Medium-Voltage Drives

Challenges and the existing technology

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This article presents an overview of state-of-art solutions, advances, and design and research trends in medium-voltage (MV) drive technologies—and also discusses the challenges and requirements associated with the use of such drives. The choice and deployment of MV drives in industries are associated with numerous requirements related to the front-end converter (grid side) and inverter (machine side). The focus is on solutions that present high efficiency; low price, size, and weight; minimum harmonic distortion; reduction in dv/dt; mitigation of common-mode (CM) voltage; avoiding torsional vibration; transformerless solutions; fault detection capability; and condition monitoring. **<AU: Can dv/dt be spelled out/defined?>**

The ever-growing demand for electrical energy and the continuous rise in energy prices compel us to conclude that energy must be used more efficiently. Modern power electronics technology with high efficiency and appropriate control approaches is needed in energy-intensive industries to decrease the immense waste of energy and improve power quality. Since electric motor drive systems are the major consumers of energy, they have the greatest potential for improvement in terms of efficient energy consumption. High-power motors, mostly operating in MV, are of most interest, due to their enormous energy consumption [1].

MV drives have found extensive applications in several industries, such as in the oil and gas, petrochemical, mining, water/waste, pulp/paper, cement, chemical, power generation, metal production and processes, traction, and marine drives sectors. To improve power quality and system response and to reduce operation cost and energy loss, the installed MV drives should be adjustable speed drives (ASDs). Figure 1(a) shows the global market growth of MV drives from 2008 to 2015 [2]. Due to the recession during 2009 and 2010, there was little or negative growth in the global market. Due to fracking of unconventional shale gas
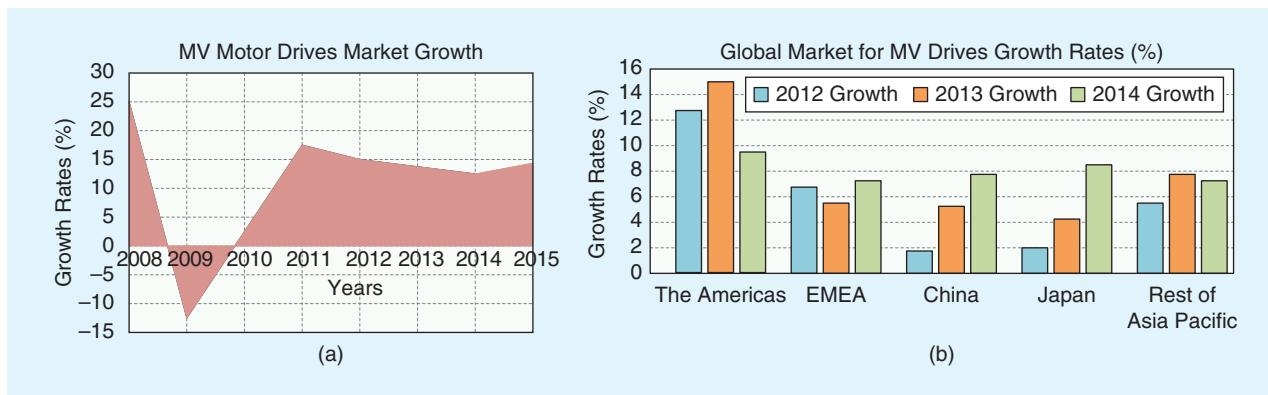
FIG 1 (a) The global MV drive market growth. (b) Global market growth for MV drives by region. **<AU: Kindly spell out EMEA.>**

and oil in the Americas, the sale of MV drives increased during 2012 and 2013, whereas, in Europe, growth was recovering. Figure 1(b) shows the market growth for MV drives during 2012–2014 by region [3].

The use of adjustable-speed MV drives guarantees significant savings in energy, as shown in Figure 2, and decreases payback time up to 2.5 years. Table 1 also shows the benefits of ASDs for pumping applications. Control techniques with transformerless solutions lead to a further decrease in the payback time [4]. Nevertheless, the deployment of such drives is associated with several requirements and challenges. Significant challenges are with the power line side (e.g., power quality, resonance, and power factor), motor side (e.g., dv/dt, CM voltage, and motor derating caused by generated harmonics, resonance, torsional vibration, and traveling wave reflections), and semiconductor devices (e.g., switching losses and reliability) [1], [4]. **<AU: Please check whether the preceding edited sentence conveys the intended meaning.>** Unfortunately, various challenges related to converters—line side as well as motor side—are faced when installing MV drives. **<AU: Please check whether the preceding edited sentence conveys the intended meaning.>** Hence, the motivation behind this article is pointing out the challenges and problems faced when using MV drives and indicating the direction for proper use and understanding of such drives. The article presents the existing MV drive technologies and emphasizes the need for further development and enhancement of MV drives.

MV Drive Topologies

MV drives are classified to cover a power range of 0.2 MW to almost 40 MW at the MV level of 2.3–13.8 kV [4]–[6]. However, most of the installed MV drives in industrial settings are in the range of 1–4 MW, with voltage ratings of 3.3–6.6 kV [6]. A typical block diagram of a MV drive is shown in Figure 3. Small size, lower cost, high efficiency and reliability, fault protection, ease of installation and maintenance, high dynamic performance, and regenerative capability in some applications are the essential requirements for MV drives. A list of some of the industrial drives is
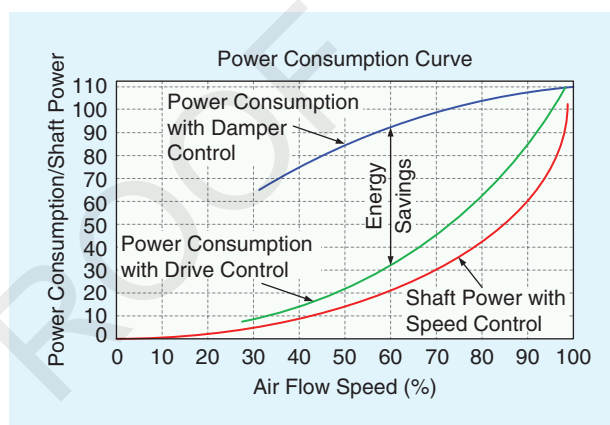

FIG 2 A comparison of power consumption for fan applications.

