Current-Source Converter and Cycloconverter Topologies for Industrial Medium-Voltage Drives

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Abstract—This paper, along with an earlier published paper as Part 1, provides a comprehensive review of the state of the art of high-power converters (above 1 MW) for adjustable-speed ac drives. In this highly active area, different converter topologies have been developed for various drive applications in the industry. Due to its extensive coverage, the subject is divided into two parts: multilevel voltage source and current source converter topologies. This paper is focused on the second part and covers the current source converter technologies, including pulsewidth-modulated current-source inverters (CSIs) and load-commutated inverters. In addition, this paper also addresses the present status of the direct converter, which is also known as cycloconverter (CCV). This paper focuses on the latest CSI and CCV technologies and an overview of the commonly used modulation schemes. It also provides the latest technological advances and future trends in CSI- and CCV-fed large drives. This paper serves as a useful reference for academic researchers and practicing engineers in the field of power converters and adjustable-speed drives.

Index Terms—Current-source inverter (CSI), cycloconverter (CCV), high-power drives, load-commutated inverter (LCI).

I. INTRODUCTION

POWER converters for adjustable-speed drives can be classified into direct and indirect converter topologies [1], [2]. In addition, indirect topologies can be grouped into two main categories: current- and voltage-source converters. The latter type of converters, particularly multilevel voltage-source converters, was previously addressed in the first part of this paper [3]. This paper will present the rest of the power converter topologies used in medium-voltage ac drives applications (2.3–13.8 kV), which appear in the darkened boxes of the classification shown in Fig. 1.

For the direct converters, the cycloconverter (CCV) is the most used topology in high-power applications, which uses an array of power semiconductor switches to directly connect the power supply to the machine, converting a three-phase ac voltage with a fixed magnitude and frequency to a three-phase ac voltage with variable magnitude and variable frequency [4]. It allows power flow in both directions in an efficient way. CCV drives are a mature technology with technical advantages in low-speed range and high-torque applications, such as grinding mills. Another example is a 400-MW hydropumped storage drive with a 20-pole generator/motor fed by a 72-MVA three-phase 12-pulse CCV [5]. Matrix converters also belong to this category but are not addressed in this paper since the power rating of these converters is only up to 150 kVA [6] until now, unable to reach the megawatt level for large drives due to the limitation of the bidirectional switching devices required by the converters.

The indirect converters can be divided into voltage source and current source topologies, depending on the dc-link energy storage components. The voltage source converters normally use dc capacitors in the dc-link circuits, whereas the current source converters employ dc inducers (chokes) in the dc circuit.

Current-source inverter (CSI) technology is well suited for high-power drives [7], [8]. The CSI can generally be divided into pulsewidth-modulation (PWM) CSI and load-commutated inverters (LCIs). The former uses symmetrical gate turn-off (GTO) or integrated gate-commutated thyristor (IGCT) as a switching device, whereas the latter inverter employs silicon-controlled rectifier (SCR) devices. Generally speaking, the current-source converters feature a simple converter structure, low switch count, low switching $dv/dt$, and reliable overcurrent/short-circuit protection, as summarized in Table I. The main drawback lies in its limited dynamic performance due to the use of large dc choke. High-power CSI drives in the megawatt range are widely used in the industry. It is estimated that a minimum of 700 units of large CSI-fed drives has annually been produced worldwide in recent years.

LCIs are one of the earliest inverters developed for variable-speed drives [9], [10]. Synchronous motors (SMs) are normally used in the LCI drives since the SCR switches in the inverter do not have self-turn-off capability and their commutation is assisted by the SM operating at a leading power factor. The LCI is suitable for very large drives with a power rating of tens of megawatts. This is mainly due to the use of SCR devices that lead to low manufacturing cost and high energy efficiency in comparison to the insulated-gate bipolar transistor or IGCT devices used in other types of drives. A typical example of the LCI drives is a 100-MW SM drive installed in NASA’s wind tunnel test facility [11].
The succeeding sections present the different converter topologies, drive configurations, and corresponding modulation schemes. The latest technological advancements and the future trends of the large drives are also addressed.

