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A Review of Modulation and Control Techniques for Multilevel Inverters in Traction Applications

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ABSTRACT Traction inverter has been the subject of many studies due to its essential role in the proper performance of the drive system. With the recent trend in increasing the input voltage in battery-powered electric vehicles, multilevel inverters have been proposed in the literature as a promising substitute for conventional two-level traction inverters. A critical aspect of utilizing multilevel structures is employing proper control and modulation techniques. The control system structure must be capable of handling a number of key issues, like capacitor voltage balancing and equal power loss sharing, which arise in multilevel topologies. This paper presents a review of the present-day traction drive systems in the industry, control and modulation techniques for multilevel structures in the inverters, as well as the principal challenges that need to be addressed in the control stage of the multilevel traction inverter. A comparison has been made between different methods based on the most important criteria and requirements of the traction drive system. Finally, future trends in this application are presented and some suggestions have been made for the next generation of traction drives.

INDEX TERMS Direct torque control, electric vehicles, model-predictive control, modulation and control schemes, multilevel inverters, traction motor drives, transportation electrification.

ABBREVIATIONS

BEV	Battery Electric Vehicle
BMS	Battery Management System
CHB	Cascaded H-Bridge
CPWM	Continuous Pulse Width Modulation
DPWM	Discrete Pulse Width Modulation
DTC	Direct Torque Control
EMI	Electromagnetic Interference
EV	Electric Vehicle
FC	Flying Capacitor
FOC	Field-Oriented Control
HEV	Hybrid Electric Vehicle
HWFET	Highway Fuel Economy Driving Schedule
ICEV	Internal Combustion Engine Vehicle
IM	Induction Motors
MMC	Modular Multilevel Converter
MPC	Model-Predictive Control
NLM	Nearest Level Modulation
NNPC	Nested Neutral Point Clamped
NPC	Neutral Point Clamped
OBC	On-Board Charger
OEWIM	Open-End Winding Induction Motor
PAWM	Pulse Amplitude Width Modulation
PCC	Predictive Current Control
PM	Permanent Magnet
PMSM	Permanent Magnet Synchronous Motor
PTC	Predictive Torque Control
SHE	Selected Harmonic Elimination
SiC	Silicon Carbide
SOC	State of Charge
SPWM	Sinusoidal Pulse Width Modulation
SRM	Switched Reluctance Motor
SVM	Space Vector Modulation
THBC	Torque Hysteresis-Band Control
UDDS	Urban Dynamometer Driving Schedule
VSI	Voltage Source Inverter
WBG	Wide Bandgap
WPWM	Window Pulse Width Modulation
XFC	Extreme Fast Charging

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I. INTRODUCTION

Electric vehicles (EVs) are the ultimate replacement of internal combustion engine vehicles (ICEVs) due to the reduced greenhouse emissions, reduced reliance on fossil fuels, and the benefits that they have to both electric grid and the costumers. Britain, China, France, Germany, and several other countries have planned for phasing out the production of gasoline and diesel vehicles in a few decades from now. With the ongoing trend, it has been predicted that 54% of the new car sales will be electric by 2040 [1]. As an example, Ford invested $11 billion for 40 new electrified vehicles by the next few years [2]. Although EVs do not produce any emissions while they are operating, the electricity generation can still produce emissions. However, an average EV still produces 50% lower greenhouse emissions compared to ICEVs. Since more than a quarter of the greenhouse gas emissions in the US is related to the transportation sector, 50% reduction in this amount results in a considerable reduction in total greenhouse gas emissions [3].

On the other hand, EVs face several non-negligible challenges. The limited energy density of batteries, long recharging time comparing to the refueling time of ICEVs, unavailability of the chargers in many urban areas, and their higher upfront cost compared to ICEVs are the major drawbacks of battery electric vehicles (BEVs) which are prohibiting the vast growth of this environmentally friendly way of transportation [4]. The rapid decrease in the battery price has resulted in a drop in EV price recently. This drop in the component cost of EVs and hybrid electric vehicles (HEVs) is expected to continue in the next decade and reach the cost of a similar ICEV before 2030. Unlike the higher initial price of EVs, their operating and maintenance costs are considerably lower than ICEVs [1]. Other than the issues related to the vehicle components and operation price, some actions are required by governments and utilities. Consumer subsidies and higher investments in the infrastructure by the government can accelerate the growth of the EV industry. Moreover, current charging stations are inadequate for the customer's needs. There is a need to increase the number and visibility of chargers. Home, workplace, and curbside charging stations are essential in dense residential areas. The potential benefits of the EVs to the electric grid stability is the other reason that the utility should get involved and improved along with the EV industry [5], [6].

Recently, there has been a trend to increase the battery voltage in traction drives, especially passenger EVs, in order to overcome the slow charging issue [7]. Higher DC-link voltage in an electric traction drive reduces the recharging time of the batteries by enabling extreme fast charging (XFC). It can also reduce the cables' size and weight, increase the overall system power density, and reduce the conduction losses in the inverter [7]–[9]. Moreover, higher-power traction applications such as electric trains or ships use much higher DC-link voltages to reduce the current rating [10], [11]. Despite the mentioned advantages, higher DC-link voltage poses new requirements on the drive system. On the inverter side, the devices or the structure must be changed in order to withstand higher voltages. Moreover, higher *dv/dt* in a two-level structure can generate higher electromagnetic interference (EMI) and damage the electric motor. From the loss perspective, the increased switching loss in the two-level inverter usually outweighs the reduced conduction loss. Therefore, the total inverter efficiency decreases [12]. Several manufacturers have moved toward higher input voltage inverters for EVs [13]–[16]. 1200V and 1700V IGBTs and Silicon Carbide (SIC) MOSFETs can be used for this purpose. Although these high-voltage switches can withstand the high voltage effectively, high switching loss and high *dv/dt* still exist as long as the two-level structure is used.

Multilevel inverters are proposed for traction applications due to their exceptional characteristics. Achieving high-voltage inverters by using lower-voltage switches, low output current distortion, *dv/dt* reduction, switching losses reduction, and efficiency improvement are the main features of these structures which make them a great fit for the next generation of traction inverters [17]–[19]. Different multilevel topologies have been proposed in the literature for traction applications. Neutral-point clamped inverter (NPC) [20]–[24], modular multilevel converter (MMC) [11], [25], flying capacitor inverter (FC) [26], and cascaded H-bridge inverter (CHB) [27], [28] are investigated in the literature to be used in traction drives. It should be noted that multilevel inverter structures are being used in high-voltage, high-power traction drives today [10], [11], [29]. A classification of the feasible topologies for traction voltage-source inverters (VSI) is shown in Fig. 1.

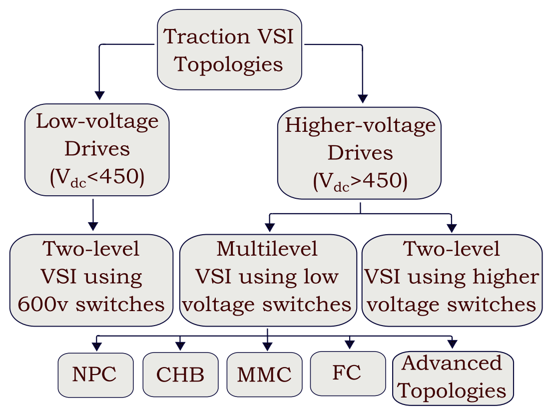


FIGURE 1. Classification of topologies for traction VSI; Multilevel structures are promising in higher-voltage applications.