Table 1. Benefits of ASDs for pumping applications.	
Speed Level	**Benefits**
Soft start of motor	No network voltage dips
	Reduced mechanical stress
High speed	Maximum capacity
	Best productivity
Low speed	Best energy efficiency
	Reduced operating costs
Precise and optimal speed	Best efficiency point of pumps
	Increased lifetime of equipment
Soft stop of motor	No water hammering
	Reduced mechanical stress

presented in Table 2. In this table, the power rating, devices and topology used, and control methods are presented. Furthermore, the popular converter topologies in MV drives are summarized in Figure 4 [7], [8]. **<AU: Table 3 is being reformatted as a figure and is being redesignated as Figure 4. All subsequent figures have been renumbered. Please check that the renumbering is correct, both in the text and in the figures themselves.>**
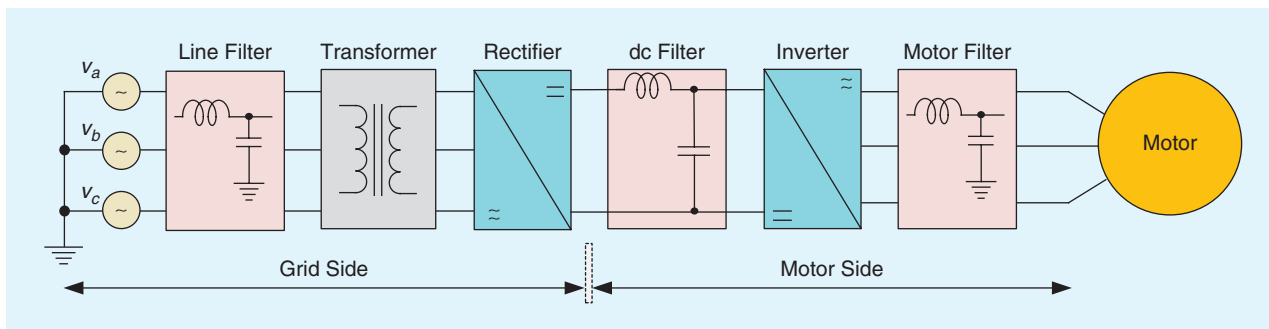
FIG 3 A typical MV ASD.

Table 2. A market overview of industrial MV drives.					
Manufacturer	**Power**	**Voltage (kV)**	**Topology**	**Semiconductor**	**Control Method**
ABB [55]	0.315–5.0 MW 0.25–72 MW 2.0–36 MW 3.0–36 MW 2.0–72 MW	2.3–4.16 4.0–6.90 6.0–13.8 up to 3.3 2.1–10	3L-NPC-VSC 5L-NPC-VSC 5L-HNPC-VSC	IGBT IGCT	DTC
SIEMENS [56]	0.15–14.2 MW 0.82–18 MW 2.8–31.5 MW 0.8–85 MW	2.3–4.16 3.3–7.2 2.3–12 4–7.2	MMC-VSC 3L-NPC-VSC 5L- NPC-VSC	IGCT IGBT low-voltage/MV IGBT	V/f FOC
TMEIC [57]	4.0–120 MVA	1.25–7.2	3L-HNPC 5L-HNPC 5L-PWM	IGBT, gatecommutated thyristor (GCT) IGCT, IEGT	V/f
AMTECH [58]	0.25–12.5 MW	3.3–11	7L-CHB-VSC (3.3kV) 9L-CHB-VSC (4.16kV) 13L-CHB-VSC (6.6 kV) 19L-CHB-VSC (11 kV)	IGBT	V/f FOC
ALSTOM [59]	1.4–7.2 MVA 2.2–8.0 MVA 7.0–9.5 MVA 8.3–13.5 MVA	up to 4.16 up to 4.16 up to 3.3 up to 10	2L-VSC 4L-FLC-VSC 3L-NPC-VSC PWM-CSI	high-voltage (HV) IGBT GTO	FOC
Schneider Electric [60]	0.5–10 MVA	2.3–6.6	3L-NPC-VSI	HV-IGBT	V/f FOC
Fuji Electric [61]	5.2–10.5 MVA	0.28–8.3	9L-NPC-VSC 17L-NPC-VSC	HV-IGBT	V/f FOC
DELTA GROUP [62]	0.28–9.52 MVA	3.3–11	7L-CHB-VSC (3.3 kV) 9L-CHB-VSC (4.16 kV) 13L-CHB-VSC (6.6 kV) 19L-CHB-VSC (10 kV) 21L-CHB_VSC (11 kV)	HV-IGBT	V/f FOC
EATON Corporation [63]	0.22–4.29 MVA	2.4–13.8	3L-NPC-VSC	IGBT	V/f
Toshiba International Corporation [64]	0.22–3.73 MVA	2.4–4.16	9L-NPC-VSC	IGBT	V/f FOC
WEG Equipamentos Elétricos [65]	up to 3.36 MVA	2.3–4.16	3L-NPC-VSC 5L-NPC-VSC	HV-IGBT	V/f
Hitachi [66]	0.31–10 MVA	2.4–11	2~9L-CHB-VSC	HV-IGBT	FOC
INGETEAM [67]	0.8–36 MVA	2.3–6.9	3L-NPC-VSC	HV-IGBT, IGCT	V/f, FOC
Rockwell Automation [68]	1.5–25.4 MVA	2.4–6.6	3L-NPC-VSC 5L-NPC-VSC	HV-IGBT SGCT, SCR	FOC
Yaskawa [69]	0.15–3.73 MVA	2.4–4.16	9L-CHB-VSI 17L-CHB-VSI	IGBT	V/f FOC