II. PWM CSIs

This section is mainly focused on CSI technology, including PWM CSIs for induction motor drives and LCIs for SM drives. The PWM CSI can also be employed for SM drives. Since the CSI drive configuration for the SMs remains the same as that for the induction motors, the CSI-based synchronous drives are not discussed here.

A. PWM-CSI-Fed AC Drives With SCRs

The PWM CSI was proposed in the early 1970s [12] and gained more attention during the 1980s [13]. The inverter uses switching devices with self-extinguishable capability. Prior to the advent of GCTs in the late 1990s, GTOs were predominantly employed in high-power CSI drives [14], [15]. Fig. 2 shows a typical 6600-V PWM CSI drive with an 18-pulse SCR.

The PWM CSI requires a three-phase capacitor $C_f$ at its output to assist the commutation of the switching devices. The capacitor provides a current path for the energy trapped in the leakage inductances of the motor at the moment when a GTO or GCT in the inverter is turned off. Otherwise, a high-voltage spike would be induced, causing damage to the switching devices. The capacitor also serves as a harmonic filter, improving the motor current and voltage waveforms. The value of capacitor is normally in the range of 0.3–0.5 per unit (p.u.) for CSI drives with a switching frequency of about 400 Hz.

Multipulse SCRs can be used as a front end for the CSI drive. Among various rectifier topologies, the 18-pulse SCR is a preferred choice due to its high performance-to-price ratio. For a given voltage and power rating, the 12-pulse rectifier has a cost advantage over the 18-pulse rectifier, but its line current total harmonic dispersion (THD) may not meet the harmonic guidelines set by most standards. The 24-pulse rectifier has a better line current THD than the 18-pulse rectifier, but it costs
more due to the increased number of SCR devices and complex phase-shifting transformer [16].

Six-pulse SCR bridges, which are used as current source rectifiers (CSRs) [17], can be connected in series to form the multipulse rectifier, as shown in Fig. 2, with three units for an 18-pulse configuration. The inverter side uses three series-connected GCT devices per branch. With a voltage rating of 6500 V for SCRs and GCTs, the drive is capable of operating at a utility voltage of 6600 V (line to line). The CSI drive with an 18-pulse rectifier can meet the harmonic requirements set by IEEE Standard 519-1992. Current source topologies may also be used for active power filters to compensate harmonic currents in electrical power systems [18], [19].

To improve the performance of the CSRs, advanced control schemes, such as state feedback controls, can also be employed [20].

B. Modulation Techniques

The switching pattern design for the CSI should generally satisfy two conditions: 1) DC current $i_d$ should be continuous, and 2) the inverter PWM current $i_w$ should be defined. The two conditions can be translated into a switching constraint: At any instant of time (excluding commutation intervals), there are only two sets of series-connected switches conducting, i.e., one set in the top half of the bridge such as $S_1$ in Fig. 2 and the other in the bottom half of the bridge such as $S_2$. Various modulation techniques have been developed for the PWM CSI, including selective harmonic elimination (SHE), trapezoidal pulsewidth modulation (TPWM), and space vector modulation (SVM).

The SHE is an offline modulation scheme that can eliminate a number of unwanted low-order harmonics in the inverter PWM current $i_w$ [21]. Because high-power applications require low losses, low switching frequency is needed. This is why three, five, or seven switching angles per quarter of a cycle are preferred. In the case shown in Fig. 3(a), five pulses are employed. The switching angles are precalculated and then imported into a digital controller for implementation. Fig. 3(a) shows a typical SHE waveform that satisfies the CSI switching constraint. There are five pulses per half cycle with five switching angles in the first $\pi/2$ period. However, only two out of the five angles, i.e., $\theta_1$ and $\theta_2$, are independent. Given these two angles, all other switching angles can be derived.

