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Review Paper

Review of Medium Voltage High Power Electric Drives

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The field of electric drives in general, and medium-voltage high-power drives in particular, has recently experienced considerable progress. Numerous interesting developments have been reported in the literature. Various reliable, efficient, and cost-effective medium voltage drive topologies, handling high powers up to 120 MW, have been proposed in the literature. This paper provides a detailed overview of the current state-of-the-art in medium-voltage high-power drives and the challenges facing them.

Keywords: medium voltage electric drives, variable frequency drives, multilevel inverters

1. Introduction

Low Voltage (LV) drives have input voltages less than 690 V and are used for Low-Power (LP) applications, while Medium Voltage (MV) drives are generally covering output power from approximately 200 kW to 120 MW and using voltages from 2.3 kV to 11 kV (1)(2). Recently, many industrial applications such as refiners, mills, crushers, blast-furnace blowers, gas compressor stations and gas liquefaction plants, require high-power (HP) ratings. Advances in power electronics made the development of HP and MV adjustable-speed electric drives possible for various industrial applications. The main objective of these drives is to control the load speed and/or torque in an efficient and reliable way, without injecting harmonics to the grid.

Electric drives, in general, went through different development eras. In the 1960–70s, electric drives were mainly DC motor based. At that time, AC motor variable-speed drive controls have not been able to go beyond a simple open-loop Voltage/frequency (V/f) control (3). HP AC motors were dominated by Induction Motors (IMs) and Synchronous Motors (SMs) types. In early 1980s, due to the introduction of the microcomputer-controlled PWM power electronics inverters, more advanced and complex AC motor drive controls became possible (4)–(8). However, these advanced and complex control techniques were limited to mainly LP and LV applications. The HP and MV drives were predominantly based on Load Commutated Inverters (LCI) or Cycloconverters, for applications such as the steel industry (rolling mills). However, the LCI-based drives suffer from drawbacks such as low harmonic torque ripples, complex starting technique, notches in their terminal voltages, and quasi-square wave currents (3)(9). Besides, limitations on the ratings of power-electronic devices have restricted the power capability of the PWM-inverter-based electric drives. This has changed since the apparition of multilevel converters and new devices such as the GTOs and IGBTs, which paved the way for the application of PWM inverters in HP and MV motor drives (1)(3)–(10). Numerous MV inverter topologies were proposed and investigated in the literature since mid-1980s (1)–(10). The efforts in advancing this technology led to the apparition of various topologies of MV drives such as: (2)(10)

1) Series connection of LV inverter modules to satisfy the motor voltage and power requirements;
2) Multilevel inverter topology implemented in three or more levels using high power switches;
3) Parallel connection of multilevel inverters which increases the power handling capability; and
4) Multilevel-inverter-based multiphase motor drives.

Beside the focus on inverters' topologies, several other issues (as depicted in Fig. 1) were also investigated in the literature. This paper reviews the state of the art in HP and MV electric drives, highlighting their related challenges and proposed solutions. The paper is organized as follows: section 2 introduces the MV machines; section 3 presents MV drives topologies; Section 4 discusses multilevel inverters for MV drives; section 5 presents multiphase machines and drives; section 6 discusses challenges related to MV drives; section 7 concludes the paper.

2. MV Motors

IMs and SMs are dominating the HP and MV drives' applications and the type of motor selection depends on the application requirements, the electric power network

