Received 13 January 2021; revised 17 February 2021; accepted 28 February 2021. Date of publication 3 March 2021; date of current version 26 March 2021. The review of this article was arranged by Associate Editor Zhixiang Zou.

Digital Object Identifier 10.1109/OJPEL.2021.3063550

A Review of Multilevel Inverter Topologies in Electric Vehicles: Current Status and Future Trends

AMIRREZA POORFAKHRAEI (Graduate Student Member, IEEE), MEHDI NARIMANI (Senior Member, IEEE), AND ALI EMADI (Fellow, IEEE)

Electrical and Computer Engineering, McMaster University, Hamilton, ON L8S 4L8, Canada

CORRESPONDING AUTHOR: AMIRREZA POORFAKHRAEI (e-mail: poorfaka@mcmaster.ca)

ABSTRACT Traction inverter, as a critical component in electrified transportation, has been the subject of many research projects in terms of topologies, modulation, and control schemes. Recently, some of the well-known electric vehicle manufacturers have utilized higher-voltage batteries to benefit from lower current, higher power density, and faster charging times. With the ongoing trend toward higher DC-link voltage in electric vehicles, some multilevel structures have been investigated as a feasible and efficient option for replacing the two-level inverters. Higher efficiency, higher power density, better waveform quality, and inherent fault-tolerance are the foremost advantages of multilevel inverters which make them an attractive solution for this application. This paper presents an investigation of the advantages and disadvantages of higher DC-link voltage in traction inverters, as well as a review of the recent research on multilevel inverter topologies for electrified transportation applications. A comparison of multilevel inverters with their two-level counterpart is conducted in terms of efficiency, cost, power density, power quality, reliability, and fault tolerance. Additionally, a comprehensive comparison of different topologies of multilevel inverters is conducted based on the most important criteria in transportation electrification. Future trends and possible research areas are also discussed.

INDEX TERMS Electric vehicles, higher-voltage batteries, multilevel inverters, power density, traction motor drives, transportation electrification.

I. INTRODUCTION

Electrified transportation has been considered as a promising solution to many issues caused by its gas-fueled counterpart. Greenhouse gas emissions of the transportation sector was 28% share of total emissions in the United States in 2018 [1]. The emission can be either reduced or eliminated by hybrid or pure-electric transportation. Other than the reduction in gas emissions, transportation electrification leads to higher energy efficiency, better acceleration, and less required maintenance [2]. On the other hand, long charging time and low maximum driving range of battery-powered electric vehicles (EVs or BEVs), trucks, and buses before recharging are still the biggest challenges which are impeding the fast growth of transportation electrification [3].

In [4], a comparison has been made between passenger EVs and internal combustion engine vehicles (ICEVs) in terms of the time required for an 845 km inter-city travel. It is demonstrated that to have comparable travel time between EVs and ICEVs based on current batteries capacities, there is a need for chargers with the power of more than 400 kW. Using extreme fast chargers (XFCs), with the output voltage of at least 800 V DC, is a possible solution to this issue [5].

Enabling extreme fast charging is one of the benefits of moving toward a higher-voltage DC-link in electrified transportation vehicles. Besides, employing higher-voltage batteries allows for a reduction in size and weight of the required cables for transferring a certain amount of power [6]. Moreover, operating at a higher voltage can reduce the motor current and

TABLE 1. Battery Voltage of Some EVs on the Market [10]–[12]

Vehicle	First Production Year	Battery Voltage (V)
Nissan Leaf	2010	350
Tesla Model S	2012	350
Chevrolet Spark EV	2013	400
Audi e-tron	2018	400
Porsche Taycan	2019	800
Lucid Air	2020	900
Aston Martin Rapide E	N/A	800

TABLE 2. Traction Inverters' Structure on the Market

Application	DC Voltage (V)	Structure	Switching Devices
Electric Ships	1.5 kV to 15 kV	Two-level or Multilevel	GTO, Thyristor, or IGBT
Trains and Tramways	up to 3 kV	Two-level or Three-level	GTO, Thyristor, or IGBT
Buses, Trucks	up to 900 V	Two-level	IGBT, MOSFET
Passenger EVs	up to 900 V	Two-level	IGBT, MOSFET

thus achieve higher efficiency [7]. A more detailed discussion of the benefits of moving toward higher-voltage batteries will be presented in Section III.

