Advanced Converter Topologies and Modular Multilevel Inverter Technologies for High-Speed Motor Drive Applications: A Comprehensive Review

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Abstract**—**The increasing demand for high-speed and medium-voltage motor drive systems has stimulated extensive research into advanced power converter topologies and control strategies. Conventional voltage source inverters suffer from high switching losses, voltage stress, and limited scalability when applied to high-power applications. To address these challenges, researchers have developed innovative converter topologies and modular multilevel converter (MMC) architectures. Various converter topology specifically designed for high-speed motor applications, demonstrate improved efficiency and power density . Subsequently, modular multilevel inverter technologies were introduced to improve voltage quality and scalability in medium-voltage drives . Further research focused on startup operation, capacitor voltage balancing, and sensor-less control methods to enhance the practicality of MMC-based motor drives.

***Index Terms* -** Modular Multilevel Converter, High-Speed Motor Drive, Multilevel Inverter, Medium-Voltage Drive, Capacitor Voltage Balancing, Power Electronics.

I. INTRODUCTION

Electric motors consume approximately 45% of the world's electrical energy, making motor drive efficiency a critical research area [1-7]. High-speed motor applications such as aerospace actuators, compressors, machine tools, and electric vehicles require converters capable of operating at high frequencies while maintaining low losses and high reliability [8-15].Traditional two-level voltage source inverters (VSIs) are widely used because of their simple structure and low cost. However, they suffer from several limitations, including high switching losses, large voltage stress across semiconductor devices, and increased harmonic distortion [7]. These drawbacks become more significant as motor operating speed and voltage rating increase. Multilevel inverter technologies emerged as an effective solution for overcoming these limitations. Rodriguez et al. presented a comprehensive survey of multilevel inverter topologies and demonstrated their advantages in terms of harmonic reduction and voltage sharing [7]. Neutral-point-clamped and cascaded H-bridge converters further improved voltage quality and efficiency in medium-voltage applications [8-13].The Modular Multilevel Converter (MMC), originally introduced for high-voltage applications, attracted considerable attention due to its modular structure, scalability, and excellent output waveform quality [4], [6]. Hagiwara and Akagi successfully adapted MMC technology for medium-voltage motor drive systems, demonstrating significant reductions in harmonic distortion and switching losses [2].

II HIGH-SPEED MOTOR DRIVE CONVERTER TOPOLOGIES

High-speed motors typically operate above 20,000 rpm and require converter systems capable of supplying high-frequency currents while maintaining high efficiency. Traditional inverter systems experience significant switching losses under such operating conditions. Guennegues et al. [1] proposed a dedicated converter topology for high-speed motor applications. Their work demonstrated improved power density and reduced switching losses compared with conventional converter architectures. The proposed topology enabled efficient operation at elevated electrical frequencies, making it suitable for aerospace and industrial drive applications.

2.1 Modular Multilevel PWM Inverters

Hagiwara and Akagi introduced a modular multilevel PWM inverter suitable for medium-voltage motor drives [2]. The converter generated near-sinusoidal output voltages while reducing switching frequency requirements. The modular structure also enabled easier expansion to higher voltage levels compared with conventional multilevel converters.Further experimental studies confirmed the feasibility of MMC technology and demonstrated effective control of capacitor voltages within converter submodules [3].

2.2 Startup and Low-Speed Operation

One of the major challenges associated with MMC motor drives is operation at low speed due to insufficient energy exchange between converter capacitors and the motor. Hagiwara et al. proposed a startup strategy using common-mode voltage injection and circulating current control to address this problem [9]. Experimental results demonstrated stable operation from standstill and improved low-speed performance.

2.3 Sensorless Control Techniques

Mechanical speed sensors increase system cost and reduce reliability. To overcome these limitations, Okazaki et al. proposed a sensorless startup method based on current feedback and feedforward frequency control [10]. The proposed approach successfully achieved stable motor startup without requiring mechanical position sensors.

2.4 Experimental Validation of MMC Systems

Experimental verification performed by Thitichaiworakorn et al. demonstrated stable capacitor voltage balancing and improved output waveform quality in modular multilevel cascade inverter systems [11]. Their results provided strong evidence supporting industrial implementation of MMC-based motor drives.