The two switching angles provide two degrees of freedom, which can be used either to eliminate two harmonics in $i_w$ without modulation index control or to eliminate one harmonic and provide an adjustable modulation index. The first option is preferred since the adjustment of inverter output current $i_w$ is normally accomplished by varying $i_d$ through rectifier control, instead of inverter modulation index control. The switching angles for the elimination of various current harmonics are given in [16].

Fig. 3(b) shows the principle of trapezoidal modulation, where $v_m$ is a trapezoidal modulating wave and $v_{cr}$ is a triangular carrier wave. Similar to the carrier-based PWM schemes for voltage-source inverters (VSIs), the gate signal is generated by comparing $v_m$ with $v_{cr}$. However, the trapezoidal modulation does not generate any gate signals in the center $\pi/3$ interval of the positive half cycle or in the negative half cycle of the inverter fundamental frequency. Such an arrangement can satisfy the switching constraint mentioned earlier.

In addition to the TPWM and SHE schemes, the CSI can also be controlled by SVM [22]. A typical space vector diagram for the CSI is shown in Fig. 3(c), where $I_1$–$I_6$ are active vectors and $I_0$ is zero vector. The active vectors form a regular hexagon with six equal sectors, whereas the zero vector $I_0$ lies at the center of the hexagon.

For a given length and position, $I_{ref}$ can be synthesized by three nearby stationary vectors, based on which switching states of the inverter can be selected and gate signals for the switches can be generated. When $I_{ref}$ passes through sectors one by one, different sets of switches are turned on or off. The inverter output frequency corresponds to the rotating speed of $I_{ref}$, whereas the magnitude of its output current can be adjusted by the length of $I_{ref}$.

The SVM scheme has not yet found practical applications mainly due to the following three facts: 1) The magnitude of the inverter output current is normally adjusted through the rectifier, instead of the inverter modulation index; 2) the bypass (shoot-through) operation of the SVM scheme will cause additionalswitching losses; and 3) the harmonic performance of the SVM

![Fig. 3. Modulation schemes for CSIs: (a) SHE, (b) trapezoidal PWM, and (c) SVM.](image-url)
The SVM scheme features easy digital implementation and superior dynamic performance. It can be used in future CSI drives with time-critical control algorithms such as active damping control for LC resonance suppression [23].

A typical switching pattern arrangement for industrial CSI drives is illustrated in Fig. 4, where $f_{SW}$ is the GCT switching frequency, $f_1$ is the inverter fundamental output frequency, and $N_p$ is the number of pulses per half cycle of the inverter PWM current $i_w$. The SHE scheme is used at high inverter output frequencies, whereas the TPWM scheme is utilized when the motor operates at low speeds. The SHE scheme has much better harmonic performance than TPWM, but it is difficult, if not impossible, to simultaneously eliminate more than six harmonics. The harmonic performance of the TPWM has minimal effects on the CSI drives since the drives normally operate at a frequency of above 30 Hz with the SHE scheme. To minimize switching losses, the maximum switching frequency of the inverter is normally below 500 Hz in industrial CSI drives [16]. The efficiency of the overall drive varies, depending on the input rectifier configuration and the modulation method; it has been reported that the CSI achieves efficiencies close to their VSI counterparts [24].

C. PWM CSI-Fed AC Drives With PWM Rectifiers

Fig. 5 shows a typical configuration of the CSI drives with a single-bridge PWM CSR as a front end. The rectifier and inverter have identical topologies using symmetrical GCTs. With the GCT voltage rating of 6500 V and two GCTs connected in series in each of the converter branches, the drive is capable of operating at the utility voltage of 4160 V (line-to-line).

The PWM rectifier can use either the SVM or SHE schemes. The SHE scheme is preferred due to its superior harmonic performance. With a switching frequency of 420 Hz and the utility frequency of 60 Hz, a maximum of three low-order current harmonics (the 5th, 7th, and 11th) can be eliminated. The other harmonics can be attenuated by the filter capacitor, leading to a low line current THD.