<AU: Please spell out MW, MVA, GTO, SGCT, NPC-VSC, HNPC, MMC-VSC, CHB-VSC, DTC, V/f, and FOC. Please also confirm if LV, HV, and GCT have been spelled out correctly in this table.>
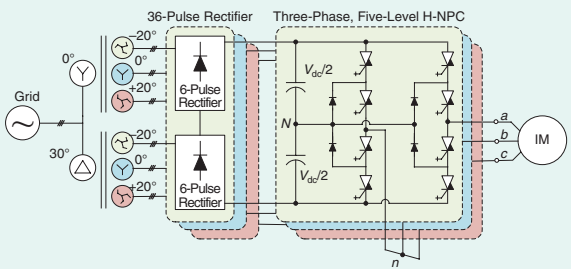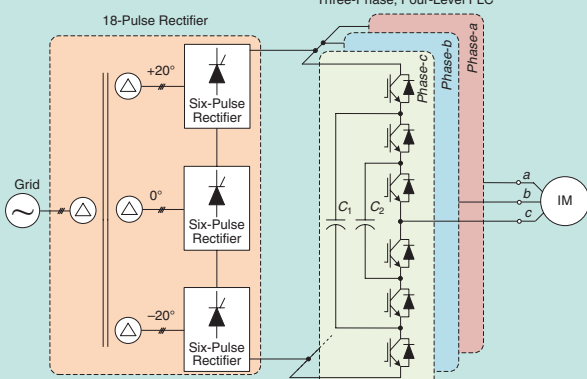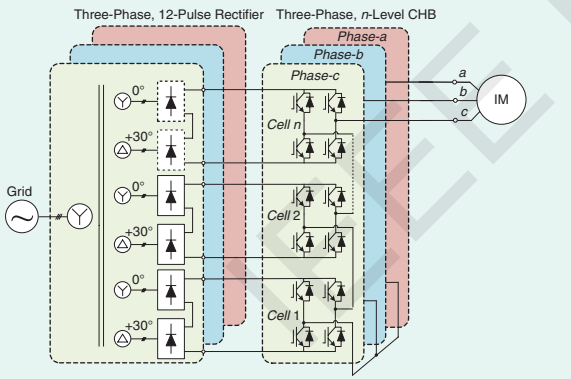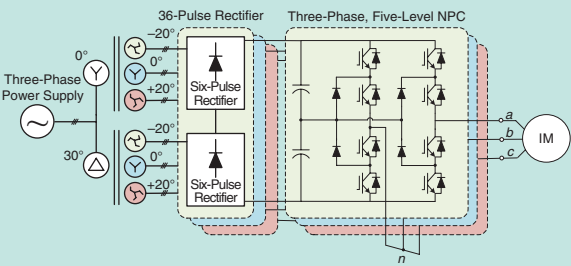
Topology	Description
1) Three-Phase 5L-HNPC [7], [55], [57] 	The 5L-HNPC bridge inverter is developed from the three-level NPC inverter topology. This inverter has some unique features that have promoted its application in the MV drive industry. The inverter phase voltage contains five voltage levels instead of three levels for the NPC inverter. This leads to lower dv/dt and THD. The inverter does not have any switching devices in series, which eliminates the device dynamic and static voltage sharing problems. However, this topology requires three isolated dc supplies, which increases the complexity and cost of the dc supply system [1].
2) Three-Phase 4L-FLC [8], [59] 	This topology has evolved from the two-level inverter by adding dc capacitors to the cascaded switches. There are three complementary switch pairs in each of the inverter. Therefore, only three independent gate signals are required for each phase. The flying-capacitor inverter can produce an inverter phase voltage with four voltage levels. In this topology, some voltage levels can be obtained by more than one switching state. The switching state redundancy is a common phenomenon in multilevel converters, which provides great flexibility for the switching pattern design. However, the practical use of the flying-capacitor inverter seems limited due to the use of a large number of capacitors and complex control scheme [1].
3) Three-Phase NL-CHB **<AU: Please confirm if NL-CHB is the correct term.>** [58], [62], [66], [69] 	The cascaded H-bridge (CHB) multilevel inverter (MI) is one of the most popular converter topologies used in MV drives. It is composed of multiple units of single-phase H-bridge power cells. The H-bridge cells are normally connected in cascade on their ac side to achieve MV operation and low harmonic distortion. In practice, the number of power cells in a CHB inverter is mainly determined by its operating voltage and manufacturing cost. The use of identical power cells leads to a modular structure, which is an effective means for cost reduction. However, the main disadvantage and limitation of this topology is that the need for a large number of isolated voltage sources increases the converter cost.
4) Three-Phase 5L-NPC [56], [65], [68] 	The diode-clamped MI employs clamping diodes and cascaded dc capacitors to produce ac voltage waveforms with multiple levels. The main features of the NPC inverter include reduced dv/dt and THD in its ac output voltages. More important, the inverter can be used in the MV drive to reach a certain voltage level without switching devices in series. In this topology, capacitors have been used to generate an intermediate voltage level. However, the voltages on these capacitors are unequal, which results in unbalancing the dc-link voltage.

FIG 4 An overview of popular converter topologies in MV drives.

The main disadvantage of multilevel inverters (MIs) is the complexity of the power circuit and controls. However, the use of MIs in MV drives offers improved power quality, lower switching losses, high voltage capability, and lower dv/dt [9]. There are different types of power switches that could be adopted for MV drives. These include the injection enhanced gate transistor (IEGT), the integrated gate-commutated thyristor (IGCT), and the insulated-gate bipolar transistor (IGBT). The gate drive circuits of IEGTs are more reliable than IGCT drive circuits. The failures in time (FIT) ratio of IEGTs versus IGCTs is four to one. Furthermore, the IGBT gate drive circuit is simpler and has fewer components than IEGT gate drive circuits. Hence, IGBT gate drive circuits are more reliable than IEGTs [10].

Modern power semiconductor switches have a peak voltage blocking capability of nearly 6.5 kV, which restricts the maximum voltage ratings of the inverter and the motor in MV high-power drives. The apparent power that can be obtained is limited by the available MV IGBT switches, which have a peak current conducting capability of 750 A. **<AU: Please check whether the preceding edited sentence conveys the intended meaning.>** Series or parallel combinations of semiconductor switches are used to overcome the limits of switch ratings, but with these arrangements, a balance of the current and voltage between devices is achieved using extra measurements [11].