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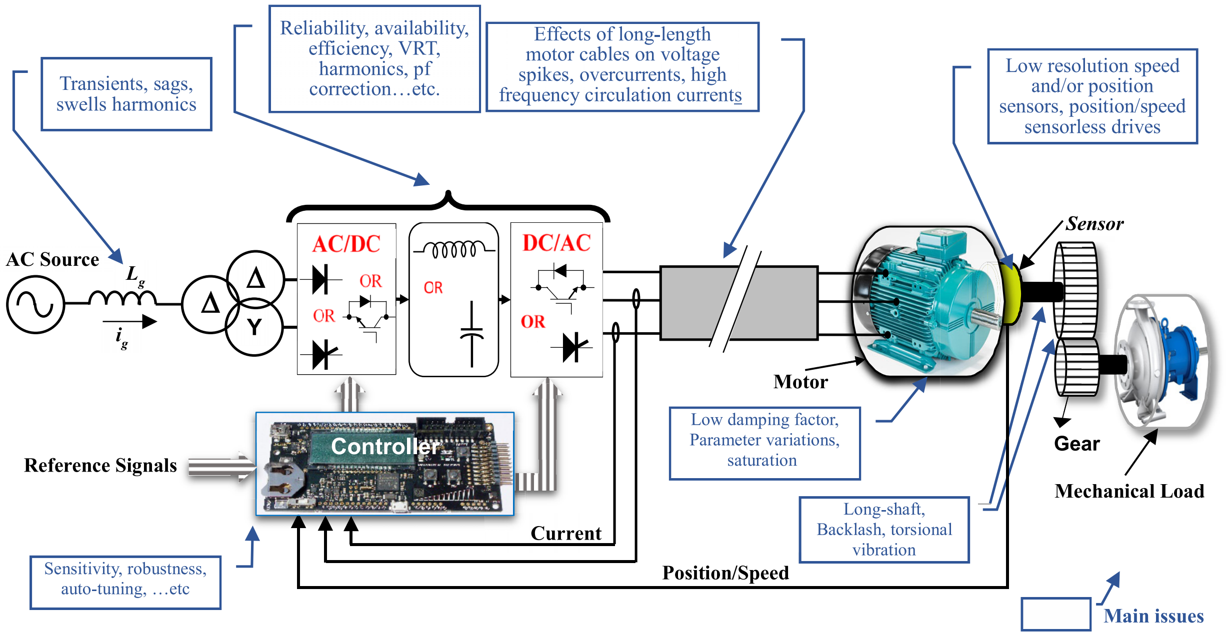


Fig. 1. General drive structure

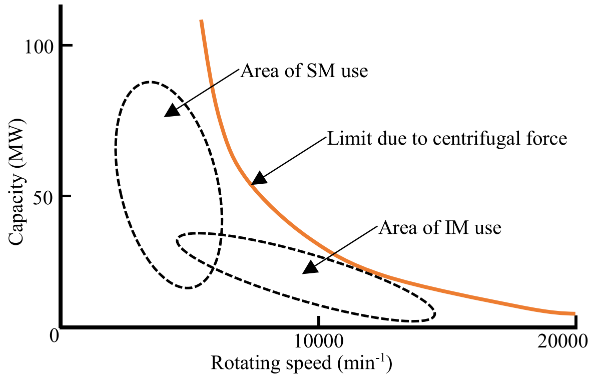


Fig. 2. Areas of IMs and SMs use

specifications and environmental conditions (11). In practice, a detailed analysis and comparison between various types of motors is necessary in order to select a suitable type for a given application. The following general facts are usually considered when selecting a motor type (10):

- IMs are stiffer, lighter, and more robust because of their simple rotor structures.
- Although SMs need exciter for proper operation, they have higher efficiency, controllable power factor, and constant rotating speed regardless of load variation.
- SMs are preferred for the HP applications since they can produce larger output torque.

Figure 2 shows the SMs and IMs power capacity versus rotating speed, along with their physical limitations (10) due to centrifugal force. Notice that, for high rotating speeds, IMs are preferred, while for larger power capacity, the SMs are better choices.

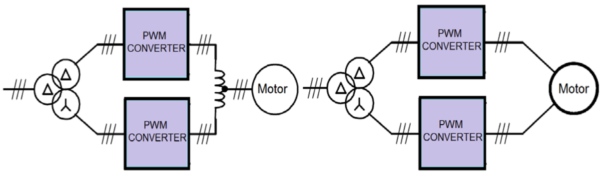
This can be explained by the fact that the higher is the rotating speed, the higher is the centrifugal force, applied to the rotor, which increases as the rotor radius increases (e.g. case of SMs due to exciter windings). Since the centrifugal force is proportional to the square of the rotor speed and the radius of the rotor (10), larger motor should withstand larger centrifugal force. The rotor should be manufactured with specific types of materials so that it has finite stiffness to withstand the centrifugal force exerted on its rotor and shaft when rotating at high speeds. Therefore, when the rotating speed is very high, a magnetic bearing may be required to levitate the rotor shaft (11) and provide mechanical-contactless rotation; thus, leading to smaller rotational losses and reduced maintenance cost. However, in magnetic levitation, the motor needs a controller to regulate its shaft position (12)(13). Besides, motor cooling consideration is necessary to reduce losses, and explosion-proof construction is also required for use in hazardous locations such as in oil and gas plants (14).