DC current $i_d$ can be adjusted by the rectifier delay angle or modulation index control. The delay angle control produces a lagging power factor that can compensate the leading current produced by the filter capacitor, resulting in an improved power factor. Furthermore, when the CSI drive is used in fan or pump applications, its input power factor can be made to be near unity over a wide speed range [25]. This can be realized by using the SHE scheme with a delay angle control and properly selecting the line- and motor-side filter capacitors. This control scheme features a simple design procedure, easy digital implementation, and reduced switching loss, and is implemented in commercial CSI drives.

Similar to the VSI drives, the rectification and inversion process in the CSI drive generates common-mode (CM) voltages [26], [27]. If not mitigated, the CM voltages would appear on the motor, causing premature failure of its winding insulation. The problem can effectively be solved by introducing an isolation transformer and grounding the neutral of the inverter filter capacitor, as shown in Fig. 5. In doing so, the CM voltages will be transferred to the transformer winding, and the motor is no longer subject to any CM voltages.

D. Transformerless CSI Drives

As discussed earlier, one of the major problems in CSI- and VSI-based medium voltage drives is the CM voltage, which would cause premature failure of motor winding insulation if not mitigated.

Generally speaking, there are four possible solutions to the CM voltages in the current-source-fed drives. 1) Add an isolation transformer to block the CM voltages. This solution has a couple of added benefits: The leakage inductance of the transformer can serve as a filter for harmonic reduction; and the transformer may be arranged as a phase-shifting transformer for multipulse rectifiers for harmonic cancellation. 2) Add to the dc link an integrated dc choke that provides both differential and CM inductances. The main advantage of this approach is the low cost due to the elimination of the isolation transformer. 3) Add a CM choke to the dc link for CM voltage suppression in addition to the differential choke that is inherently required by current-source-fed drives. 4) Add a three-phase ac CM reactor either on the supply side or on the motor side to block the CM voltages. The first brings a few drawbacks such as high cost, increased drive size and weight, and high operating cost due to transformer power losses. The latter two solutions are considered not practical due to the high cost of additional components and the loss of the benefits that the isolation/phase-shifting transformer can provide. In summary, the integrated dc choke technology is a viable and practical solution for the time being to the elimination of the isolation transformer in a current-source-fed drive.

Fig. 6 shows the schematic of a transformerless CSI drive, where an integrated dc choke with a single magnetic core and
The concept of the integrated choke is verified on a low-power laboratory CSI drive. The laboratory drive has the same configuration as that in Fig. 6, except that a six-pulse SCR was used, instead of the PWM rectifier. The inverter operates at a fundamental frequency of 57.7 Hz with the filter capacitor of $C_f = 0.31$ p.u. The switching frequency of the inverter is 180 Hz. The motor operates under no-load conditions, at which the CM voltage reaches its highest level.

Fig. 7 shows the measured waveforms of the drive with the integrated dc choke installed, where $v_A$ is the stator line-to-ground voltage, $v_o$ is the stator neutral-to-ground voltage, and $i_{cm}$ is the common current [16]. Fig. 7(a) shows the waveforms of the drive with $L_d = 1.0$ p.u. and $L_{cm} = 0$ (the CM coils are not used). The neutral point of filter capacitor $C_f$ is left open. The stator neutral-to-ground voltage $v_o$, which should be zero when the motor is powered by a three-phase utility supply, is essentially the total CM voltage $v_{cm}$ generated by the rectifier and inverter. It contains triplen harmonics, which are of zero-sequence components, with the third and sixth harmonics being dominant. Line-to-ground voltage $v_A$ is composed of two components: the motor phase (line-to-neutral) voltage $v_{Ao}$ and its neutral-to-ground voltage $v_o$. Obviously, the CM voltage superimposed on phase voltage $v_A$ is severely distorted with high peaks, causing damages to the motor insulation system.