Challenges and Requirements of MV Drives

Power Quality and LC Resonance Suppression
Harmonics in the voltage and current waveforms of the utility grid is a crucial problem that needs to be effectively resolved. Diode-based rectifiers draw distorted current from the grid and cause notches in the voltage waveforms. This results in numerous problems in the power grid, such as equipment failure, computer data loss, and malfunction of communications equipment. Various standards such as IEEE 519-1999, IEC 1000-3-2, and IEC 61000-3-2 define the limit of harmonics injected into the power grid [6]–[8]. To reduce current harmonics or to compensate for the input power factor, an LC line-side filter is a common solution. However, the low damping LC resonances may cause undesired oscillations or overvoltages in the grid side because of the low impedance of the MV grid. This may destroy the switching devices or other components of the rectifier circuits. Solutions to this problem should assure low harmonics and low dv/dt using just a reactor instead of an LC filter, or using a small filter.

Inverter Switching Frequency
High dv/dt is generated with the use of high-switching-frequency semiconductor devices in power electronic converters, which can produce CM voltage and currents, electromagnetic interference (EMI), shaft voltages, bearing currents, and high voltage stress that negatively affect the insulation life of motors and transformers [12]. **<AU: Please check whether the preceding edited sentence conveys the intended meaning.>**

The harmonic distortion of the output waveforms increases with the decrease of inverter switching frequency. MIs provide voltage/current waveforms with improved harmonic spectrum and lower dv/dt, which limits the insulation stress on the motor windings. However, the higher number of switching devices in MIs tends to reduce their overall reliability and efficiency. On the other hand, an inverter with a lower number of output voltage levels requires a large LC output filter to decrease the motor winding insulation stress. The challenge is to reduce waveform distortions and total harmonic distortion when the lower switching frequency is used, to ensure high power quality, and to allow fast transient operations. The switching loss due to the fast transition is an important issue that should be considered in MV drives. The maximum and minimum modulation depth and a power factor range between 1 and –1 are the critical operating points of MIs. When applying continuous modulation methods, some switching devices reach their maximum allowable junction temperature, while other switches remain much cooler. Unbalanced distributions of junction temperatures depend on the type of modulation method used. These problems can be resolved at the expense of additional effort and cost. The operating cost can be reduced with the minimization of switching losses. This also enables reducing the cooling requirements. Hence, the cost and size of the drive are reduced. The switching losses of MV semiconductor devices contribute the major portion of the total device losses. Hence, a reduction in switching frequency allows increasing the maximum output power. On the other hand, harmonic distortion at the line and motor side increases with the decrease of switching frequency [13].

A comparison of losses in a three-level neutral point clamped (3L-NPC) converter, a three-level flying capacitor (3L-FLC), a four-level flying capacitor (4L-FLC), and a nine-level series-connected H-bridge (9L-SCHB) is reported in [14], [15]. **<AU: Please check whether the preceding edited sentence conveys the intended meaning.>** Figure 5 shows switching losses as a function of frequency at different classes of output voltage (2.3 kV, 3.3 kV, and 4.16 kV) of various types of MIs [15]. It can be observed that in all types of converters, the losses increase with an increase in the switching frequency and with the voltage. The smallest losses are found in the 9L-SC2HB MI. At 2.3 kV, losses in the 3L-NPC and SC2LHB MIs are almost the same, but at 4.16 kV, losses in the 3L-NPC MI are almost double those of the SC2LHB [15].

Motor Side Challenges

High dv/dt and Wave Reflection
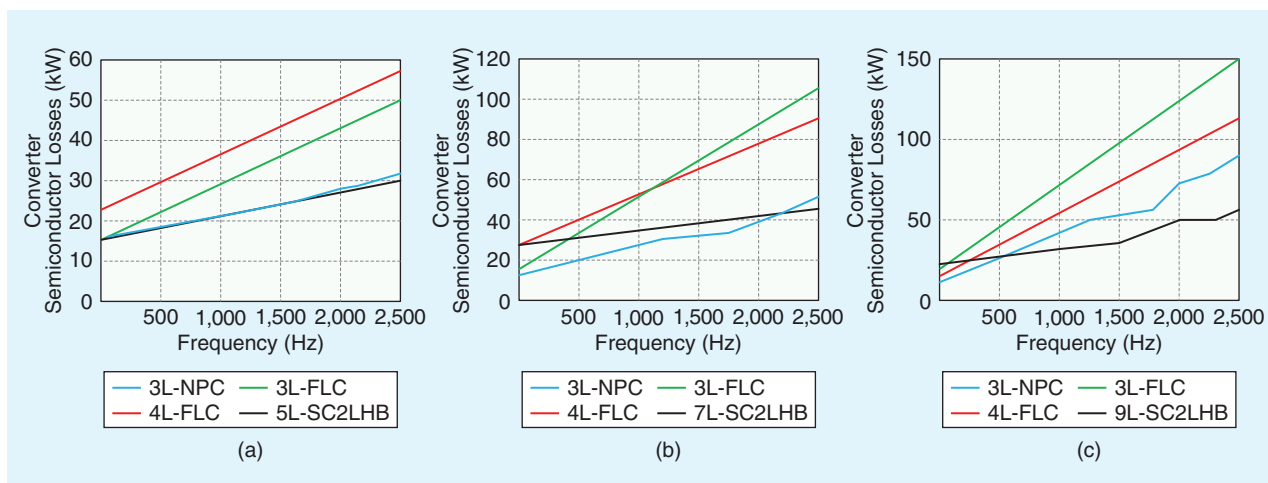The high switching frequency of power devices results in high dv/dt at the rising and falling edges of the inverter

FIG 5 NPC, FLC, and Series Connected converter semiconductor losses versus switching frequency at (a) 2.3 kV, (b) 3.3 kV, and (c) 4.16 KV.