Comparison of multilevel and two-level structures has been made in the literature. Efficiency is increased by using multilevel structures in standard driving cycles [30], [31]. The comparison of the cost of two systems is made in [18], [30]. While the cost of the inverter is shown to be slightly higher with multilevel structures, the overall system is cheaper due to the lower filter and battery cost in the case of the multilevel drive. The aforementioned studies have investigated topologies. However, there are two other aspects of multilevel traction drives that need investigation and comparison: Control techniques and modulation schemes. The study of control and modulation techniques for general multilevel drives has been conducted in the literature. However, most of the studies are not focused on traction applications, where there are certain requirements such as fast dynamic response, wide range of operating speed including zero speed, low torque ripple, and extremely high power density [32]. There are also specific control issues that arise in the transition to multilevel inverters. Voltage balancing of capacitors, especially in low-speed needs to be solved in the control system [33], [34]. A proper voltage balancing control method results in capacitor size reduction. Consequently, control and modulation techniques can directly affect the power density and cost of the traction inverter. However, the complexity of the control system is another issue that needs to be handled, especially in large number of levels.

This paper aims at presenting a literature review and comparison of control and modulation techniques for multilevel drives in this specific application, as well as predicting future trends and challenges. The structure of the paper is as follows; An overview of the traction drive systems is presented in section II. A set of selection criteria is presented in section III based on the most important requirements in traction application. In section IV, classic and advanced control methods for multilevel drives are investigated and compared to each other. The same approach is conducted in section V for modulation schemes. The main contribution of this review paper is to:

- present challenges and future trends after a thorough literature review
- make suggestions for future works in this area such as:
  - present-day and future inverter solutions
  - effect of wide bandgap devices on control
  - fault-tolerant multilevel traction inverters
  - model-predictive control for multilevel inverters
  - controller robustness

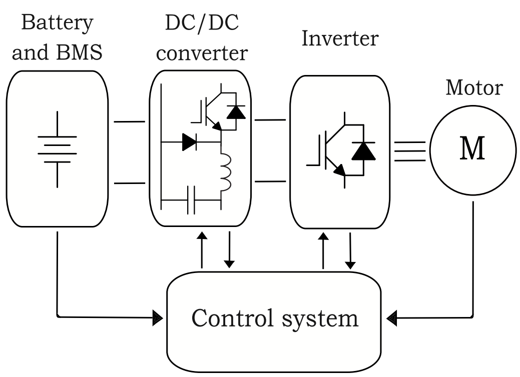


FIGURE 2. General structure of electrical drive system of an EV; Battery voltage, inverter structure, motor type, and control system have experienced major improvements in the last decade.

II. AN OVERVIEW OF THE TRACTION DRIVE SYSTEM

The general block diagram of the electrical drive system of a BEV is shown in Fig. 2. The batteries, BMS, DC/DC converter, inverter, and electric motor are the main parts of this system. Except for the DC/DC converter which can be eliminated with some considerations, the other parts are essential in all battery-powered light or heavy-duty electrified transportation. This section presents a review of each of the mentioned blocks, as well as their trends in the past decade.

A. BATTERY AND BMS

A few years ago, the battery voltage in all the commercial EVs was limited to 400V. The EVs manufactured by Tesla, Nissan, Chevrolet, and Audi are still using 400V batteries. Recently, some of the manufacturers have chosen higher battery voltages due to some advantages like reducing the recharging time, reducing the conduction loss, and increasing the power density of the drive system. Among the most well-known manufacturers, Porsche, Aston Martin, and Fisker have moved toward 800V batteries for their new products [35], [36]. Also, Lucid Motors has gone further and announced that their model Air EV will be equipped with an over 900V DC system [37]. One important concern is that the charging infrastructure and stations for direct 800V charging of EVs are not available globally now. However, with the current trend in the battery voltages of EVs, high-voltage charging stations capable of XFC will be installed. Another concern about the batteries is the shortage of lithium and cobalt. As a result, some manufacturers are moving toward alternatives, like lithium phosphate [38]. BMS is in charge of monitoring and protecting the battery pack as well as balancing the state of charge (SOC) of the cells. With higher EV battery pack voltage, the number of cells in series increase [7]. Therefore, new BMS designs, capable of protecting and balancing the larger number of cells in series are required.

TABLE 1. Inverter structure of some of the well-known passenger EVs and HEVs as well as the utilized semiconductors.

EV model	Inverter structure	Semiconductors type
Chevrolet Volt	Two-level	DSC IGBT
Toyota Prius	Two-level	DSC IGBT
Nissan Leaf	Two-level	IGBT Modules
Audi e-tron	Two-level	DSC Modules
Tesla Model S	Two-level	Discrete IGBTs
Tesla Model 3	Two-level	Discrete SiC MOSFETs

B. INVERTER

Wide range of operating voltages and powers in traction applications has brought a large variety of options for the traction inverter. The required characteristics of the electric ships, with 1.5-15 kV DC-link voltage, vary from the requirements of low-voltage, low-power EVs. The inverter topology that is currently used for EVs on the market is the conventional two-level structure. Table 1 shows the inverter structure and semiconductor type in some of the well-known EVs. Tesla Model S, with the input battery voltage of 400V, uses a two-level structure with 6 single TO-247 IGBTs in parallel per switch to handle the high current. In its model 3, Tesla is using SiC MOSFETs from STMicroelectronics with the custom package which is designed for it. Although the semiconductor technology has improved, the inverter technology is still the conventional two-level structure with four MOSFETs paralleled per each switching device. Other than Tesla, all other EV manufacturers are also using two-level structures. IGBT modules or paralleled single IGBTs have been the most popular switching device in the power range of the EV due to their price and availability [39]. With the increase in the voltage levels of EVs, TM4, Eaton, and Delphi have introduced 800V two-level inverters with higher-voltage semiconductors [13], [14], [16].

Unlike EVs, high-power traction applications have taken advantage of multilevel inverters due to their high voltage DC-link. ABB, Siemens, and General Electric have implemented industrial multilevel inverters for ship propulsion system with DC-link voltages up to 15 kV [11]. Multilevel solutions are also used in electric train drive systems. Swiss Federal Railways, Swedish State Railways, and Deutsche Bahn are using three-level inverters with high-power IGBTs made by ABB [10], [29].

C. ELECTRIC MOTORS

With the rapid changes that happen in the EV industry, the preferred options for electric motors have varied continuously. High power density, high efficiency, and low cost are the foremost criteria in the selection of the electric motor. One decade ago, induction motors (IMs) were the prominent choice for most of the light and heavy-duty electrified transportation applications. Nowadays, almost entire light-duty EV manufacturers are using permanent magnet synchronous motors in their designs [40]. When it comes to electric bicycles and motorcycles, out-runner brushless DC motors are widely preferred. Hullikal, Tronx, Spero, 22 Motors, and NDS Eco Motors are using BLDC motors for their products [41].

While many heavy-duty and railway vehicles are still using IMs as their electric motors, permanent magnet synchronous motors (PMSMs) have shown a growing interest in the last years due to their higher power density and efficiency. Other than IMs and PMSMs, switched reluctance motors (SRMs) are considered as the potential option for future vehicles. These motors can overcome the concerns about the rare earth permanent magnets (PMs) that are needed for PMSMs. There had been several traditional concerns about the SRMs which are noise and vibration. One goals of the automotive industry has been elimination of the noise and vibration for the passenger's comfort. Hence, this should be considered in design and selection of a motor for automotive applications [42]. However, these concerns for SRMs have been resolved recently. Tesla model 3 is using SRM with internal PMs (PMSRM). Table 2 shows the motor type in some of the well-known EVs on the market. Based on these criteria, Fig. 3 presents a comparison of the three mentioned options for the type of electric motor in traction applications [40], [43], [44]. While IMs are cheaper, more reliable, and more mature, they are replaced with PMSMs due to the importance of high power density and efficiency.

TABLE 2. Classification of some of the well-known passenger EVs and HEVs based on the type of their electric motor.