Due to the advantages mentioned above, recently, there has been a trend among manufacturers to move toward higher DC-link voltage in traction drives. Table 1 lists some of the commercial passenger EVs, and their battery voltage. Porsche manufactured its all-electric car in 2019, 4 years after unveiling a concept car named Mission E, and named it Porsche Taycan [8]. This car is capable of being charged with a maximum power of 270 kW at 800 V. With the use of higher voltage DC system inside the car and also in the charger, it takes only 22.5 minutes to recharge its 93 kWh battery from 5% to 80% [9].

Other than Porsche Taycan, Aston Martin Rapide E is among the first vehicles which announced utilizing 800 V batteries to exploit its advantages [13]. Lucid Air, manufactured by Lucid Motors will be the first car using over 900 V batteries for reduction of weight and charging time [11]. Hyundai has also announced that it joins IONITY, collaborating with BMW Group, Daimler AG, Ford Motor Company, Volkswagen Group, and Porsche AG to enable utilizing 800 V systems in its EVs to use 350 kW charging system [14]. GM has also announced that it will use 800 V batteries with 350 kW chargers for its truck platform [15]. Increase of DC voltage will happen in other electrified transportation applications as well. For example, in future all-electric aircrafts DC voltages of up to 3 kV will be utilized to supply the high-power electric motors [16]. Also, DC-link voltages up to 15 kV are recommended to be used in the electric ship propulsion system [17].

Despite all the benefits mentioned, new challenges emerge in the drive system by moving toward a higher voltage DC-link. Although reducing current results in lower conduction loss, higher voltage increases switching losses which usually reduce total efficiency if the same inverter technology is used [18]. A conventional six-switch 2-level inverter with 650 V switches cannot be used for high voltage DC-link. As a result, either the semiconductors or the inverter topology must change. High-voltage semiconductors lead to an increase in the cost and switching losses of the components. Therefore, a possible solution is to use multilevel inverter topologies in electrified transportation.

Multilevel inverters are gaining attention in many medium to high-power, high-voltage applications due to their exceptional characteristics. Reduced voltage stress and loss of each individual semiconductor device, better power quality, and lower electromagnetic interference are among the foremost advantages of multilevel inverters. However, voltage balancing, increased number of semiconductors and capacitors, and more complex control are the most important challenges in multilevel inverters [19]. Classic and advanced multilevel inverter topologies make a wide variety in the selection of the best structure. The best choice depends on the application, load, and requirements. A detailed discussion of the topologies is presented in Section IV, and the pros and cons of them in traction applications are also investigated.

Although employing multilevel inverters in traction drives has been the topic of several studies, they have not been used widely in low-power transportation electrification yet. While these structures are being used in high-power electric trains and ships [17], [20], [21], lower-power vehicles like electric buses and passenger EVs are equipped with the conventional 2-level inverter due to their lower DC-link voltage and simplicity in design and implementation [22]. While 800 V multilevel inverters seem to have more semiconductor devices at first glance, it should be noted that 400 V two-level inverters usually have more parallel switches because of high current. As an example, Tesla Model S and Model 3 use six IGBTs and four SiC MOSFETs, respectively, in parallel per each of the switches to be able to handle the high current [22]. A comprehensive comparison will be presented in Section V.

The goal of this paper is to investigate the use of multilevel inverters in traction drives and compare the available topologies, both classic and advanced ones, in terms of efficiency, power density, power quality, cost, and reliability. This paper has the following structure; A brief review of the current status of available traction inverters on the market is presented in Section II. A comprehensive review of the benefits and challenges of moving toward higher DC voltages is given in Section III. In Section IV, classic and advanced multilevel topologies are compared with the focus on traction application. Section V compares efficiency, power density, power quality, performance, cost, reliability, and fault tolerance between the conventional 2-level inverters and multilevel inverters. Finally, future trends in the structure of traction inverters will be investigated in Section VI.