output waveform. Such a high rate of change of voltage may result in failure of the motor winding insulation due to partial discharges. Furthermore, such rapid voltage transition induces rotor shaft voltages that cause current flow in the shaft bearing, which finally leads to motor bearing failure [16]. The switching pattern of the power switches affects the wave reflection value, which is produced by the mismatch between the cable and the inverter and the motor wave impedances. The motor cable works as a transmission line where the voltage pulses will travel very fast, up to 150–200 m/µs [15]. When the pulses take more than half the rise time to move from the inverter to the motor, a full wave reflection occurs. For that worst case, the wave reflections will double the voltage on the motor terminals at each switching transient. The critical cable length for 500 V/µs is in the 100-m range and for 10,000 V/µs in the 5-m range [1]. The wave reflection coefficient Γ is depended on the ratio between motor and cable wave inductances $\Gamma = (Z_{\text{motor}} - Z_{\text{cable}})/(Z_{\text{motor}} - Z_{\text{cable}})$ **<AU: Please verify that this equation is written correctly.>** Nevertheless, cable diameter (Z_{cable}) is around 80–180 Ω, which is much smaller than motor wave impedance, which is around 2–0.4 kΩ [17]. **<AU: Please verify that the preceding sentence conveys the intended meaning.>**

The high dv/dt also causes EMI on the cables between the inverter and the motor. The expensive shielded cables are used to avoid these effects; nevertheless, the electromagnetic emission may affect the operation of nearby installed electronic equipment. In the inverter, the dv/dt still depends on the switching characteristics of the power devices, and it could still be problematic if no output filter is used. To get guaranteed low THD in both motor and line ends, passive filters are commonly employed. **<AU: Kindly spell out THD.>** The high value of the inductor in the LC filter must be used in most high-power drive systems, but that causes a higher voltage drop across the inductor.

The increase in the capacitor value of the filter reduces LC resonant frequency, which is affected by the parallel connection of the filter capacitor and motor magnetizing inductance. This leads to instability in the drive system. To overcome this issue, active damping could be proposed while at the same time suppressing LC resonance to achieve high efficiency [18]. **<AU: Please check whether the preceding edited sentence conveys the intended meaning.>** Furthermore, the use of an LC filter introduces a phase shift between the voltages at the output of the feeding converter and the voltage at the motor terminal [19]. This phase shift may pose a control problem if not taken into account. Hence, the control algorithm should be modified accordingly.

CM Voltage

The CM voltage on the motor side is produced because of the switching actions of the power converters. This phenomenon has to be taken into consideration while designing the motor drive [20]. CM voltage is mostly responsible for the ground leakage current through stray capacitances that ultimately may damage the motor bearing. Replacement of the bearing is an expensive and time-consuming process, and hence unplanned maintenance must be avoided. Normally, the bearings should be replaced or maintained during the scheduled or planned maintenance. Great effort has been invested to minimize the CM voltage in MV drives to save the drive system from catastrophic failure. The most widely used approach is to modify the pulse-width modulation (PWM) strategy toward minimizing the CM voltages. **<AU: Kindly check that PWM is spelled out correctly.>** Another approach is to employ passive filters at the output of the PWM inverter. However, the weight and cost of the drive system will increase [20].

For the MIs, the CM voltage is similar to the traditional two-level inverter, but with a lower level. Therefore, this topic is still a subject of research, and several contributions
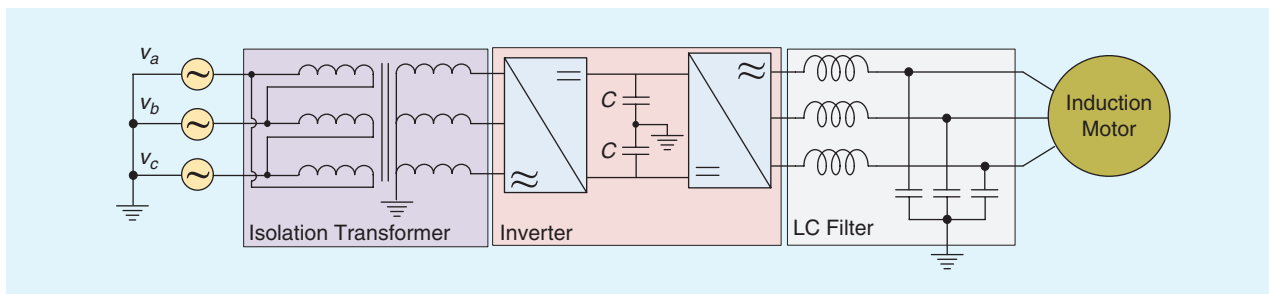
FIG 6 The use of the isolation transformer.

have been reported in recent years [21]. An effective solution to the issues mentioned above might be found mainly by offering a lower-switching-frequency drive system with very low harmonic content. Other possible solutions for such a problem could be grounding the brushes on the motor shaft [16] and using dv/dt-resistant winding insulation [22]. Furthermore, a dual inverter-fed open-end winding (neutral if the winding is removed) induction motor drive with two isolated dc power supplies for CM voltage elimination and to maintain dc-link capacitor voltage balancing is reported in [12]. **<AU: Please check whether the preceding edited sentence conveys the intended meaning.>** The neutral point of the dc link and motor and/or star point of the output filter capacitors has been grounded through a grounding network using isolation transformers to reduce CM voltage. The use of the isolation transformer is shown in Figure 6.

At a low modulation index, the three-phase system looks continuous, which leads to very low dwell time, resulting in an increase in CM voltage. There will also be high spikes in the dc side that affect the reliability and performance of the motor drive. To overcome this, the dwell time is modified to decrease CM voltage. The adjusted dwell time is compensated for in the subsequent cycles of the switching periods [23].

Use of Inverter Output Filters

Passive and active filter-based solutions are employed to mitigate the problems that arise due to PWM actions [19], [24], [25]. Presently, passive filtering is commonly used for such problems. Passive filters are hardware circuits that are installed at the output terminals of the converter structure [26]. The most common approach is using filters based on inductors, capacitors (low-pass LC filters), or CM chokes or CM transformers [26]. **<AU: Please check whether the preceding edited sentence conveys the intended meaning.>** For reducing the overvoltages at the motor terminals (especially in the case of long cable connections) differential-mode LC filters are used [16]. On the other hand, differential-mode LC filters make it extremely difficult to apply precise control in these motors. Control system design under low-speed conditions is complicated because of phase shift between voltages at input and output of the LC filter installed at the output of an inverter. Also, there is a voltage drop across the LC [26]. Usually, it is assumed in

the drive control that the output voltage and current of an inverter are equal to the motor input voltage and current. The region of proper motor operation remains limited if there are any discrepancies. Hence, it is necessary that the measurement circuits or the control algorithms of the electric drive be modified [27].