Motor type	EV model
IM	Tesla Model S, Tesla Model X
PMSM	Chevrolet Bolt, Toyota Prius, Nissan Leaf BMW i3, Porsche Taycan, Hyundai Kona
SRM	Tesla Model 3 (PMSRM)

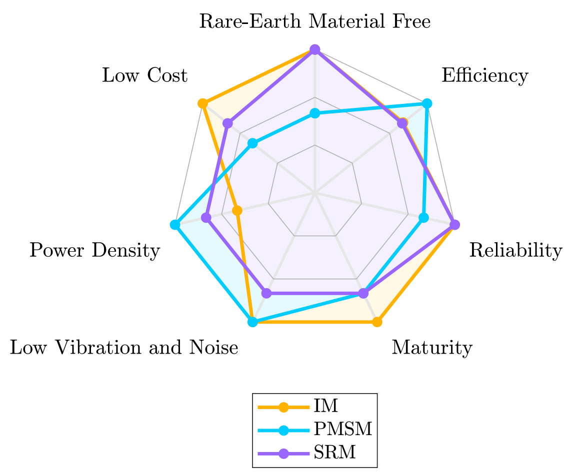


FIGURE 3. A Comparison of IM, PMSM, and SRM for EVs and HEVs. IMs have been replaced by PMSMs mostly due to their lower power density.

D. CONTROL SYSTEM

Due to the different dynamic equations of the current in each of the aforementioned machine types, control parameters and equations differ in each [34], [45]. Despite various control and modulation techniques for different machines, there are usually four general stages in the operational structure of a conventional cascade-controlled multilevel drive: Outer control loop, inner control loop, modulator, and a mid-stage which mostly deals with the capacitor voltage balancing [34]. This structure is presented in Fig. 4. In this structure, the outer loop, or the primary controller, controls the speed of the motor and feeds the current reference into the inner loop. In a conventional drive application, the external loop, which is also called the speed controller, is normally a PI controller [46]. Advanced speed control strategies like adaptive PID controller for PMSM [47] are proposed in order to improve the operation of the speed control loop. However, the outer control loop is out of the scope of this study.

As mentioned before, the objective of the secondary controller is to follow the output of the primary controller,

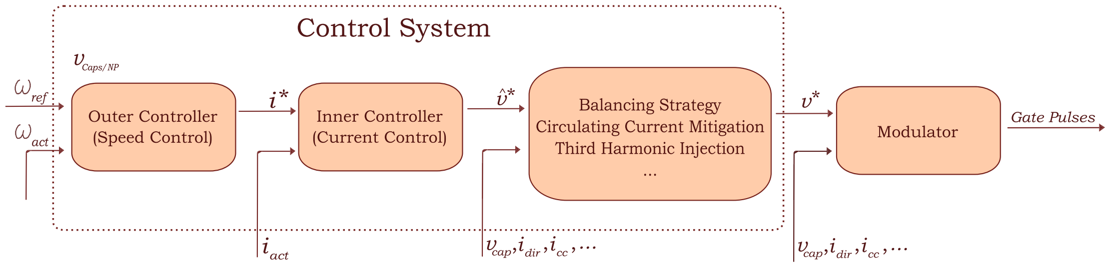


FIGURE 4. General structure of a multilevel drive control and modulation system; Incorporating proper capacitor voltage balancing strategies is essential in multilevel structures [34].

TABLE 3. Summary of past, present-day, and future solutions for traction drive components.

Component	Past solutions	Present-day solutions	Future solutions
Battery	Battery voltage was limited to 400 V.	A few EVs are manufactured with up to 900 V batteries.	Higher battery voltages are expected in all future EVs.
Inverter	Two-level inverters were the only option for traction inverters.	Multilevel inverters are used in high-power applications.	Multilevel inverters are expected to be used in higher-voltage, low-power traction drives.
Electric Motor	Induction motor was the most popular choice in both high-power and low-power applications.	Induction motor are replaced with PMSMs mostly in low-power traction drives.	PMSMs and SRMs are expected to dominate electrified transportation industry in different voltage and power levels.

which is usually current in the case of the traction drive. The dynamic equations of the output, which differ based on the motor type, need to be determined for designing the inner control loop [34]. Various control schemes can be used in this stage. Scalar control, field-oriented control (FOC), direct torque control (DTC), and model-predictive control (MPC) are among the most well-known techniques [48]–[52]. Before applying the reference voltage into the modulator, additional measures need to be taken into account. Although other stages are present in both two-level and multilevel inverters, the third stage plays a vital role in multilevel structures. The injection of a third harmonic voltage into the reference voltage balances the DC-link capacitor in NPC structure [53], increases DC-link utilization, and reduce the common-mode voltage [54]. Moreover, this stage can perform in-phase capacitor charge balancing strategies applicable to MMC and CHB inverters [34].

The modulator stage provides gating signals for the multilevel inverter switches based on the output of the third stage. The generated output signals ensure proper control of the fundamental output voltage waveform which is essential for accurate control of the traction motor. Similar to the selection of the topology and control method, choosing the best modulation scheme for multilevel inverters is a key step in each application. It should be mentioned that DTC and MPC techniques do not require a modulator stage since they can generate proper gate signals directly [55], [56].

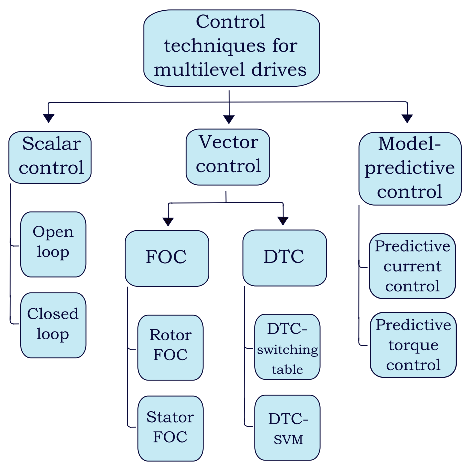


FIGURE 5. Classification of the most popular motor control techniques; Vector control techniques are suitable for fast traction applications.

Classification of the control and modulation techniques are presented in Figs. 5 and 6, respectively. Further investigation and comparison of these techniques, with focus on multilevel traction inverters is presented in Sections IV and V. Also, a summary of past, present, and future trends in traction drive components is listed in Table 3.

III. SELECTION CRITERIA

Like any other drive application, traction drive system has its own requirements that need to be met in order to have

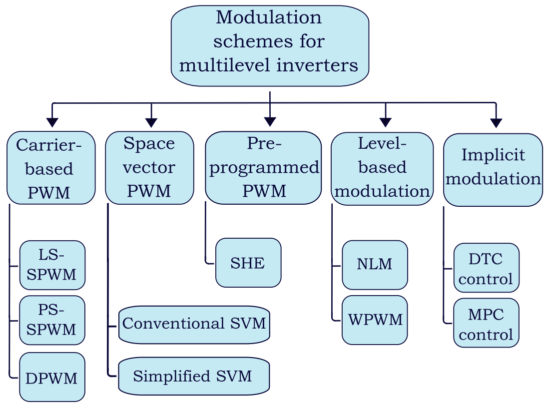


FIGURE 6. Classification of the most popular modulation schemes; SVM and SPWM are the most popular options in traction applications.

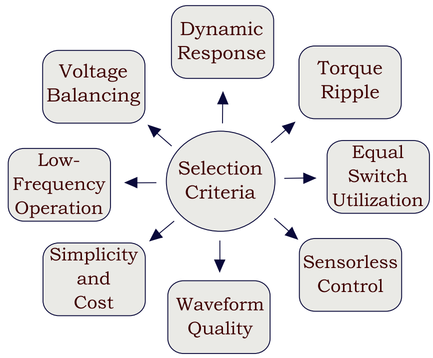


FIGURE 7. Selection criteria for control and modulation techniques based on the traction drive requirements.

favorable performance. In a general powertrain, fast response to the changes in speed and torque references, low torque ripple, wide operating range from zero speed to field-weakening region, high efficiency, high power density, low cost, and high reliability are the critical demands [32] which specify a set of criteria for adopting the proper techniques. However, when it comes to multilevel drive structures, other issues need to be addressed as well. Equal switch utilization, voltage balancing, and smooth vector switching are essential in multilevel traction drives [57], [58]. Each of these requirements is investigated in this section. The role of control strategy and multilevel structures in improving or deteriorating each of the criteria will also be explored. A proper solution must address all the aforementioned issues in the best possible way. For example, while the voltage balancing issue in industrial multilevel drives can be solved partially by increasing the capacitor value, this solution is not acceptable in traction application since it results in a drop in the inverter power density.