2.5 Constant Torque Operation

Antonopoulos et al. investigated the ability of MMC motor drives to produce constant torque from zero speed to rated speed [12]. Advanced balancing algorithms were developed to minimize capacitor voltage ripple and maintain stable converter operation throughout the operating range.

III MODULAR MULTILEVEL CONVERTER TECHNOLOGY

The Modular Multilevel Converter was originally introduced for high-voltage power transmission applications [4]. Subsequently, Hagiwara and Akagi adapted MMC technology for motor drive systems [2].

The MMC consists of multiple submodules connected in series, enabling the generation of staircase voltage waveforms with low harmonic content. The modular architecture provides several advantages:

- Excellent voltage scalability
- Reduced harmonic distortion
- Lower switching losses
- Improved fault tolerance

Experimental studies demonstrated that MMC-based motor drives produce superior output voltage quality compared with conventional multilevel inverter systems [2], [3].

IV STARTUP AND LOW-SPEED OPERATION OF MMC DRIVES

A major challenge in MMC-based motor drives is maintaining stable operation at low speeds, where the electrical frequency is too low to ensure sufficient energy exchange between the converter capacitors and the motor. Under these conditions, the submodule capacitor voltages can fluctuate significantly, leading to poor voltage balance and degraded drive performance. To overcome this limitation, Hagiwara, Hasegawa, and Akagi proposed the use of common-mode voltage injection combined with circulating current control. Their approach improves the internal energy balancing of the MMC by creating a controlled high-frequency energy exchange between the upper and lower arms, thereby reducing capacitor voltage ripple and stabilizing converter operation at low speed. Experimental validation using a 15-kW prototype demonstrated that the proposed method enables stable startup from standstill, reduces capacitor voltage ripple, and improves overall low-speed performance. These results confirm that proper control of common-mode voltage and circulating current is essential for extending MMC operation into the zero- and low-speed regions without compromising converter reliability or drive quality.[9]

V SENSORLESS CONTROL STRATEGIES

Mechanical speed sensors increase system cost and reduce reliability. To eliminate these drawbacks, Okazaki et al. [10] proposed a speed-sensorless startup strategy based on stator current feedback and feedforward frequency control.

Experimental results demonstrated:

- Successful startup without speed sensors
- Stable operation under varying load conditions
- Reduced hardware complexity

The study contributed significantly to the industrial feasibility of modular multilevel motor drives.

VI COMPARATIVE ANALYSIS

A. Performance Comparison

Table 1:Comparision

Parameter	VSI	MLI	MMC
Efficiency (%)	90–94	94–96	96–98
THD (%)	8–15	3–8	<3
Voltage Quality	Medium	High	Very High
Switching Losses	High	Medium	Low
Fault Tolerance	Low	Medium	High
Scalability	Low	Medium	Very High

Table 1 compares the performance of VSI, MLI, and MMC across key technical parameters, including efficiency, THD, voltage quality, switching losses, fault tolerance, and scalability. The comparison shows a clear progression from conventional VSI toward more advanced converter structures, with MMC offering the strongest overall performance in high-power and medium-voltage applications.The results indicate that MMC systems outperform conventional inverter technologies in terms of efficiency, harmonic performance, and scalability as shown in Table 1 [2], [9], [12].

B. Harmonic Distortion Analysis

MMC systems generate staircase-like output voltage waveforms that closely approximate a sinusoidal signal, thereby significantly reducing harmonic distortion. As a result, THD values below 3% are commonly reported in practical MMC applications, which is substantially better than conventional VSI and even many multilevel inverter configurations.This improvement in harmonic profile reduces the need for bulky filters and enhances power quality at the load side. Lower THD is especially important in grid-connected and renewable-energy interfacing systems, where compliance with power-quality standards and minimization of electromagnetic interference are critical design requirements.[2], [7].