Using MIs in drive systems results in a reduction of motor winding insulation stress. However, the reliability and efficiency of the inverter may decrease. The practice is to make it possible to use very small LC filters or even exclude them by ensuring low harmonic voltage waveforms while maintaining a low switching frequency. Furthermore, the control strategy that is chosen must actively damp filter oscillations and allow fast dynamic operation with very low switching frequencies [28].

Regeneration Capability and Power Factor Correction

In general, for all electric devices, a high power factor is desired. Therefore, rectifiers with low current harmonics and those capable of operating at almost unity power factor are required as utility interfaces for many ASDs. The requirement of a high power factor is especially important for MV drives due to their high power rating. The rectifier design is a decisive factor for the optimum size, cost, and efficiency of the MV drive.

The most popular solution for high-power regenerative loads is the use of a multilevel active front-end (AFE) converter that provides the regeneration at reduced harmonics and operation at a high power factor and active/reactive power combination [29]. Therefore, it is important in some applications to use an AFE multilevel converter providing harmonic mitigation in the power grid and an almost unity power factor for all operating points. It is highly advantageous for MV applications that require regeneration capability. **<AU: Please check whether the preceding edited sentence conveys the intended meaning.>** Figure 7 shows a cycle of power and speed trajectories [29]. The use of multilevel AFE solutions makes it possible to improve the input power factor, power quality, total cost, and volume by possibly eliminating line side transformer. Back-to-back converters (converters with AFE) are almost double the cost of a single converter. Still, they are a worthy investment to achieve the solution with nearly perfect sinusoidal input currents at nearly

unity power factor and with regenerative capability. **<AU: Please check whether the preceding edited sentence conveys the intended meaning.>**

Torsional Vibration

In the MV drive, torsional vibration can occur because of the large inertia of the motor and its mechanical load. This occurs when the natural frequency of the mechanical system matches the frequency of torque pulsations caused by the motor current harmonics [30]. Excessive torsional vibrations at resonance can result in high twisting torque and hence breakage of shafts and couplings. The undamped response is shown in Figure 8(a) [31]. The torsional vibrations can also damage other mechanical components in the system. Pulse width modulation control with harmonic elimination can be helpful to overcome such problems. The operating points that excite the shaft in PWM inverter-fed motors can be predicted without torque sensors as shown in Figure 8(b) [31].

Transformerless Solution

Complex multiwinding transformers can mitigate harmonics through phase shifting in modular converters. However, an isolation transformer can represent 30–50% of electric drive system size and 50–70% of the system's weight. **<AU: Please check whether the preceding edited sentence conveys the intended meaning.>** The comparison of the average drive system space and weight with and without a transformer is shown in Figure 9. In addition to soaring raw material costs for the transformer itself, an isolation transformer adds to total drive costs with extra cabling, air conditioning to cool the transformer, engineering time, concrete pad construction for outdoor transformers, and overall installation [32].

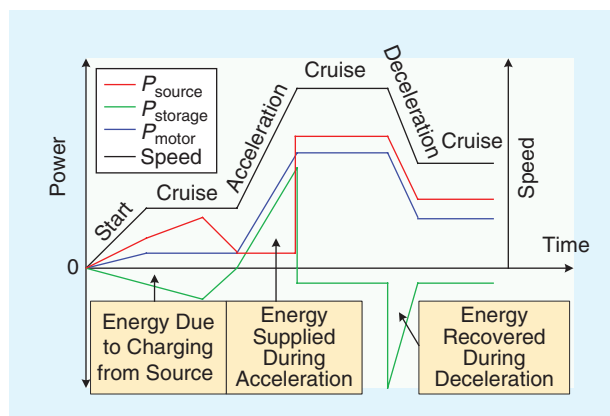Issues such as cost, space, weight, and platform balance can be improved significantly with fewer transformers for

FIG 7 Power (source, storage, motor) and speed trajectories. **<AU: From where was this image obtained, and do you have permission from the source to use it?>**

an offshore platform. To control pump motors on downhole wells, each drive requires a multiton transformer. Offshore platforms typically require 20 MV drives (sometimes up to 40 or more) [32]. A significantly large cooling system is required in a tropical environment, because a 1,000 kVA transformer generates up to 2 kW of heat energy. The transformerless solution provides substantial energy savings [33]. This feature is also important in applications such as utility distribution systems and high-voltage vehicle drives [34]. Solutions are desired that reduce CM voltage, produce sinusoidal output waveform, and limit dv/dt in a transformerless MV drive.

Even though transformers protect the motor from CM voltage, the high-level CM voltage stress on the motor is imposed on the transformer and cable insulation. To withstand the CM voltage stress, specific transformer and cable insulation is required. But in transformerless solutions, MV
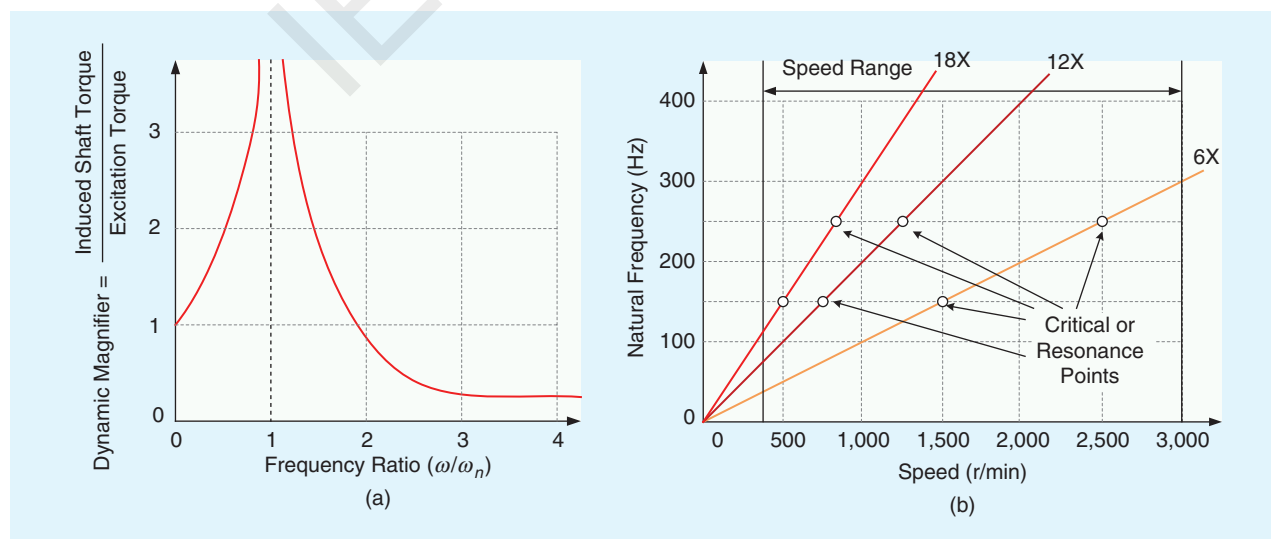