With the CM coils connected in the drive ($L_{cm} = 4.8$ p.u.) and the capacitor neutral grounded, the measured waveforms are as shown in Fig. 7(b). Comparing with Fig. 7(a), we can make two observations.

1) The waveform for $v_A$ is close to sinusoidal and free of CM voltages. The CM voltage is fully blocked by the integrated dc choke. This observation can be verified by the waveform for $v_o$ ($v_o = v_{cm}$), which is essentially zero.

2) A small amount of CM current $i_{cm}$ flows to ground through the filter capacitor. For the CSI drive with a PWM rectifier shown in Fig. 6, the CM current $i_{cm}$ flows between the rectifier and inverter through the two capacitor neutrals and therefore will not cause any neutral current in the utility supply.

Finally, it should be noted that the design of the integrated dc choke is not unique. A cost-effective design with only two coils on a magnetic core is currently employed in the transformerless CSI drive, but the details of this choke cannot be released here. This technology has been used in commercial CSI drives since 2002 by one major manufacturer, Rockwell Automation Canada. Another valid design is given in [29].

E. Parallel CSIs

To increase the power rating of a CSI-fed drive, two or more CSIs can operate in a parallel manner [30]. Fig. 8 illustrates such a configuration where two inverters are connected in parallel. Each inverter has its own dc choke, but the two inverters share a common filter capacitor $C_f$ at their output.

The parallel operation of the two inverters may cause unbalanced dc currents. The main reasons for the unbalanced operation include the following: 1) unequal ON-state voltages of the semiconductor devices, which affect steady-state dc current
balance; 2) variations in the time delay of the gating signals of the two inverters, which affects both transient and steady-state current balance; and 3) manufacturing tolerance in dc choke parameters. The dc current can be balanced by making use of redundant switching states of the parallel inverters [16].

Fig. 9 shows a set of waveforms measured from a laboratory parallel CSI drive operating at 1500 r/min. The dc currents \( i_1 \) and \( i_3 \) in Fig. 9(a) are kept balanced by the drive controller, except for the middle portion of the current waveforms, where the current balance control algorithm is temporarily disabled. The steady-state motor voltage and current waveforms are shown in Fig. 9(b), which are close to sinusoidal. The parallel CSI technology can find applications in the CSI drives with a power rating of higher than 10 MW. However, while there are functional and cost advantages to a single dc link, having two or more dc current supplies has advantages in terms of reliability, redundancy, and ac mains capability for canceling current harmonics, which are issues that also need to be considered.

III. LCI-FED SM DRIVES

A. Topology Description

LCI is one of the earliest inverters developed for variable-speed drives [9], [10]. Fig. 10 shows a basic configuration of the LCI-fed SM drive. It is mainly composed of a phase-controlled rectifier and an SCR inverter. The rectifier provides an adjustable dc current \( i_d \), which is smoothed by a dc inductor \( L_d \) and then feeds the inverter. Since the SCR device does not have self-extinguishing capability, it can naturally be commutated by load voltage with a leading power factor. The ideal load for the LCI is, therefore, SMs operating at a leading power factor, which can easily be achieved by adjusting rotor field current \( i_f \).

The LCI is unable to use any PWM scheme. Inverter output current \( i_A \) is of a quasi-square wave. However, the motor voltage waveform \( v_{AB} \) is close to sinusoidal superimposed with voltage spikes caused by SCR commutations. The motor current contains low-order harmonics, such as the 5th, 7th, 11th, and 13th. These harmonic currents cause torque pulsations, as well as additional power losses in the motor [31].