High torque ripple in a traction motor results in a higher vibration, acoustic noise, and malfunction in the drive system. Although different types of motors exhibit different values of torque ripples, selection of the control and modulation scheme also affects the ripple value [59]. Various modifications are proposed for control techniques to decrease the torque ripple value. These techniques are investigated in the next sections. Using multilevel inverters helps further reduction of the motor torque and flux ripples without increasing switching frequency [60].

An essential characteristic of a suitable control system in electrified transportation is the fast dynamic response of the machine to torque demand [61], [62]. This allows proper tracking of the commanded speed and torque. In addition to the fast response to a step torque demand, meeting the maximum required torque ramp also needs to be ensured [63]. In multilevel inverters, the large number of available voltage vectors increases the computation time which will have a negative effect on the response time. On the other hand, employing intermediate voltage vectors enable smooth vector switching that can ensure smooth transitions unlike the conventional two-level structures [64].

Different control and modulation techniques vary from the complexity perspective. The simpler techniques are preferred due to their higher reliability and lower computational burden. However, with the advancements in digital signal processing, more complex techniques have become viable. Multilevel inverters increase the complexity, cost, and computation time of the control system. Large number of capacitors, pre-charging circuits, and voltage sensors reduce the inverter reliability especially in topologies with plenty of floating capacitors. On the other hand, intrinsic fault-tolerance of some of the multilevel structures can enhance the reliability of the system [56], [65], [66].

The voltage imbalance issue in capacitors or on the neutral point of a multilevel topology depends on the operating point. The worst-case happens in low power factor and high modulation index, including the field-weakening region. The solutions to this issue are investigated in section V. Moreover, low-speed operation of the motor, which is pretty common in traction vehicles, causes additional unbalance. This unbalance between voltages can produce load current imbalance, and more importantly, can damage the switches by exceeding the switch voltage limit [33], [67]. It should be mentioned that balancing control techniques may inject common-mode voltages and increase the THD value. A comparison of some neutral point balancing algorithms is presented in [68]. Regarding the power density of the inverter, a robust voltage balancing technique can reduce the minimum required capacitance of the floating capacitors and increase the power density.

Multilevel inverters offer traction motor loss reduction compared to two-level converters due to lower THD and EMI [69]. However, the amount of reduction depends on the employed modulation scheme. Therefore, techniques with lower THD can increase the powertrain efficiency. Moreover, some of the multilevel topologies require specific modulation techniques in order to ensure equal power loss in the semiconductor devices [57]. without power loss equalization, the temperature of some of the switches will be higher than others which will result in a non-optimal package and cooling design.

TABLE 4. Primary and secondary requirements in different traction applications.

Requirements	Aerospace	High-power, Heavy-duty vehicles	Low-power EVs
Critical (Primary requirements)	Reliability, Power density, Efficiency	Cost, Efficiency	Cost, Power density, Efficiency
Important (Secondary requirements)	Cost, Low torque ripple	Reliability, Low torque ripple, Power density	Reliability, Low torque ripple

Although all the aforementioned requirements need to be addressed in traction drives, the priority of them differs based on the application. For example, while high reliability is an extremely important factor in aerospace application, low cost is not one of the major criteria. On the other hand, cost and power density are extremely important in low-power EVs. Based on the principal requirements of each application, Table 4 classifies these criteria. Another issue in this regard is the intrinsic trade-off among different criteria. As an example, increasing number of output voltage levels decrease the value of THD and motor losses. However, Inverter cost and complexity increase significantly at higher number of levels. Therefore, the number of levels is determined by the trade-off between THD and cost [70]–[72].

IV. CONTROL TECHNIQUES FOR TRACTION MULTILEVEL DRIVES

A comparison of different control methods for multilevel inverters in traction drives is presented here. Scalar control and FOC in multilevel drives are similar to the two-level inverters since the control stage provide the input to the modulator stage [73]. Conversely, other control techniques, like DTC and MPC need to be adjusted to match the inverter topology since the modulator and control stages are combined together. For example, neutral point balancing needs to be addressed in designing a controller based on the DTC method for an NPC traction inverter. Consequently, this section mostly deals with the DTC control technique with the implicit modulator. MPC technique will be investigated in section VI.

A. SCALAR CONTROL

Scalar control aims at controlling the magnitude of the control variables and is founded on the steady-state model of the machine. In other words, it does not consider the coupling effects in the motor [74]. Although scalar control is a cheap and simple method to implement, it has a poor performance, especially in applications with fast dynamic requirements [75], like traction applications. However, it is used in specific multilevel traction applications with slower dynamics, like electric ships [11]. The dynamic response of the scalar controller can be improved by adding two feedforward paths for the slip and stator voltage magnitude to the control scheme. Its performance improvement depends on the accuracy of these feedforward paths [63]. The scalar controller is not investigated further here for traction applications.

B. FIELD-ORIENTED CONTROL

Field-oriented control, which is a vector control method is a suitable option for traction drives due to its enhanced dynamic performance over the entire speed range. The motor flux and torque are represented as functions of the stator currents which are controlled directly [63]. This in turn results in a relatively fast dynamic response and low current and torque ripple in FOC-based drives [75], [76]. However, the presence of a modulator stage in the control diagram slows down the control process [77]. FOC has been applied for multilevel-based drives in the literature [78], [79]. The schematic of a FOC-based multilevel PMSM drive is shown in Fig. 8. As mentioned before, there is no difference in FOC-based control of multilevel and two-level drives except in the modulator stage.

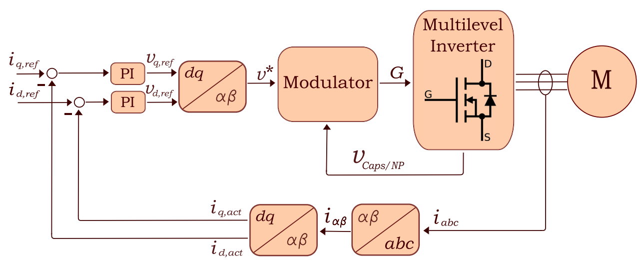


FIGURE 8. FOC Scheme Block Diagram; Modulator stage and PI regulators are essential in this scheme.

C. DIRECT TORQUE CONTROL

Direct torque control, which is a well-established motor control scheme, aims at controlling the flux and torque directly, not through the stator currents. Hysteresis controllers are used for tracking the torque and flux. Then, the optimum voltage vector and gating signals are selected using a switching table [74], [80]. The schematic of a DTC scheme for a traction motor is depicted in Fig. 9. The main advantages of the DTC scheme are the very fast torque response, robust operation, and simple structure with low computation time [80]. The simplicity of the DTC scheme stems from eliminating the need for current regulators, coordination transformations, and modulators. Moreover, the DTC method is considered intrinsically sensorless since it is capable of presenting good

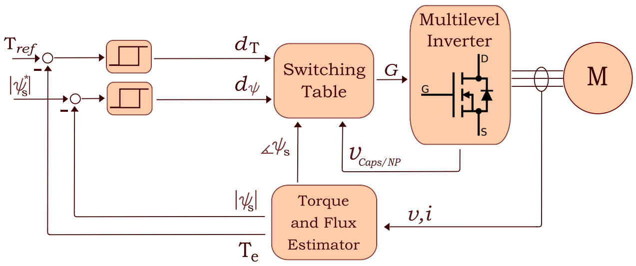


FIGURE 9. DTC scheme block diagram; Modulator stage and PI regulators are eliminated in this scheme.

dynamic torque response without using a mechanical sensor on the shaft [76]. The mentioned advantages make it a potential option for traction drives. However, higher noise and more difficult control at very low speed, higher torque and current ripple, varying switching frequency, absence of current control, and large start-up current are the disadvantages of this method comparing to FOC [58], [76].

