised, smooth and accurate. Advanced hoist technologies in coal mines in China and zinc and copper mines in Finland with high-power SM (e.g 2.5 MW, 3 × 3050 V, 8.7 Hz, 65.8 rpm by ABB in Pyhasalmi mine in Finland with shaft depths of 1450 m) are enumerated in Chadwick (2010). The Pyhasalmi mine hoist is the first in the world to
use ABB’s state-of-the-art ACS6000SD with DTC control using IGCTs to power the 16-pole 2.5 MW synchronous motor of the mine hoist. This technology offers several advantages over the alternative systems like cycloconverter and PWM converter in terms of footprint, high reliability, high torque control over the entire speed range, unity power factor and lower energy consumption. The Siemens has supplied two winders for a 537.5-m-deep Majaling coal mine in China equipped with one 3 500 kW synchronous motor and another 435 kW, having Simatic programmable logic controllers for the automation system. Gearless AC drive system-Simine DRAG has been developed by Siemens and Bucyrus with 13 000 hp drive with a performance of 9.7 MW for hoist and dragline for use in Zhungeer coal line in China. The drive with ring motor is controlled by IGBT inverters supplied by Siemens Energy & Automation and is in operation since 2007 (Siemens 2011).

### Pumps, Fans and Compressors in the Industry

Pumps, compressors and fans are used in the widest range of industry: oil and gas sector, water supply and waste water, chemical and pharmaceutical, cement plants, textile and paper, mining, food and beverage, power plants, climate control and refrigeration systems. AC drive applications in this market, sometimes referred as HVAC (Heating, Ventilation and Air Conditioning) have been developing over the last 35 years. An adjustable speed 10 000 hp ac drive utilising a doubly-fed wound rotor ac motor and a cycloconverter in the rotor circuit was proposed in 1974 (Weiss 1974) for driving a pump or compressor for transportation of gas or liquid through a pipe line. Later in 1980s, adjustable-speed LCI-fed synchronous motor drive system with constant V/Hz control for pump and compressors were discussed in Weiss (1983). LCIs with typical power range of 10–75 MW have emerged for these applications (Hiller et al. 2010). Learning experiences encountered on a large variable frequency induction motor drive installation for retrofit of 22 pipeline pumping stations with 3000 HP motors are reported in (Rossman and Ellis 3000). Largest variable-speed synchronous motor fan drive is for the NASA 100 MW wind tunnel consisting of a converter with two independent channels, resulting in a total of four identical six-pulse thyristor bridges and a six-phase synchronous motor having two sets of stator windings with 30° electrical phase shift between them (Bhatia et al. 1999). The efficiency of the LCI drive is very high (99%) and is very important in high-power drives in energy saving.

Oil & Gas utilities and LNG (liquefied natural gas) plants requiring large compressors make use of large-scale variable speed drive systems such as VSI and high-power ac motor drive. TMEIC (Toshiba-Mitsubishi Electric Industrial Systems Co) has developed a 30 MVA IGCT controlled five-level VSI-fed synchronous motor (25 MW, 7.2 kV, 3600 rev min) drive system applicable to oil and gas industry (Tsukakoshi et al. 2009). The five-level inverter is configured with two NPC legs per phase, connected in a single phase and these phases are combined with a star connection for three-phase output. The five-level inverter output voltage and current are much more sinusoidal and of higher magnitude compared to three-level inverter. The 7.2 kV 30 MVA converter can be applied in parallel up to four sets for a maximum capacity of 120 MVA using balancing reactors. Recently, TMEIC has developed a 20 MVA 6.0 kV five-level IEGT Inverter for the LNG Industry with efficiency more than 99% (Tsukakoshi et al. 2010). Commercial drives developed by Siemens (e.g. Siemens Sinamics GM150 converter with IGBTs) and ABB (e.g. ACS 1000, ACS 5000 & ACS 6000 with IGCTs and DTC) are widely used for high-power pump and compressor applications.
23.7 New Developments and Future Trends

With the continued development of power semiconductor devices, multi-level inverters, control and estimation technologies, variable speed high power ac drives have gone through a dynamic evolution and poised for new developments in future. Few among various promising fields are as follows:

- The application of silicon carbide (SiC) power semiconductor devices (Singh and Pecht 2008) replacing the present silicon power devices (as described) in high power drives is expected to improve the system performance, reduce system size, reduce power loss, process high power for a given temperature and thus potentially lowering the overall cost. However, the challenges are the SiC device fabrication processes which are expected to advance in the next few years.

- FPGAs (field programmable gate array) are being progressively used in high-performance industrial control systems (Monmassom and Christea 2007) including rotor flux oriented control (Sinard et al. 2009) and direct torque control of IM (Kowalski et al. 2007). The extremely fast FPGA computation time allows higher throughput and parallel architecture to overcome the typical bottlenecks of DSP sequential algorithms.

- Adaptive, optimal and intelligent control based on fuzzy logic (FL) and neural network are emerging technologies (Bose 2012) that, when commercialised, will have dominant impact on high power drives in future. Adaptive controls can be self-tuning control, model reference adaptive control and sliding mode or variable structure control. Optimal control may be model-based predictive control where a performance parameter like response time, efficiency, or energy consumption is optimised. It has shown lot of promise recently in the high-performance drives (Kouro et al. 2009). Intelligent control is based on artificial intelligence (AI) techniques like expert system, FL, artificial neural network and genetic algorithm. Fuzzy logic has been used in online search-based flux programming efficiency optimisation control of indirect vector-controlled induction motor drive (Sousa et al. 1995). Neural network applications have been proposed in motor drives and power electronics as discussed in Bose (2007). Various fault tolerant control systems of ac motor drives have been researched (Wechko et al. 2004; Delgado et al. 2008) to improve reliability in their operation. The concept here is that the drive will continue to operate at a minimum level of performance as per system requirements after sustaining a fault.

23.8 Conclusions

A comprehensive but brief state-of-the-art review of the development of AC motor control in industrial high-power drives involving high-power semiconductor devices, power converter topologies, induction and SM, advanced control strategies used and their implementation, along with their application examples is presented in this chapter. Scalar and VC of induction and synchronous motor drives using VSI, CSI, LCI and cycloconverter are discussed. Scalar control includes V/Hz control and DTC control as used extensively in high power industrial drives. Vector-controlled IM and SM drives including sensorless control have been elaborated. Recent improvement in MC, for medium-voltage highpower drives is also reported. Application
examples of AC motor control in high-power drives such as steel mills, cement and ore-grinding mills, ship drives, mining winders and hoists, pumps, compressors and fans as developed for these industries by the leading drive manufacturers worldwide are highlighted. At the end, new technology developments and future trends in this field have been indicated. It is hoped that this chapter will serve as a useful reference for the academic researchers as well as the practicing engineers working in the field of high power converters and control of adjustable-speed drives.

References


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