Multiphase motors with more than three phases, in their stators, are becoming a better choice for HP and MV drives' applications. The first 5-phase induction motor drive was proposed in 1969 (15) for LV applications. The real interest on multiphase machines at that time was due to the $(2n \pm 1)f$ torque ripples produced by an n-phase machine (16). When using a three-phase inverter six step mode of operation of the torque ripples are of low order frequency which is not desirable. Therefore, the use of a machine with higher phase number looked as the best solution to overcome the low order torque ripples. Henceforth, multiphase drives using various types of inverters were developed (17)–(21). However, with the development of better PWM techniques, this is no more an issue (16). Multiphase machines have several superior features when compared to their three-phase counterparts. These features are: better fault tolerance, smaller wires (low cross section area) used in the winding and hence lower skin effects, lower power per phase and hence lower converter devices' rating. Actual HP and MV industrial drives' development, using multiphase machines for applications, such as in oil pumping (23) and wind energy (24), are also promising. Recently, the focus is on high-reliability, small-size, and fault-tolerant configurations development. Moreover, under fault conditions, multiphase motors are more reliable and maintain self-starting ability, with minimum effect on the output power level(25). New designs aiming at higher torque density were achieved through stator current harmonic components injection(26)(27). For instance, authors in(28) proposed a fractional-slot concentrated-winding (FSCW) design for five-phase IM that has a better flux-weakening capabilities. Owing to their advantages, the multiphase FSCW surface and interior PM machines are becoming an interesting choice for low voltage applications, especially for electric vehicles(29)(30). However, at high speeds, they suffer from excessive rotor losses due to large spatial harmonic components(31). The fluctuation of magnets price and availability, as well as the need for a higher power wind generation without excess of weight and size, have enforced researchers to explore and develop multiphase (nine-phase) superconducting high power (12 MW) electrical generators for large-scale direct-drive wind turbines(24)(32). The trends in HP and MV multiphase machine technology is expected to grow, and significant new improvements are likely to appear in the near future. More details and progresses in multiphase machine design, modeling, and control can be found in several review papers(33)–(37).

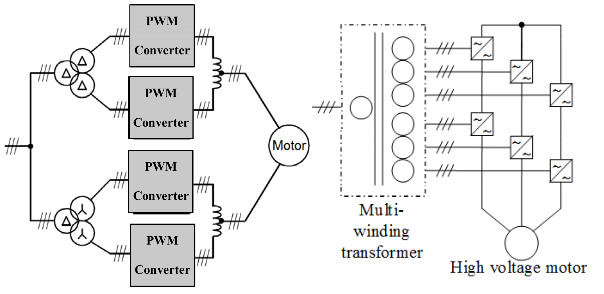
3. MV Drives

In the variable frequency operation of HP and MV drives, to match the inverter power to the power of the motor, various topologies or combinations of many inverters are used. Figure 3 shows the main used topologies for high power motor drives. To create an adequate output satisfying high power as well as the medium voltage level of the motor, multiple inverters are used via a parallel connection through balanced reactors at the output (Fig. 3(a)), or through multi-winding transformer at the output (Fig. 3(b)). The two other options to use either multi-phase/multi-winding motor (Fig. 3(c)), or/and multilevel inverter (Fig. 3(d)).

For the first two topologies, installation space is required for the balance reactors or the transformers in addition to the motor and the inverters(10). The combination of multilevel topology based drive system and one of the first two connections can form a very large power drive system(2)(10).



(a) Parallel connection using reactor (b) Multi-winding motor drive using dual converters



(c) Parallel connection using reactor and Multi-winding motor (d) Series connection using multi-cell converter

Fig. 3. Main MV motor drive topologies

Multilevel inverters based drive systems are addressed in section 4.