The LCI-fed drive features low manufacturing cost and high efficiency due to the use of inexpensive SCR devices and lack of PWM operation. The LCI is suitable for very large drives with a power rating of tens of megawatts, where the initial investment and operating efficiency are of great importance. However, the input power factor of the drive changes with its operating conditions. In addition, the rectifier input current is highly distorted. In practical applications, the LCI drive is equipped with harmonic filters to reduce line current THD, as shown in Fig. 10. The filters can also serve as a power factor compensator.

B. Latest Technology for Large LCI-Fed Drives

Fig. 11 shows a block diagram of a 100-MW variable-speed LCI-fed SM fan drive [32]. The power converter section of
the drive consists of two independent channels, resulting in a total of four identical six-pulse SCR bridges. To reduce the line current THD, the line-side bridges are configured as a 12-pulse rectifier, where the 5th, 7th, 17th, and 19th harmonic currents produced by the six-pulse bridges are canceled by a phase-shifting transformer with 30° phase shift between its two secondary windings.

The line current distortion can further be reduced by harmonic filters connected to the tertiary winding of the transformer or active filters [33]. These series-resonant LC filters are normally tuned to the 3rd, 5th, 11th, and 13th harmonic frequencies to attenuate possible 3rd and 5th harmonic currents produced by the voltage distortion/unbalance of the utility grid and also to mitigate the 11th and 13th harmonic currents that are not eliminated by the 12-pulse rectifier. Power factor correction can be achieved by the proper design of the LC filters [32]. These filters can produce a leading current that can compensate the lagging current produced by 12-pulse rectifier.

Both the line-side and motor-side bridges can operate in rectifying or inverting mode, allowing the synchronous machine to operate as a motor or generator. For fast dynamic braking, the load mechanical energy can automatically be converted to electrical energy by the LCI and then sent back to the utility supply.

The SM has two sets of stator windings with 30° electrical phase shift between the two windings. It is essentially a six-phase motor for the reduction of torque pulsations caused by quasi-square current waveforms in each of the stator windings. As a result, the torque pulsations and mechanical stress on the shaft train are greatly reduced.

The efficiency of the LCI drive is usually very high. When the drive operates under the rated conditions, the converter efficiency can be higher than 99%. This is very important in large drives, where a small reduction in energy efficiency translates into high operation costs.

Megawatt-range drives require high reliability due to downtime production losses. LCI-based drives have been a cost-effective solution for very large power applications for adjustable-speed drives; even its reliability comes close to that of CCV drives [34]. Production losses due to converter unavailability in a typical grinding mill application can rise up to USD 17,000 per hour. Hence, fast and accurate detection and diagnose of a fault can reduce emergency maintenance or troubleshooting times. Some fault conditions due to asymmetrical operation of a 12-pulse LCI drive and remedial strategies have been presented [35], [36]. A review of important failure sources involved in grinding mill applications is presented in [37]. In [38], the switching failure of CSIs is analyzed, and a detection and protection method is presented, to avoid overcurrents and system damage.

C. Applications

Because of its simplicity and reliability, the LCI configuration is applied in large drives where high dynamical performance is not required, such as high-power fan drives, grinding mills, and high-power motor and generator starters. The starting function is very important for the black starting of large generators with island operation, especially for recovering after a power blackout.

In a conventional LCI-fed drive, the drive can slowly be started by pulsing the dc-link current produced by the rectifier. This process continues until the SM generates sufficient induced voltage to naturally commutate the inverter. This method features no extra components but suffers a long starting time. To solve the problem, an LCI-fed commutatorless series motor drive has been proposed [39]. The drive is composed of a three-phase diode rectifier, an LCI, and an SM with its field winding connected in series with the dc link. This unique design enables the drive to operate over the entire speed range, including startup, with better dynamic performance.

Another interesting application of LCIs has been proposed for a container ship [40], where a 24-pulse SCR rectifier–inverter system serves as a frequency converter. This converter converts a voltage of 14 Hz to 25.7 Hz generated by a shaft generator to a bus voltage of 6.6 kV with a fixed frequency of 60 Hz for the ship’s main distribution system. In addition, LCI-based medium-voltage ship electric propulsion is available in the industry with 24- or 48-pulse configuration, from 0 to 150 r/min and up to 2 × 21 MW.