A multilevel DTC motor drive benefits from the enhancement of the low-speed performance and reduction of the torque ripple when compared to its two-level DTC counterpart [60]. However, the common switching table that is employed for a two-level inverter cannot be used for the multilevel drive since the issues of smooth vector switching and balancing the capacitor voltages or neutral points need to be addressed when applying the DTC scheme to a multilevel drive [58]. A three-level medium voltage, high power inverter with DTC control scheme is manufactured for encoderless drive applications by ABB, where the manufacturer has announced that the application of this drive system is marine propulsion system [81]. DTC technique for high-power multilevel multiphase traction motors has also been investigated in the literature. In [82], a three-level five-phase drive is proposed and implemented for high-power applications like electric aircraft, ship, locomotive, and vehicles. The proposed control scheme has also ensured equal voltage balancing in a wide speed range by utilizing the redundant small vectors in the modulation scheme.

In [83] a torque hysteresis band control technique (THBC) is introduced for an open-end winding IM (OEWIM) fed by dual two-level inverters for EV applications. The space vector combination of this structure has 64 switching combinations which are spread over 19 different vector locations, similar to a three-level structure. In the mentioned study, the authors explored three-level, five-level, and seven-level THBC strategies and provided switching tables for each. In a comparison with two-level DTC, torque ripple and converter losses have reduced significantly with the proposed strategy. Moreover, the algorithm execution times are shown to be slightly lower compared to the conventional two-level DTC.

In an attempt to use the advantages of both FOC and DTC, a combined control method for an NPC multilevel inverter is presented in [84]. The authors have claimed that this control method benefits from fast dynamic response and simplicity of the DTC scheme as well as low current and torque ripple of the FOC method. However, using a modulator stage and current regulators has increased the complexity of the system comparing to the conventional DTC. In [58], two modified DTC methods are presented for a multilevel-fed induction motor drive in order to solve the smooth vector switching and neutral point balancing issues. A DTC scheme is proposed in [85] for a three-level traction drive, where extremum seeking control is used to determine the optimum flux with a model-free adaptive controller. A dynamic look-up table method is proposed in [86] which is capable of reducing torque ripple regardless of the motor speed. However, the flux ripple is increased slightly at low speeds. A DTC-based control scheme for a five-level FC drive is presented in [52]. The proposed control scheme maintains the floating capacitors' voltages in the required value while providing the required output voltage.

Although most of the studies on the multilevel DTC scheme in the literature are dealing with IM drives, [60] proposes a DTC scheme for three-level IPMSM drives which are getting more popular in traction applications. The proposed scheme is a duty cycle DTC (D-DTC) based method, aimed at minimizing torque ripple while avoiding a significant increase in the switching frequency. A generalized DTC scheme for multilevel inverters is proposed in [87] for any number of levels. By replacing the conventional torque hysteresis controller with a PI regulator and two carrier-fed comparators, the inverter can operate with a constant switching frequency. Torque ripple values have been reduced by more than 50% at different speeds by using the proposed method at the cost of about 25% increase in computational cost. A DTC-based induction motor for EV propulsion in a seven-level single source CHB inverter is proposed in [88]. Capacitor voltage control is achieved by the adjustment of the active and reactive powers. While simplicity is the interesting feature of DTC-based drives, the proposed methods, which improve the characteristics of the control system, lead to an increase in its complexity [76].

D. A COMPARISON BETWEEN FIELD-ORIENTED CONTROL AND DIRECT TORQUE CONTROL

Following the mentioned characteristics for each of the methods, a comparison based on the simulations is presented in this subsection. Fig. 10 exhibits the torque response to a change in the applied torque when the speed is constant. Although the DTC method has a faster dynamic response compared to FOC, the torque ripple is shown to be higher with the DTC scheme. However, the torque ripple of the DTC method can be reduced at the cost of higher complexity by adding a space vector modulator (SVM) instead of the conventional switching table as can be seen in Fig. 10.

Following speed reference in an electric vehicle can be a more accurate measure of the dynamic performance of a traction control system. Here, two standard driving cycles are selected to measure the RMS error in following the speed reference using each of the control techniques. Urban dynamometer driving schedule (UDDS) (Fig. 11) and

TABLE 5. A comparison of control techniques for multilevel traction drives.

Control Technique	Advantages	Disadvantages
Scalar	• Simple and cheap • No feedback required	• Poor dynamic response • Inaccurate control • High torque ripple • Torque is not controlled
FOC	• Good dynamic response • Low torque and current ripple • Fixed Switching Frequency • Full torque at zero speed • Small sensitivity to motor parameters	• Feedback is required • Costly • Slower response comparing to DTC and MPC • Requires an external modulator • More complex compared to DTC
DTC	• Very fast dynamic response • Intrinsically sensorless • Simple structure • Low computation time	• Variable switching frequency • Difficult control at low speed • Higher torque and current ripple comparing to FOC • Large start-up current • Higher sensitivity to motor parameters

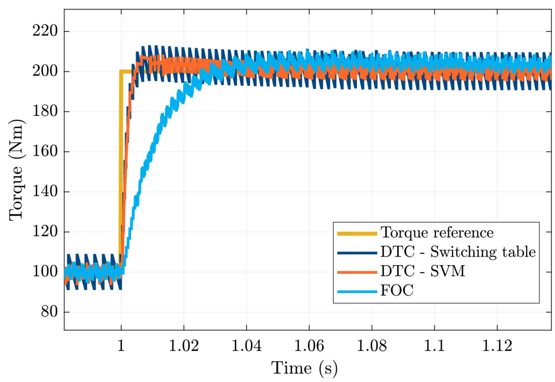


FIGURE 10. **Comparison of response to a change in applied torque with DTC-Switching table, DTC-SVM, and FOC schemes; DTC scheme shows a slightly faster response compared to FOC.**

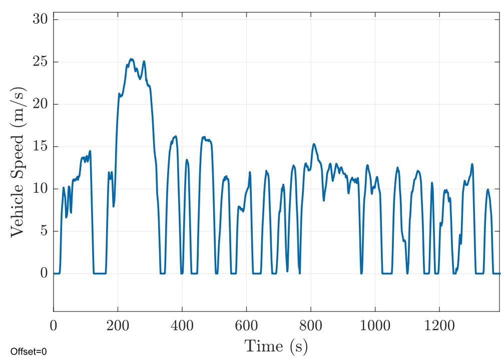


FIGURE 11. **UDDS driving cycle; Frequent changes in the reference speed are present in the urban cycles.**

highway fuel economy driving schedule (HWFET) (Fig. 12) driving cycles are selected as urban and highway driving cycles respectively. Table 6 shows the RMS error percent in following the reference speed. Due to the frequent changes of the speed in the urban cycle, the amount of RMS error is higher compared to the highway cycle. Fig. 13 magnifies some parts of the UDDS driving cycle and response of each controller to the reference speed.

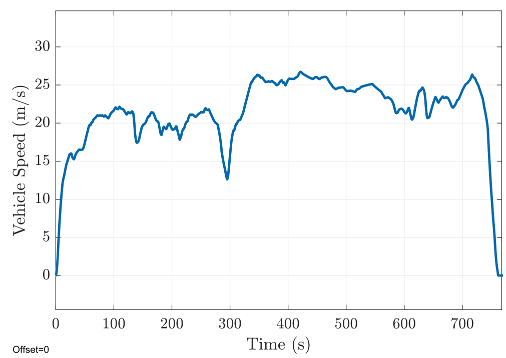


FIGURE 12. **HWFET driving cycle; The reference speed changes are much less in the highway driving cycles.**

TABLE 6. **RMS error in following speed reference (% of reference).**

Control Method	UDDS	HWFET
FOC	0.94 %	0.34 %
DTC	0.29 %	0.11 %

V. MODULATION SCHEMES FOR MULTILEVEL TRACTION DRIVES

Modulation techniques for multilevel converters can be classified into carrier-based pulse-width modulation, space vector modulation, pre-programmed pulse-width modulation, and level-based modulation. As mentioned before, conventional DTC and MPC methods do not require separate modulators.