4. Multilevel Inverters Topologies for HP-MV Drives

Multilevel inverters experienced tremendous growth after the introduction of the Gate Turn Off Thyristors (GTO), Insulated Gate Bipolar Transistor (IGBT), Gate Controlled Thyristor (GCT), and Insulated Enhanced Gate Transistor (IEGT) devices.

4.1 Switching Devices The historical progress of the power electronic devices used for HP and MV motor drive is illustrated in Fig. 4. Thyristor, GTO, IGBT, IEGT and GCT are the main power electronics components used in the MV and HV inverters construction. The first released high power devices were the thyristor. In 1990s, Thyristors were able to handle several kV and several kA power.

Transistors are the second developed devices and in the 1980s were released for high power applications. IGBTs were developed to handle higher voltage than the conventional transistor. A continuous progress of IGBT technology has led to the commercialization of its 6th generation and the development of the enhanced IEGT, which can handle larger range of current (few kAs) and low voltage drop by the injection enhanced effect(38). All the devices from GTO to IEGT were made of silicon wafer. New devices, with better performances, were developed using Silicon Carbide (SiC) wafer(38). Although, presently the SiC device development is for low power and low voltage applications, the SiC material exhibits better performance than the silicon one, especially for high voltage and high current applications(40)(41). SiC switching devices can operate at higher switching frequencies while exhibiting lower switching losses. Many companies are working hard to develop high-voltage and high-current switching devices. The successful development of inverters for large-capacity AC motor drives rated at MW ranges using this switching device is considered as a matter of time(42). New progress in power semiconductor devices will be the key element to achieving MV drives up to end-users' expectations, such as simplicity, greater functionality, and better reliability.

4.2 Multilevel Topologies Although the concept of multilevel converters has been first introduced in 1975(43), it was only in the late 1980s, early 1990s that the multilevel PWM inverters topology was used for PWM electric drives with higher power capability(44). The multilevel era began with the Neutral Point Clamped (NPC) three-level converter(45). Successively, various new topologies of multilevel

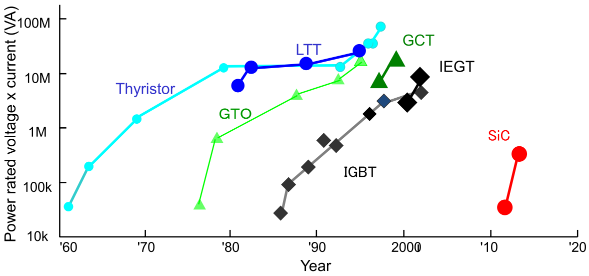


Fig. 4. Development of semiconductor switching device

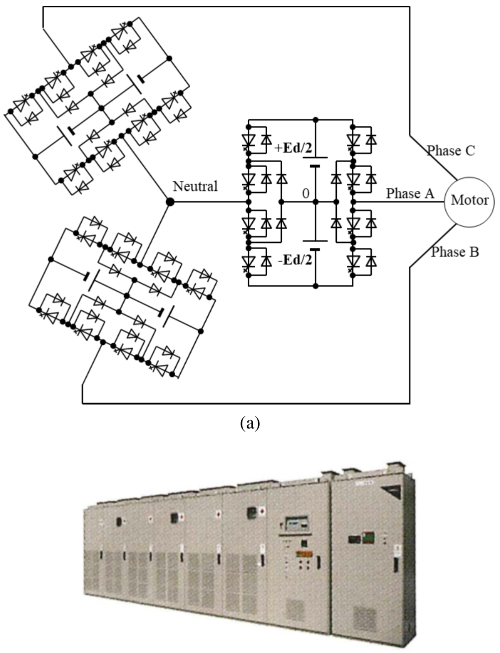
converters have been developed(46)–(55)(61)–(94). The output voltage, of multilevel converter, is mainly obtained by appropriately cascading several individual DC voltage sources. The synthesized voltage waveform has a staircase shape, which becomes closer to its sinusoidal reference when a higher number of levels (stairs) is used. The main advantages of such converters over conventional two-level converters are the low harmonic distortion of the generated output voltage, low electromagnetic emissions, high efficiency, the capability to operate at higher voltage ranges, and modularity. In many cases, capacitors can be used instead of the DC voltage sources. In order to achieve high voltage at the output of the inverters, the power electronics switches' controls are synchronized to aggregate these multiple DC voltage sources. However, the rating of the switching devices depends on the individual DC voltage source from which they are powered. The multilevel inverter uses low voltage steps to produce a staircase AC output terminal voltage waveform. These low voltage steps make a significant contribution to mitigating the so-called "*dv*/*dt* stresses" in a broad sense of the equipment and, therefore, reduce the long-cable effects and the electromagnetic compatibility (EMC) problems. Furthermore, they produce smaller Common-Mode (CM) voltage and, therefore, reduce the stress on the motor bearings. Advanced PWM techniques can also further reduce the CM voltage(95). Beside the excellent output waveforms, input currents drawn from the grid have lower distortions. Multilevel converters can operate at lower switching frequencies, which results in higher efficiency of the overall drive system. Applications of multilevel inverters for MV drive systems(78)–(102) and to power systems(105)–(107) are becoming widespread. A quiet large number of multilevel converter topologies have been proposed since 1996. Most of these proposed multilevel converters are based on the three following basic topologies:

1) Neutral Point Clamped (NPC) or diode clamped inverter(45)
2) Cascaded H-Bridges (CHB) inverter(49)–(54)
3) Flying Capacitors (FC) inverter(46)–(48)
4) Modular Multilevel Converters (MMC)(54)–(56)
5) Multilevel Matrix Converter(57)–(60).

For proper operation of these converters, several PWM control techniques were developed. Four main categories of PWM exist: sinusoidal pulse width modulation (SPWM), space vector modulation (SVM)(62)(63), selective harmonic elimination (SHE-PWM)(64) and discontinuous PWM (DPWM)(65)(77). For more information on multilevel inverters, a survey of topologies, controls, and applications are published in(78)(79).

4.2.1 NPC Inverter based MV Drives Many drives based on NPC inverters have existed since early 1990s(3)–(10)(44). A high power 5-level motor drive topology that can handle up to 30 MW capacity, was introduced using the NPC as a cell, as shown in Fig. 5(a)(2). Each phase of the motor is powered by a single-phase inverter consisting of two legs of a 3-level inverter.

A 7.2 kV, 30 MW, 5-level drive based on Fig. 5(a) topology was implemented and constructed as shown in Fig. 5(b) which is available in the market. Low number large-capacity semiconductor switching devices, GCT, are used. The high voltage, large capacity drive is using a simple circuit topology and a small number of devices, which improved the converter reliability(47). The resulting line-to-line voltage has nine levels. By paralleling four 30 MW inverters through the reactors, 120 MW drive system can be realized(2).



(a)

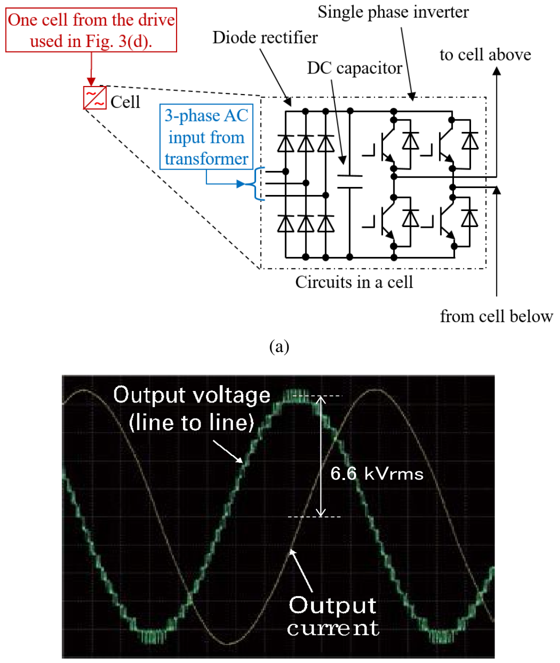
(b)

Fig. 5. (a): Circuit configuration of star-connected 5-level inverter(99), (b): 30 MW NPC cell-based 5-level inverter set

4.2.2 CHB Inverter based MV Drives CHB multilevel inverter topology is made of several series connected cells. Each cell is composed of a diode rectifier, a DC link capacitor, and a single phase H-Bridge inverter as shown in Fig. 6(a). The series connection of the cells yields high output voltage with staircase waveforms. Figure 6(b) shows the output voltage waveform of the drive inverter with 6 cells in series. By increasing the number of levels in the converter, the output voltage has more steps generating a near sinusoidal waveform. A multi-winding transformer is used to offer insulation among cells and will not inject any lower order harmonics into the grid due to the proper phase shifting between phases of windings(10)(49)–(54).