C. Reliability Assessment

The modular architecture of MMCs contributes strongly to fault tolerance and operational reliability. If one submodule fails, bypass or reconfiguration strategies can often maintain partial or even near-normal operation, which is a major advantage over monolithic converter structures. Experimental and comparative studies also report stable MMC performance under varying operating conditions, supporting the claim that MMCs are well suited for applications demanding high availability and robust operation. This reliability advantage becomes especially valuable in medium-voltage drives, renewable integration, and high-power transmission systems where converter downtime can be costly.[11]

VII CONCLUSION

Research shows significantly advanced converter technologies for high-speed and medium-voltage motor drives. The development of dedicated converter topologies and modular multilevel converter architectures improved efficiency, voltage quality, reliability, and scalability. Contributions related to startup operation, low-speed performance, sensor-less control, and voltage balancing established MMC technology as a practical solution for industrial applications. These developments provided the technological foundation for future integration of wide-bandgap semiconductor devices and intelligent control methods.

REFERENCES

[1] V. Guennegues, S. Lefebvre, J. P. Ferrieux, and M. Cousineau, “A Converter Topology for High Speed Motor Drive Applications,” 13th European Conference on Power Electronics and Applications (EPE), 2009.

[2] M. Hagiwara and H. Akagi, “A Medium-Voltage Motor Drive with a Modular Multilevel PWM Inverter,” IEEE Transactions on Power Electronics, vol. 25, no. 7, pp. 1786–1799, 2010.

[3] M. Hagiwara and H. Akagi, “Control and Experiment of Pulsewidth-Modulated Modular Multilevel Converters,” IEEE Transactions on Power Electronics, vol. 24, no. 7, pp. 1737–1746, 2009.

[4] A. Lesnicar and R. Marquardt, “An Innovative Modular Multilevel Converter Topology Suitable for a Wide Power Range,” IEEE PowerTech Conference, 2003.

[5] K. Nishimura, M. Hagiwara, and H. Akagi, “Medium-Voltage Motor Drive Applications of MMCs,” 2010.

[6] S. Allebrod, R. Hamerski, and R. Marquardt, “New Transformerless, Scalable Modular Multilevel Converters,” IEEE PESC, 2008.

[7] J. Rodriguez, J. S. Lai, and F. Z. Peng, “Multilevel Inverters: A Survey of Topologies, Controls, and Applications,” IEEE Transactions on Industrial Electronics, vol. 49, no. 4, pp. 724–738, 2002.

[8] J. Rodriguez et al., “A Survey on Neutral-Point-Clamped Inverters,” IEEE Transactions on Industrial Electronics, vol. 57, no. 7, pp. 2219–2230, 2010.

[9] M. Hagiwara, I. Hasegawa, and H. Akagi, “Start-Up and Low-Speed Operation of an Electric Motor Driven by a Modular Multilevel Cascade Inverter,” IEEE Transactions on Industry Applications, vol. 49, no. 4, pp. 1556–1565, 2013.

[10] Y. Okazaki, M. Hagiwara, and H. Akagi, “A Speed-Sensorless Start-Up Method for an Induction Motor Driven by MMCI-DSCC,” IEEE ECCE, 2013.

[11] N. Thitichaiworakorn, M. Hagiwara, and H. Akagi, “Experimental Verification of a Modular Multilevel Cascade Inverter Based on Double-Star Bridge Cells,” IEEE Transactions on Industry Applications, vol. 50, no. 1, pp. 509–519, 2014.

[12] A. Antonopoulos, L. Ängquist, and H. P. Nee, “Modular Multilevel Converter AC Motor Drives with Constant Torque from Zero to Nominal Speed,” IEEE Transactions on Industry Applications, vol. 50, no. 3, pp. 1982–1993, 2014.

[13] P. Barbosa et al., “Active Neutral-Point-Clamped Multilevel Converters,” IEEE PESC, 2005.

[14] S. Debnath et al., “Operation, Control, and Applications of the Modular Multilevel Converter: A Review,” IEEE Transactions on Power Electronics, vol. 30, no. 1, pp. 37–53, 2015.

[15] B. Wu, High-Power Converters and AC Drives, Wiley-IEEE Press, 2006.