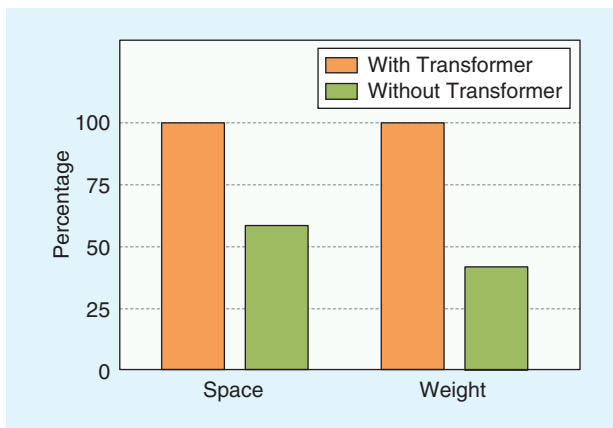**FIG 8** (a) An undamped response. (b) A Campbell diagram.

FIG 9 A comparison of average drive system space and weight with and without a transformer.

variable speed drives require very good insulation on the motor side to sustain high CM voltage stress. **<AU: Please check whether the preceding edited sentence conveys the intended meaning.>** Hence, the integrated CM dc choke is used to block the CM voltage and reduce motor neutral to ground voltage. The structure of the integrated choke and its connection diagram in transformerless motor drives is shown in Figure 10 [35].

Transformerless MV motor drives usually require a high level of motor insulation to overcome CM voltage stress or require the use of an additional inductor with approximately the same impedance as the transformer to be replaced [36]. The use of shunt active hybrid filters solves this problem [24]. In Figure 11, a calculation of FIT rates of the considered transformerless converter topologies is

given and compared to a conventional traction drive system using a low-frequency transformer [37].

Fault Detection and Condition Monitoring

Under severe operating conditions, there should be accurate techniques for fault diagnosis and condition monitoring of MV drives to avoid financial losses due to unscheduled and forced shutdown. Therefore, condition monitoring and fault diagnosis of electrical motors is another important challenge to be met for MV drive systems. In this area, a significant amount of work has been done in recent years, and a comprehensive review is presented in [38]. The interesting possibility of sensorless fault detection involves using observer-based diagnostic methods for mechanical fault detection [39]. **<AU: Please check whether the preceding edited sentence conveys the intended meaning.>** More advanced solutions are also possible to detect failures when LC inverter output filters are installed on the drive [40]. Any partial discharge in the stator of high-voltage rating machines can be monitored by using high-frequency current transformer sensors located at hazardous locations such as oil and gas facilities [41].

Research and Industrial Trends

Components
The present research and industrial trends in the area of MV drives are multidimensional, encompassing the front-end converter, inverters, motor, and control. A new trend is using advanced materials for power semiconductor switches, such as silicon carbide (SiC)-based switches. Simulation of SiC thyristors has given excellent conduction and switching
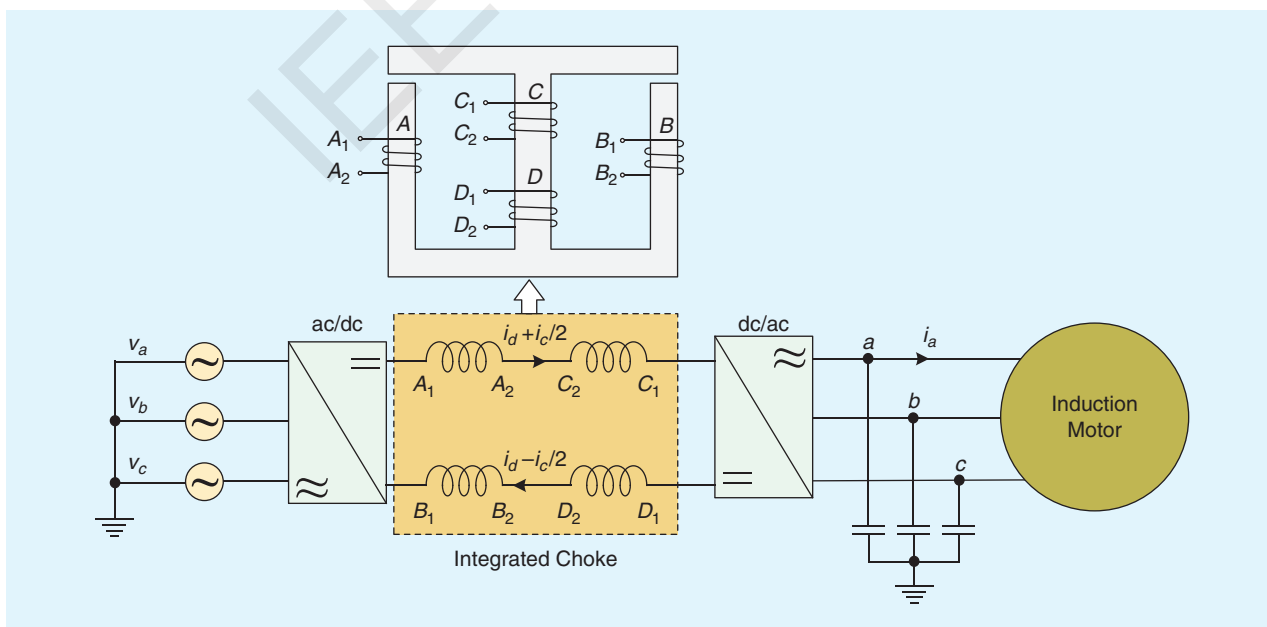