When required, CHB drive inverters can use bypass switches to improve the reliability of the system. However, if this switch is not well designed it will lead to unreliable system(81). The use of film capacitors in the DC-link by the advanced paralleling design is expected to further improve the reliability of the drive(81).

4.2.3 MMC based MV Drives Several researches are focusing on MMC for high power motor drive applications(88). Due to the floating capacitor voltages, it is known that, at low speed operation, MMC suffers from a power imbalance between the upper and lower arms. This results in a limited use (pumps, compressors and fans) of MMC for drives(82). Several techniques were proposed to overcome this imbalance problem(80)(84)–(88)(90)(91). These techniques are based on redistributing power between the upper and lower arms by injecting a common-mode voltage and circulating current to the three phases of the converter(80)–(84). Authors



(a)

(b)

Fig. 6. (a): Typical full bridge cell configuration used in Fig. 3(d), (b): Line-to-line output voltage and current waveforms of 6-cell configuration used in Fig. 3(d)

in(88) improved these techniques and were able to reduce the peak value of circulating current by up to 50%. However, the techniques proposed so far, improve the power imbalance in detriment of larger common-mode voltage that may harm the motor bearings(89). Other techniques, are based on modified control strategy(90) to reduce the power imbalance and to allow larger capacitor voltage ripples at low speed operation without injecting common mode voltage(89)(90). This technique is effective in the medium to high speed ranges. At low operating speed, the common-mode voltage and circulating current can hardly be avoided(91). Another topology called active cross connected MMC (AC-MMC) is proposed to mitigate the common-mode voltage for medium-voltage motor drives in the full motor speed range. The imbalance of power is reduced through a physical path formed by the cross-connected branch. The proposed topology makes the MMC more complex and expensive(92). In summary, more research efforts are needed to make the MMC more suitable for high power motor drives operating at low frequency range.

5. Multiphase Motor Drives

In the last three decades, multiphase motors were developed and are gaining popularity over the conventional three-phase motors, due to their high-power density, fault-tolerant capability, and high efficiency(25)(110)(111). Moreover, under fault conditions multiphase motors are more reliable, maintain self-starting ability with minimum effect on the output power level(25). Some of the recent research topics on multiphase motor drives are: torque enhancement by injecting lower order harmonics into the stator currents(112)(113), open-ended winding multiphase IM(41) and matrix converter for five-phase IM(114). These research works showed the importance and necessity for high-power multiphase motor drive applications. However, there are still no clear knowledge and certainty of the optimum number of phases required for a given application. It is obvious that increasing the number of phases increases the reliability of the drive system, but at the same time it also increases the complexity and cost of the related converter and control systems.

A comprehensive review of multiphase motor drives is presented by authors in works(33)(34), where they presented the recent advances in the design, modeling and control of multiphase machines and discussed the open challenges and future research directions in this area. Even though the modeling of multiphase machines was extensively studied in the past century, some interesting and more accurate models are still being developed. These new models take into account the effect of the magnetic saturation in the machine that affects the main airgap flux density and produces coupling between different planes(33).

Since modeling of any electric machine requires the knowledge of its electrical parameters, procedures for their identification are also becoming an interesting area of research(33). In fact, motor parameters' identification (resistances and inductances) in conventional three-phase electrical machines is well-established, but their extension to the multiphase machines is currently limited. Therefore, more work is expected in the near future because only a few recent works have attempted to tackle this issue(33).

6. Challenges for High Power Motor Drives

6.1 Long Cables Motors fed by PWM inverter with high *dv/dt* pulses, via long cables, are subject to voltage spikes, which in turn induce severe nonlinear inter-coil and inter-turn voltage distributions in the motor windings. These voltage spike phenomena are caused by a combination of impedance mismatches, long motor cables, and inverter switching transients. If the cable is long enough, the voltage spikes at the receiving end (motor terminal connections) may reach twice the amplitude of the pulse voltage at the sending end (inverter terminals)(119). This may damage motor windings' insulation and may lead to premature motor failures(115)–(118).