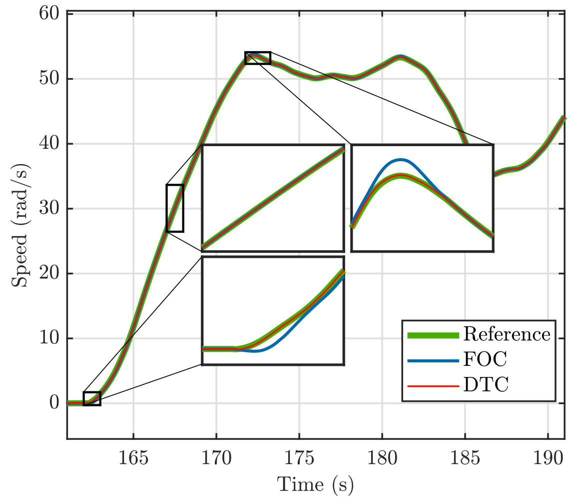


FIGURE 13. Following reference speed in UDDS driving cycle with different control methods; DTC method shows a more accurate reference tracking than FOC.

Generally, switching schemes with low switching frequency result in low switching losses and higher efficiency. On the other hand, the value of THD is high with low frequency switching sequences [70].

A. SINUSOIDAL PULSE WIDTH MODULATION

Sinusoidal pulse width modulation (SPWM), in both phase-shifted (PS-SPWM) and level-shifted (LS-SPWM) types, is an extension of the well-known SPWM technique for the two-level inverter. Both techniques are considered simple modulation schemes. This is more considerable in large number of levels, where other modulation schemes become more complex [57]. In a comparison of the PS-SPWM and LS-SPWM, the latter benefits from a lower THD in the same modulation index. However, due to unequal switch utilization, there might be a need to rotate the switching patterns in LS-SPWM. In a three-level inverter, voltage balancing and maximum DC-link utilization can be achieved by adding a third harmonic content to the carrier. However, in large number of levels, voltage balancing cannot be achieved simply. The THD and losses are higher in this technique compared to more advanced schemes. Also, the response of the SPWM-based multilevel drives in low-speed operation as well as their dynamic response are relatively slow [39], [57], [89], [90]. These drawbacks make them unsuitable for fast traction applications.

There have been studies to improve the characteristics of the SPWM technique. In order to overcome unequal switch utilization of LS-SPWM cascaded multilevel inverter, [91] has proposed a sorting strategy that ensures equal distribution of pulsed even in the fault condition of one or more cells. In [67], the issue of balancing the neutral point in NPC inverter is addressed for the entire power factor range by introducing a modulating voltage component which is in phase with the load currents. The issue of low-frequency oscillation in the neutral point of NPC drive is addressed in [92] by using two modulating signals for each inverter phase. A capacitor voltage balancing method based on SPWM for nested neutral point clamped (NNPC) inverter is proposed in [93] where the proper switching state is determined based on the required output voltage level and current direction. It should be mentioned that the proposed improvements for the SPWM scheme deteriorate its simplicity by adding additional stages in the modulator.

While SPWM scheme is known for its simplicity, its implementation for high-level converters becomes challenging due to the need for accurate synchronization between the carrier waveforms. Inaccurate synchronization happens due to computational delays, sampling times and memory constraints. In [94], this issue has been addressed by introducing a modulation scheme by using a single triangular carrier which is capable of producing both $N + 1$ and $2N + 1$ output waveforms. The proposed technique shows same THD and fundamental voltage with traditional PS-SPWM when the modulation index changes from 0 to 1.

B. SPACE VECTOR MODULATION

With the widespread use of fast microprocessors, space vector modulation (SVM) has been more popular due to lower THD, lower *dv/dt*, higher flexibility, more redundant states, lower common-mode voltage, and higher efficiency in both inverter and motor. It is believed that SVM in the linear region, and six-step modulation (square-wave modulation) in the over-modulation region, are mostly utilized in two-level traction application [39], [63], [95]. SVM for multilevel drives suffers from high computation times. As the number of levels of an inverter increases, the number of switching states increases dramatically. Consequently, simplification of the SVM technique for multilevel inverters has been the subject of many studies [95]–[98]. In [95] the required memory for a multilevel inverter is reduced by storing the switching states of only the first vertex of the modulation triangle. The switching states of other vertices are achieved by a mapping technique. This method has increased the speed of computations by eliminating the look-up tables.

In [17], [99], a switching sequence is presented for balancing the voltages of the DC-link capacitors of a three-level NPC inverter used in EVs. The proposed sequences reduce the number of transitions and switching losses while ensuring a low difference between the capacitors' voltages. The effect of the wide range of speed and torque in a typical EV is also considered in these studies. A modified virtual SVM technique, which is designed for traction inverters, is proposed in [100] with the purpose of minimizing neutral point voltage fluctuations in transient conditions.

With the high modulation index and leading power factor that occurs in the field-weakening operation of a traction motor, the well-known balancing schemes are unable to balance the neutral point voltage in NPC structure. This happens due to the fact that medium vectors are utilized more often in high values of modulation index. Since there is no redundant state for the medium vectors in three-level NPC, the voltage difference of the capacitors increases drastically in a few switching cycles. This issue is explored in [24], [101] for EV applications and some modifications are proposed in order to eliminate or reduce the use of medium vectors in certain operating conditions. In [101], although the voltage balancing issue is solved using the proposed schemes, current THD is increased from 1.75% to 2.58%. Also, the voltage transitions are not smooth anymore.

SVM technique is modified and simplified in [11] for an MMC-based electric ship propulsion system. Without a suitable voltage balancing strategy, the capacitor voltage imbalance can cause circulating current in the phase legs which leads to increased power loss. Utilizing a capacitor balancing method is essential in order to avoid voluminous capacitors for each sub-module. Simplification of the SVM technique is done by mapping the reference vector to a two-level SVM structure. The required computation time with this method is independent of the number of sub-modules.

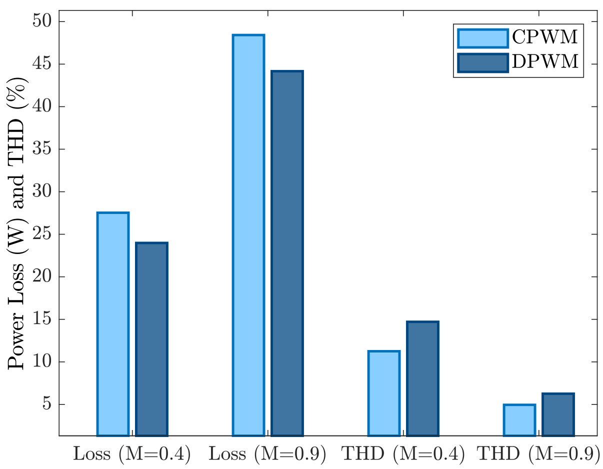


FIGURE 14. Comparison of CPWM and DPWM; DPWM shows lower loss but higher THD compared to CPWM.

C. DISCONTINUOUS PULSE WIDTH MODULATION

The discontinuous pulse width modulation (DPWM) scheme, which was first proposed for two-level inverters, is capable of reducing switching losses considerably by eliminating switchings at the peak of the sinusoidal currents. However, applying this technique to multilevel inverters is challenging due to the issue of voltage balancing in multilevel inverters [102]. Moreover, the value of current and voltage THD is high in this modulation technique. Fig. 14 compares power loss and current THD in continuous PWM (CPWM) and DPWM schemes presented in [103]. The switching frequency in this study is 10kHz.