FIG 10 The structure of the integrated choke and its connection diagram in single word motor drives.

performance. So SiC thyristors hold promise as devices for high-power applications. They have the drawback that they need a di/dt snubber and also a dv/dt snubber for turn-off. This drawback has been overcome by development of the SiC emitter turn-off thyristor, improving the speed and dynamic performance of the device [42]. In [43], a full bridge converter was realized using SiC MOSFETs. **<AU: Kindly spell out MOSFETs.>** In semiconductor research, SiC power switches promise to increase efficiency by 10% due to reduced switching losses. However, up to now no MV drive manufacturer has declared adoption of SiC devices. This may be due to the high cost of the devices and anticipation of the high current switching devices yet to come on the market. **<AU: Please check whether the preceding edited sentence conveys the intended meaning.>**

An Intelligent Power Module has been developed to protect IGBTs from short circuit and to provide a negative voltage to avoid false switching signals, which reduces switching losses [44]. Furthermore, to obtain closed-loop gate control, a new technique has been proposed in [45]. The voltage across parasitic inductance of IGBTs is monitored to measure switching speed and di/dt, so that the gate drive voltages are adjusted to control the switching speed, allowing the full capability of power devices to be utilized. **<AU: Please check whether the preceding edited sentence conveys the intended meaning.>**

Topologies
For more than 6 kV, the modular multilevel converter is the best solution to dispense with transformers and isolated power sources. But they have the problem of voltage fluctuation and voltage balance of capacitors. The research trends in modular multilevel cascaded inverters have been discussed in [46], which proposes methods to mitigate the fluctuation in ac voltage to stabilize operation at low speed and low frequency, and those methods are compared with two other methods.

Control and Modulation Techniques
To control MIs at low switching frequency, the synchronous optimal PWM technique was proposed in [47]. This modulation technique provides considerable benefits. For example, the THD level of the machine current doesn't effect from low switching frequency. **<AU: Please check that the previous sentence is correctly worded to achieve the intended meaning.>** The technique also maintains an optimal CM voltage and neutral point potential balance. To improve the dynamics of the control system, the hybrid direct torque control was proposed in [48]. In this control system, the torque is shown to be proportional to the quadrature axis component of the current. This can improve the calculations of error (between quadrature reference current and actual quadrature current). Initially selected harmonic elimination was proposed in [49] and then in [50]. After that, new techniques to eliminate the selective harmonic elimination PWM schemes were suggested, such as
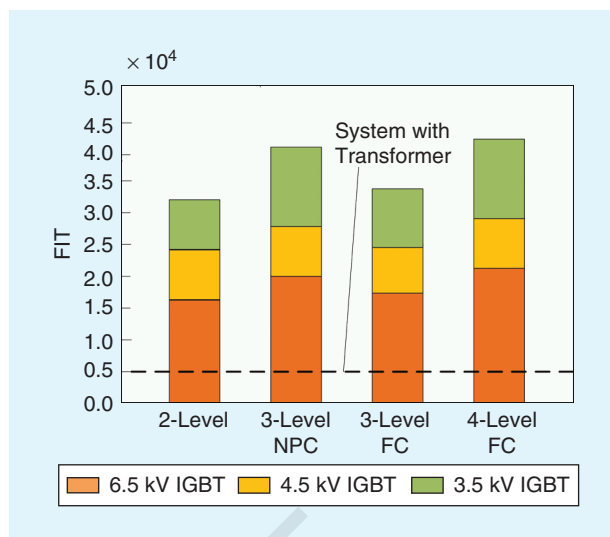

FIG 11 A comparison of the reliability of converters.

Programed PWM [51], and Multilevel SHE-PWM for series-connected inverters [52], [53]. The major challenge with SHE is solving online the algebraic equations obtained for specific harmonic cancellation [54].

Conclusions
This article discusses the problems associated with controlled MV ac drives and the trend toward lowering switching frequency and improving the efficiency of MV drive systems. In analyzing MV drives, the quality of current and voltage wave shapes at both the input and output terminals is an important factor. The application, the topology used, the size of filter components, the switching frequency, and the control strategy handle the current waveforms. There will be minimal effects on the motor side if a better power factor and power quality with higher efficiency are obtained. **<AU: Please check whether the preceding edited sentence conveys the intended meaning.>** In this article, most of the existing shortcomings—such as overvoltage due to dv/dt or wave reflection, bearing currents due to CM voltage, regeneration capabilities, torsional vibration, isolating transformer or transformerless solutions, fault detection, and condition monitoring—were discussed, and solutions were noted whenever possible.

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PEM

MV drives have found extensive applications in several industries, such as in the oil and gas, petrochemical, mining, water/waste, pulp/paper, cement, chemical, power generation, metal production and processes, traction, and marine drives sectors.

The use of adjustable-speed MV drives guarantees significant savings in energy and decreases payback time up to 2.5 years.

Small size, lower cost, high efficiency and reliability, fault protection, ease of installation and maintenance, high dynamic performance, and regenerative capability in some applications are the essential requirements for MV drives.

The high switching frequency of power devices results in high dv/dt at the rising and falling edges of the inverter output waveform.

Passive and active filter-based solutions are employed to mitigate the problems that arise due to PWM actions.

Complex multiwinding transformers can mitigate harmonics through phase shifting in modular converters.

Issues such as cost, space, weight, and platform balance can be improved significantly with fewer transformers for an offshore platform.

A new trend is using advanced materials for power semiconductor switches, such as SiC (SiC)-based switches.

To control MIs at low switching frequency, the synchronous optimal PWM technique was proposed in.

An Intelligent Power Module has been developed to protect IGBTs from short circuit and to provide a negative voltage to avoid false switching signals, which reduces switching losses.

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