To reduce overvoltage and spikes at the motor terminals, several solutions were analyzed and proposed. A comprehensive research has been conducted on the modeling and analysis of these phenomena(120)–(126). Passive RLC filters have been placed on the output terminal of the inverter to reduce the inverter *dv/dt*(127)–(135). Alternatively, these passive filters can be placed at the motor terminal side(136)(137). Other types of passive filters and their placements are also possible(138)(139). However, passive filters are bulky and increase power losses and costs. On the other hand, active filtering combined with new inverter topology (extra switches) has been proposed to reduce the overvoltage(140). An active power filter with conventional inverter has been proposed in(141). Also, a modified PWM switching pattern for a conventional three phase inverter was introduced in(142)(143). An open-end winding electrical motor fed by two inverters of the same type and size has been also proposed(144). An additional RC filter and PWM pulses dwell time control system are used to reduce the peak of the overvoltage. The proposed approach is independent of cable parameters and their variations. A good review of mitigation methods for overvoltage in long-cable-fed PWM AC drives can be found in (145).

6.2 Common Mode Voltage An inherent drawback of conventional two-level PWM inverter drive systems, is the generation of significant common-mode voltages (CMVs) with high frequency (146)(147). Ground leakage and bearing currents along with conducted and radiated electromagnetic interference (EMI), are direct causes of the CMVs (148)–(150). These common mode related problems will intensify with the availability of new fast switching devices that work at high speed and high frequency (151)–(154). The CMV in PWM inverter-based motor drives is not a new issue (149). Many practical industrial solutions were developed to mitigate the effects of CMVs in AC drive systems. Common-mode (CM) chokes were used to suppress the ground leakage current (155)–(157), grounding brush or insulated bearings are commonly used to eliminate the bearing current (148), CM filters are used to suppress the conducted CM EMI (158)(159), while the use of shield cables reduce the radiated EMI. As they are dealing with CMVs effects and not the CMVs source, these techniques can only mitigate one particular effect at a time. More recently, some techniques were proposed to suppress the CMV itself using active filters (160)(161). However, active filters are somewhat difficult to implement due to their high-bandwidth and the need of an external voltage source. Authors in (162)(163) reduced the CMV using modulation strategies that avoid zero switching states. Although, these PWM techniques are effective in reducing CM currents, they make the control more complex, increase the current harmonics, and cannot reduce the high-frequency EMI.

On the other hand, an effective way to cancel CMV is to use multilevel inverter topologies (164)(165). Authors in (166)–(169), proposed some inverter topologies for CMV cancellation Dual conventional two level inverters were used to cancel each other CMVs and drive the motor (167)(168). However, this topology uses twice the number of switching devices and requires a good synchronization between the inverters. A cost-effective and minimum-size topology using common-mode voltage cancellation in PWM motor drives with balanced inverter topology was proposed in (170). The proposed balanced voltage source inverter (VSI) topology uses 3 switching devices in series per phase-leg. It eliminates the CMVs and their related problems in electric drives.

6.3 Torsional Vibrations (Long Shaft) In many applications, the load is coupled to the driving motor with a long shaft that is characterized by a small elasticity that may get magnified and cause torsional vibration effect on the load speed. This vibration is not only undesirable but can be often a source of system instability, and can result in coupling failure, shaft and gears damage. This in turn may cause undesired plant shutdowns (171)–(173). Interactions between the electrical and mechanical sides of the drive system are the main source of magnification of torsional vibration excitations (174)(175). Due to the DC link voltage fluctuation in VSI, the pulsating air-gap torque spectrum is composed of harmonics and inter-harmonics. Critical operation points, where the rotational speed of the motor causes harmonics and inter-harmonics coincident with one of the shaft torsional natural frequencies, can cause resonance and lead to system failure (174)(175). Beside the conventional losses, a recent study shows that additional losses are introduced in the electric motors under torsional vibration (184).