In order to utilize the DPWM method in NPC structure, additional measures need to be taken to ensure a low ripple on neutral point voltage. In [104], three switching patterns are proposed to be used based on the operating speed of the drive in order to ensure a low imbalance on the neutral point. In [105], two offset voltages with opposite influences are used and reduced neutral point voltage fluctuations effectively. This method has increased inverter losses comparing to conventional DPWM. However, the loss value is still lower than other modulation schemes. DPWM technique is also proposed for traction inverter applications [106]–[108]. A hybrid strategy is proposed in [108] with a variable to control the discontinuous interval in a three-level traction drive which is operating under different load and power factor conditions. The control of the discontinuous interval addresses the tradeoff between switching loss and neutral point voltage imbalance.

D. SELECTIVE HARMONIC ELIMINATION

Selective harmonic elimination (SHE) modulation technique uses pre-determined angles of commutation in order to eliminate low-order selected harmonics. Although the SHE scheme lacks fast dynamic response, in high-power traction drives like electric trains, the SHE method is used at the high-speed region of operation of the motors [63], [109], [110]. This scheme benefits from low switching frequency, high efficiency, and small filter requirements [111]. SHE technique has been expanded to multilevel topologies [111]. In [22], a SHE technique is proposed for a traction inverter in railway transportation which is based on NPC multilevel inverter. Pulse amplitude width modulation (PAWM) is another low-frequency modulation technique, described in [112], which has the advantage of low switching losses. However, it should be mentioned that capacitor voltage balancing in a multilevel inverter that uses SHE or PAWM schemes is an issue due to the low switching frequency. Large capacitors are required which makes it uninteresting, especially for low-power battery-powered traction applications like EVs, where the power density of the system plays a vital role in the design process.

E. NEAREST LEVEL MODULATION AND WINDOWED PULSE WIDTH MODULATION

The switching frequency in the nearest level modulation (NLM) technique is low, like the SHE scheme. However, this technique does not require the calculation of commutation angles which makes it simpler. The main drawback of this technique is low-quality output waveform in small number of levels [113]. Consequently, this modulation technique is not suitable for low-power traction drives. It is proposed for high-voltage MMC-based multilevel inverter for railway electrification in [114]. A large number of levels ensure acceptable waveform quality. Some modifications and improvements have been applied to the NLM method. In [115] a modulation technique called windowed pulse width modulation (WPWM) is proposed for traction drives. The idea behind this scheme is to combine NLM and PWM in order to take advantage of low switching loss of NLM and good quality output waveform of PWM methods. In this scheme, PWM is applied at some specific intervals. These intervals are determined dynamically based on the traction drive's operating condition.

TABLE 7. A comparison of modulation schemes for multilevel traction drives.

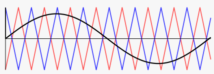
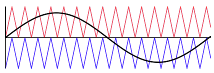
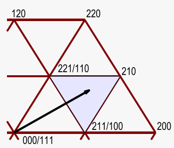
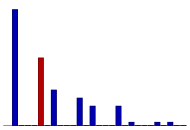
Modulation Technique	Scheme	Advantages	Disadvantages
PS-SPWM		• Simple structure • No need to rotate switching patterns • three-level voltage balancing achieved by adding third order harmonic content	• Higher THD than other techniques • Not flexible for voltage balancing in high-level structures • Poor response in low-speed motor operation • Poor dynamic response
LS-SPWM		• Simple structure • Better output waveform quality than PS-SPWM • three-level voltage balancing achieved by adding third harmonic content	• Higher THD than SVM • Not flexible for voltage balancing in high-level structures • Poor response in low-speed motor operation • Poor dynamic response
SVM		• Redundant switching states • Effective voltage balancing strategy • Low output THD • Good dynamic response • Low *dv/dt* • High Efficiency	• Complex in high-level structures • slower dynamic response than MPC with implicit modulator
SHE	 $cos(5\theta_1)+cos(5\theta_2) = 0$	• Suitable for high-power applications • Effective low-order harmonic elimination, resulting in smaller filters • Good steady-state response • Very low switching losses • High efficiency	• Slow dynamic response • Not suitable for low-power traction drives • Poor response in low-speed motor operation • Not flexible for voltage balancing • Requires large capacitors

Table 7 lists the advantages and disadvantages of the most popular modulation schemes in traction applications.

VI. OUTCOMES AND FUTURE TRENDS

This section of the paper summarizes the major outcomes of this paper and future trends in multilevel traction inverters.

A. OUTCOMES

1) SELECTION CRITERIA

Since the selection of the most suitable techniques requires certain criteria, this paper specified the principal requirements in traction drives. Fast response to transitions, low torque ripple, voltage balancing techniques, low-speed operation, simplicity, reliability, and cost are the chief items in traction drives. Also, a classification of these requirements into critical (primary) and important (secondary) criteria was made in Table 4 for different traction applications. For example, while cost, power density, and efficiency are the principal requirements of low-power EVs, reliability plays an essential role in aerospace applications.

2) CONTROL TECHNIQUES

In a comparison of the control techniques, it is shown that the scalar control is the cheapest and simplest control technique, but it shows poor tracking of the reference signal which makes it unsuitable for the fast transitions in the reference speed and torque. Vector control and MPC techniques have an acceptable response time to the changes in the reference. DTC method shows faster response compared to FOC. Due to the elimination of current regulators, it has a simpler structure compared to FOC. On the other hand, the amount of torque ripple is higher with DTC scheme. Also, variable switching frequency and higher sensitivity to motor parameters are other drawbacks of the DTC method.

3) MODULATION SCHEMES

Modulation techniques have also been compared in this paper based on the pre-determined criteria. A critical aspect of modulation schemes for multilevel inverters is ensuring capacitor voltage balancing and smooth voltage transitions. Carrier-based techniques are simpler but are not flexible for the purpose of the capacitor and neutral point voltage balancing in multilevel inverters, specially in high-level structures. Techniques with low switching frequency such as SHE and NLM are not suitable for low-power traction drives since they require large capacitors to be used which reduces the power density of the drive. Space vector modulation technique shows good flexibility and response. However, due to the increase in number of voltage vectors, its complexity in high-level structures needs to be addressed effectively. DPWM scheme reduces switching losses in inverter switches at the expense of higher output THD.

B. FUTURE TRENDS

1) PRESENT-DAY AND FUTURE INVERTER SOLUTIONS IN TRACTION DRIVES

Table 8 summarizes the market status for present-day traction applications. As mentioned earlier in this study, current

TABLE 8. Current traction inverter topologies on the market.

Application	Maximum voltage	Current topology on the market
Electric ships	15 kV	Two-level and multilevel
Electric trains	3 kV	Two-level and three-level
EVs	900V	Two-level

manufacturers of light-duty passenger EVs including Tesla, Toyota, Nissan, and Chevrolet have used two-level inverters in their drive system. Even with the higher battery voltages, higher-voltage semiconductors are used by the industry for the two-level structures. However, heavy-duty high-power traction applications have been using multilevel inverters. ABB has manufactured three-level inverters for high-voltage electrified trains in Swiss Federal Railways, Swedish State Railways, and Deutsche Bahn. Also, multilevel inverters are used for the electric ship industry with a maximum voltage of 15 kV [10], [11], [29].

As mentioned in this paper, the DC voltage level in EV inverters has increased to 800V by several well-known manufacturers recently. Moreover, the standards are enabling even higher voltages. CHAdeMO and China Electricity Council have developed 1500V, 600A, 900kW charging standard [116]. Consequently, the DC-link voltage inside EVs can go higher, which increases the importance of using multilevel inverters due to their higher efficiency, higher power quality, and lower generated EMI. Consequently, there will be more studies on innovative topologies, control techniques, and modulation schemes in this particular application. Regarding topologies, innovative topologies and modified classic topologies must be studied in future. Possible topology modifications are reduction in the number of switches and increasing the efficiency with the same number of output voltage levels. As an example, in [70] a modified CHB inverter with a reduced number of switches is proposed and implemented. This modification has increased the efficiency and reduced the cost and complexity of the inverter.