IV. CCVs

A. Topology Description

Phase-controlled CCVs are direct ac–ac converters based on the antiparallel connection of thyristor converters without a dc link employing a well-known and mature control technology of natural commutation, as described in [41] and [42].

The basic operating principle is to use a switch arrangement, as shown in Fig. 12(a) (six-pulse CCV), to synthesize a variable-amplitude and low-frequency ac voltage by successively connecting the load to the different phases of the ac supply Fig. 12(b).

The main advantages are the low switching losses and, therefore, high efficiency; the inherent bidirectional power flow capability through the complete speed range; very high power ratings with low space requirement; simple and robust structure; low maintenance; and high reliability. The drawbacks are the limited frequency range (< source frequency), low power

![Fig. 11. Block diagram of 100-MW LCI-fed drive system.](image-url)
factor at low modulation indexes of about 0.8, and generation of harmonic currents, which cause harmonic voltages in the power supply network. Installation of filter circuits is often necessary. This has enabled the use of CCVs for the development of high-power drive systems for control in low-speed range and high-torque applications, such as cement mills, ore grinding mills, ship propulsion, and mine winders [34], [43].

This section highlights the applications in ore grinding mills, where near 60% of the electrical energy consumed in mining plants is employed by grinding mill drives in concentrator facilities. Economy of scale pushes the trend for larger mill sizes in the range of 11–21 MW, as presented in [37], with applications for semiautogenous and Ball grinding mills. The mechanical limitations of girth gears have motivated the use of wraparound SMs for gearless motor drives (GMDs) fed by high-power CCVs operating with variable speed [37], [44], [45]. Fig. 13(a) presents the power circuit of a CCV-fed mill drive with an SM with a single three-phase winding, where two sets of six-pulse CCVs fed by transformers with star-delta secondaries built a 12-pulse CCV, using 72 thyristors for reducing the harmonic interaction at the network and at the machine side. Double stator winding motors are also employed.

The voltage and current output waveforms of a 12-pulse CCV under steady-state operation are illustrated in Fig. 13(b) and (c), respectively. The controlled three-phase voltages and currents of the machine follow the references given by the control system, to meet the position, speed, and torque required by the grinding process.

B. Latest Advances

In order to improve the performance and reliability of CCV-fed drives, two current issues are being faced: network harmonic interaction and commutation failures [46]–[49]. Harmonic interaction and reactive power compensation are mitigated with proper modeling and filter design, including the behavior of weak network and interharmonics, as described in [50]–[52]. The network harmonic interaction is mainly characterized by the injection of interharmonics and subharmonics components by the CCV operation, which affects the power quality of the supply. This important subject has been addressed in many contributions, including its analysis, modeling, simulation and experimental studies, harmonic reduction methods, and their impact on the power quality [52]–[58].

Loss of control of natural commutations under abnormal operating conditions at the power network is a very important weakness to be mitigated. A commutation failure can produce a short circuit at the machine terminals through the CCV, as
described in [59]. At short-circuit condition, important forces can be generated within the machine against the soil plates in fundamentals, resulting in system shutdown and even damages. This demands proper coordination of electrical protection and sizing of machine fundamentals for avoiding stator frame displacement and friction between stator and rotor poles of the machine, as presented in [46]. In addition, harmonic torque components may excite mechanical resonances [48]. Methods for mitigating these effects are under development.

In order to improve reliability and performance, current R&D work is dedicated to reduce the probability of such failures with improved structural dynamics modeling with finite-element analysis for the following: 1) improved monitoring of the network and drive operating conditions; 2) improved electrical and mechanical robustness of the motor; 3) improved foundation system; and 4) improved control for eliminating the chance of a two-phase short circuit at the machine terminals. In addition, improved process control of grinding within the mill is a current target in order to smooth the load fluctuations and to gain better availability and reliability of the system, avoiding stresses and overloads. New instrumentation such as Impactmeter and SAGanalizer has been described in [48] and [50].