To mitigate the torsional vibrations, several control strategies were proposed (176)(183). These are based on: torque ripple suppression method with multilevel inverter and feedforward dead-time compensation (176)(177), the fast and slow disturbance observers (178), optimization techniques (179), state-space controller (180)(181), Model Following Control (MFC) and Simulator Following Control (SFC) (182), and Kalman filter (183). The research on this issue will nurture as new drives are aiming for better bandwidth and therefore torsional vibrations will magnify.

6.4 Low-Voltage-Ride-Through (LVRT) to Grid-Voltage Sags Electric drives often trip during voltage sags, thus interrupting production and resulting in considerable financial losses. There are various types of electric drives, on the market, with different reactions to voltage sags. Therefore, by designing drives capable of riding through grid voltage sags with certain magnitude and duration, processes' downtime can be significantly reduced (185). In order to prevent tripping due to voltage sags, various techniques have been proposed (186)(187). These are mainly aimed at maintaining the DC-link voltage at a desirable level. This can be done based on:

1) Using compensation at the distribution level based on Dynamic Voltage Restorer (DVR) or STATCOM (188), and
2) Modifying of drive topology using an extra boost converter between the rectifier and the DC-link capacitor (189)(192).

As the above techniques tend to be bulky and costly, another approach was proposed, which allows the DC-link voltage to vary, but a better inverter control technique is used (192). However, if the process is sensitive to drops in torque and speed, it is better to proceed to controlled shutdown in order to minimize the damages, and have the process ready for starting when the voltage sag disappears (192). Recently developed systems are based on energy storage using supercapacitor systems which can maintain the DC-bus voltage at the required level during the voltage sag (193). Ride through time, voltage sags level, and load level are the main factors affecting the selection of the ride-through technique to be used for a given application.

6.5 Reliability and Availability Reliability and availability are key factors for the industry choices of high power motor drive, as it determines the lower downtime of their plants. Therefore, users of drive systems place reliability and availability on top of their wish list. The reliability is a measure of how long the drive system performs its envisioned function, while the availability is the time percentage during which the equipment is in the state of normal operation. However, the definitions of reliability and availability, or better the calculation of reliability and availability, are difficult to be directly converted into exact technical requirements.

The Mean Time Between Failures (MTBF) is normally used to calculate the reliability. (194) gives the parameters for calculating MTBF, and clarification of these calculations is given in (195). In this paper, we will highlight some technical guidelines about reliability (196).

For inverter-driven motors, the use of simple topology with minimum number of switching devices is crucial for achieving high system reliability. The use of reliable switching devices, such as IEGT and GCT, will further enhance the reliability. Few proven inverter topologies such as 3-level NPC are becoming a standard for the industry. Especially the simple star-connected 5-level NPC inverter is appropriate for use with MV and HP motor drive (196). Selection of a suitable control technique that eliminates low order harmonics and realizes smooth operation, also contributes to the increase of the overall drive system reliability. A proper testing at the manufacturing stage at various operating conditions is crucial for reliable operation in the real plant (196).

The simplicity of the used grid side converters, such as diode rectifiers, will contribute to the overall reliability and availability of the drive system. As a general concept, simpler drives are normally more reliable and available than the complex ones (196).

7. Conclusion

This paper surveyed and highlighted recent developments in HP and MV drives. This area in particular has recently experienced a considerable progress. A detailed overview of the current state-of-the-art in MV drives and their challenges, were described. Numerous interesting MV drives topologies, realizing the power up to 120 MW, were proposed. A highlight of the most prevalent topologies with a discussion of their features was presented.

New progress in power semiconductor devices will be the key element to achieving MV drives up to end-users' expectations such as simplicity, greater functionality, and better reliability. The number of researches published in this area is tremendous. The authors tried to refer to all important published works, and apologize to all authors whose important work may have been overlooked.

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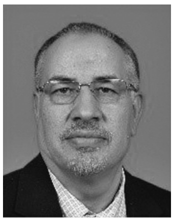

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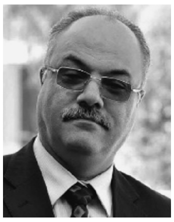

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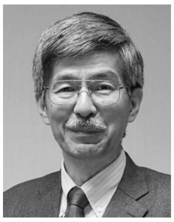

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