2) EFFECT OF WIDE BANDGAP DEVICES ON MODULATION AND CONTROL

Recently, there has been a trend among manufacturers to take advantage of wide bandgap (WBG) semiconductors in their products. As mentioned earlier, Tesla has used SiC MOSFETs in its model 3 EV inverter. Other than Tesla, MEDCOM has implemented inverters for electric buses using SiC MOSFETs which has led to more than 30% reduction in the size of the inverter [117].

With the appearance of WBG devices in traction inverters, the switching frequency can increase considerably [118]. Increasing frequency can decrease the size of the passive devices, like DC-link capacitors and output filters. Since most of the harmonics are generated around switching frequency, the output filter needs to have high attenuation at that frequency [70]. Therefore, higher switching frequency with WBG devices usually results in smaller filter footprint. TM4 has announced that it reached 195 kW/L power density which is almost 100% higher than the goal which is set by US Department of Energy [72]. The increased switching frequency can also help the control system and modulator to decrease the torque and current ripples, improve dynamic response, and balance the voltages more effectively. As a result, some of the issues regarding the control of multilevel traction drives can also be solved easier. However, fast transitions of the switches which increase *dv/dt* need to be considered in the proper design of the inverter system.

3) FAULT-TOLERANT MULTILEVEL TRACTION INVERTERS

An important criterion in the traction drive system is fault-tolerance capability. The vehicle should remain operating in limp-home mode in case of fault occurrence [56], [119]. This criterion applies to all the components in the drive system, including the inverter. In the conventional two-level inverters, fault-tolerance is provided by using a fourth inverter leg which operates in case of failure in one of the main inverter legs.

In the case of multilevel inverters, fault-tolerance can be achieved without adding the fourth leg. This unique characteristic of multilevel inverters opens an area for future studies. The control system, structure, and component selections must ensure the proper operation of the inverter after fault occurrence in one of the switches. The number of voltage levels, equal loss distribution among the remaining switches, and controller robustness need to be studied prior to utilizing multilevel structures in future EVs.

4) MODEL-PREDICTIVE CONTROL

With the development of digital processors, model-predictive control has also become an attractive option. MPC technique calculates the optimum variables based on the system's mathematical equations in order to satisfy drive requirements. The predictive control technique has a fast dynamic response, can handle non-linearities, and satisfies multiple control objectives simultaneously. The amount of torque ripple is lower comparing to DTC. However, the problems of varying switching frequency and model-sensitivity still exist. Moreover, the MPC method requires a higher calculation time than FOC and DTC. Predictive motor control can be divided into predictive torque control (PTC) and predictive current control (PCC) [65], [120].

Exploiting the MPC technique in traction drives is investigated in the literature [121]–[124]. The computational burden of the MPC technique increases as the number of levels in the inverter goes higher. Consequently, most of the future studies on multilevel MPC-based traction drives will focus on the reduction of the computation times. An efficient finite set MPC is proposed in [120] for a seven-level inverter. The control objectives are to control the output currents and maintain floating capacitors' voltage on the determined value. In the proposed method, an approximation has been made in order to separate the phase voltages, output currents, and the voltages of floating capacitors. The proposed technique has reduced the number of calculations and execution time by 48 and 6 times, respectively. Another issue that needs to be addressed in the MPC scheme is to improve the robustness of the controller and reduce the effect of the parameter mismatches. Some studies have investigated this issue [125], [126]. In short, the aforementioned reductions in computation times of the MPC controller, as well as a continuous increase in the computation speed of the processors introduce new opportunities for this control method in multilevel traction drives, where multiple control objectives need to be addressed simultaneously.

5) CONTROLLER ROBUSTNESS

DTC and MPC techniques usually need motor parameters like stator resistance and inductance to estimate the flux and currents. Due to unavoidable mismatches that happen in the manufacturing process and high-temperature operation of the motor, the estimation is not accurate. Hence, robust controller designs are required for this application. In multilevel traction drives, parameter uncertainty can be expanded to the mismatch among numerous capacitors and switches that are used in the inverter. Regarding capacitor mismatch, a robust controller might be designed using disturbance observers to ensure that the difference in the capacity of them will not result in unequal voltage sharing. Sliding-mode observers are good options for designing robust controllers [126].

Another issue that might be a topic for further studies is equalizing temperature rise in MOSFETs. while conventional modulation schemes try to keep the losses same for all the switches, in reality, the switches that are placed farther from the coolant input are the design bottleneck. The amount of power loss difference in the switches is also related to the operation point. Consequently, the switching scheme might need to be tuned based on the operation point of the system and its thermal model in order to reduce the number of switchings in the hotter switches. This change can result in increasing the power density of the inverter.

6) INTEGRATION OF INVERTER, ON-BOARD CHARGER, AND BATTERY MANAGEMENT SYSTEM

Efforts have been made to increase the overall power density of power electronic converters inside the traction system. Integration of the inverter and on-board charger (OBC) is one of the proposed solutions in this regard that enabled a single power electronic converter for both purposes [127]. Although this idea has been applied to the case of two-level structures in present-day traction drives, it requires accurate control and modulation techniques in the case of multilevel inverters to ensure equal voltage balancing on the capacitors in both operation modes. Moreover, integration of the battery management system (BMS) with the aforementioned inverter/OBC is an innovative idea that can only be feasible in the case of high-level inverters. Although the mentioned integration techniques increase the power density of the drive system, they make control and modulation schemes more complex. Therefore, further studies are required in this regard to ensure a robust and stable control system.

7) MICROPROCESSORS

As mentioned, one issue regarding the implementation of multilevel WBG-based drives for traction drives is higher computation times compared to the conventional two-level inverters. Two important factors in this regard are the larger number of switching states and capacitor voltage balancing requirement. In order to fully utilize the multilevel structure features, fast microprocessors are required. Performance of the microprocessors has had a continuous rate of improvement in the past decades. This continuing trend in processing improvement will enable higher-level inverters with fast switching devices.

8) MODULATION TECHNIQUES

One possible research topic in modulation techniques can be equal power loss distribution among switching devices. This issue directly affects the reliability and lifetime of the traction inverter. Modulation techniques should be improved in order to ensure an equal temperature rise of the devices in all operating conditions of the motor. This will increase the inverter power density as well since there will not exist a single hot switch acting as the weak spot of the system.

Further simplification of modulation techniques, especially in large number of levels is another research area. Digital signal processors are continuously improving in terms of computation speed, introducing new opportunities to modulation techniques. Low *dv/dt* is an important feature of multilevel structures. Consequently, when new or simplified techniques are proposed, smooth vector transitions must be ensured.

9) VOLTAGE BALANCING OF CAPACITORS

Reduction of the weight and volume of the inverters in traction application, especially battery-powered vehicles, is of great importance according to the requirements announced by the US Department of Energy [72]. Regarding the power density of the inverter in EVs, the goal for 2025 is set to 100kW/L. Consequently, reduction in the size of capacitors in multilevel structures can be beneficial in increasing the power density of the inverter. As investigated in this paper, capacitor size reduction will not happen without a reliable and fast voltage balancing strategy in different operating conditions. The topology, control method, and modulation technique are all responsible for effective capacitor size reduction.

VII. CONCLUSION

Recently, several well-known EV manufacturers have increased the battery voltage from 400V to over 800V and more in order to benefit from lower current, faster charging time, and higher power density. With the new standards in this area, DC-link voltages up to 1500V are also expected in near future. This trend toward higher input DC-link voltage in traction inverters has provided multilevel topologies with a great chance to surpass two-level structure in some of the operating characteristics. This paper presented a literature review and comparison of the most well-known modulation and control techniques for multilevel inverters in this specific application.

This review paper specified a set of selection criteria based on the requirements of traction systems. Based on these requirements, control and modulation techniques for multilevel traction inverters were investigated and compared. As mentioned in this study, multilevel traction inverters are not mature yet. These structures need to adapt to the requirements of the traction industry. Therefore, the last section of this paper presented future trends and some suggestions for possible studies on this topic.

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