C. Applications

As mentioned earlier, CCVs are used for high-power low-speed applications, due to their high efficiency and speed-frequency limitations. They have found a special market: gearless cement mills, steel rolling mills, ore grinding mills, pumps and compressors, mine winders, and ship drives [60]. Fig. 14 shows a simplified diagram of the semiautogenous grinding mill process for copper production, in which four CCV-fed gearless SM drives are controlled using space vector control [61].

Table II presents the typical parameters of an SM for a GMD mill drive of 12.7 MW, highlighting the estimation of the short-circuit torque as six times the rated torque.

Table II

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<td>( \eta )</td>
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V. Future Trend

The current source converter technology has been used in high-power adjustable-speed drives over the past two decades. The drive technology has evolved with three major technological developments. In the late 1980s, the current source drive was composed of a 12- or 18-pulse SCR and a GTO PWM inverter operating at a switching frequency of about 200 Hz. This drive configuration was used until late 1990s when the GCT device became commercially available, with which the GTO devices in the inverter were replaced. In the meantime, the switching frequency of the GCT inverter was increased to about 420 Hz. To overcome the drawbacks of the SCRs, the latest generation current source drive employs a GCT PWM rectifier with a GCT inverter. This drive configuration has been on the market since 2003.

The use of the GCT rectifier incorporated with the integrated d\-c choke technology presented in the previous sections has led to the elimination of the phase-shifting (or isolation) transformer in the drive, resulting in significant cost reduction for the drive manufacturer and end user as well. Considering the unique features of the current source drive, such as simple converter structure, reliable short-circuit protection, transformerless design, and inherent four quadrant operation, it is expected that this drive technology will increasingly be used in various industrial applications in the future.

In today’s current source drives, the SHE technique is a dominant modulation scheme. When the drive operates at low motor speeds, where it is very difficult to eliminate a large number of low-order harmonics, the trapezoidal PWM can be employed. Although the SHE scheme provides a superior harmonic
performance in comparison to other modulation schemes, this is an offline scheme with less flexibility and limited dynamic performance.

With the improvements of GCT switching characteristics, it is expected that the SVM scheme with a switching frequency of 500 Hz or higher will play a role in the future drives. The increased switching frequency will improve the harmonic and dynamic performance of the drive, whereas the flexibility of the SVM scheme will facilitate the implementation of advanced drive control schemes. As a result, the current source drives can be extended to other industrial applications that require high system dynamic performance.

On the other hand, CCVs are a mature and well-established technology. It seems that CCVs will still dominate high-power low-frequency operation applications for some years to come, due to their efficiency, reliability, and very high power ratings with low space requirement. Despite the maturity of the technology, power quality and interharmonic performance remain a topic of interest and study of many researchers [52]–[58]. System monitoring, fault detection, and diagnosis are also some trends under development for this technology [48], [59].

VI. CONCLUSION

With the recent technological advancements, high-power adjustable-speed drives are increasingly used in industry. Together with the first part [3], this paper provides a comprehensive overview of the state-of-the-art high-power drive technologies. This part focuses on current source converter and CCV technologies for high-power drives. Current-source-converter-fed drives are today’s converter family with the highest power rating in industrial drive applications. CSI-PWM converter drives offer new interesting performance, overcoming some drawbacks of natural commutated LCI- and CCV-fed drives. However, LCI and CCV drives have a strong presence in the industry with a niche in very high power applications (>10 MW).

This paper covers various converter topologies and drive configurations. In addition, different PWM techniques were reviewed, latest drive technologies were discussed, and future trends were analyzed. This paper serves as a useful reference for academic researchers and practicing engineers working in the field of high-power converters and adjustable-speed drives.

REFERENCES


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