II. TRACTION INVERTERS ON THE MARKET

Although numerous studies have investigated multilevel structures in different traction applications, the market hasn't relied on these topologies yet, especially in low-power applications. Table 2 shows the maximum DC voltage and the conventional structures in different traction applications. Due to the higher power and input voltage in electrified trains, tramways, and ships, multilevel solutions are suggested in these applications. ABB provides Deutsche Bahn, Swedish State Railways, and Swiss Federal Railways with 3-level IGBT-based traction converters which resulted in lower stress on the motors, and high energy efficiency [20], [21]. Also, multilevel inverters are implemented by ABB, Siemens, and General Electric for electric ship applications [17].

Two-level voltage source inverters are used as the inverter structure for electric buses. Using SiC devices in MEDCOM inverters for electric buses has led to a 40% reduction in size and 30% loss reduction [23]. In the case of electric buses and heavy traction equipment, multiphase inverters are also an interesting option. For these applications, TM4 has developed multiphase inverters and permanent magnet motors [22].

Currently, all passenger EVs with 400 V batteries utilize two-level inverters. A detailed investigation of the inverter structures in some of the well-known EVs is presented in [22]. It is shown that, due to the low voltage and high currents, Nissan and Tesla are using three and six switches in parallel, respectively, in their two-level voltage source inverters (VSI). With the recent trend in increasing battery voltages in traction applications, new alternatives have become available. For low-power passenger EVs, TM4, Eaton, and Delphi have developed traction inverters for 800 V input voltage [24]–[26].

Regarding the switching devices, silicon IGBTs are the most common choice in low-power traction inverters due to well-established technology, availability in required power levels, and low price [22]. TM4 and Delphi have announced that they are using SiC switches in their designs. TM4 has reported 195 kW/L inverter power density, which surpasses other traction inverters on the market. Other than power density, the quality of output voltage and current has improved due to the significantly increased switching frequency with SiC devices [24], [26]. However, faster switching results in higher *dv/dt* which may cause damage to the traction motor.

III. HIGHER DC-LINK VOLTAGE: BENEFITS AND CHALLENGES

According to Table 1, several EV manufacturers have used 800 V DC-link for their latest passenger products. Lighter cables, lower weight and loss, lower manufacturing cost, higher power density, faster charging, and more efficient motors have been reported as the benefits of higher DC-link voltage. This section deals with the motivations and challenges of moving toward a higher voltage system inside electrified passenger and large vehicles.

A. CABLES

Copper is one of the key materials in the electric transportation industry since it is required inside vehicles, in charging stations, and in infrastructure. Inside an electric vehicle, bus, or train, copper is mostly used in the cables, in the electric motor(s), and in the battery. A typical passenger EV utilizes about 80 kg copper, which is equal to approximately 4% of the total weight of a typical EV. For a typical battery-powered electric bus, the copper weight is about 370 kg [27].

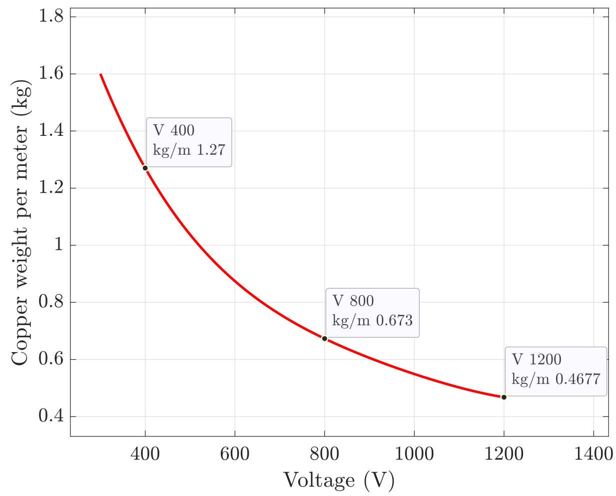


FIGURE 1. Copper weight per meter versus voltage in a 150 kW system.

An important factor in copper weight inside an EV is DC-link voltage. Porsche says that it has reduced 30 kg from electrical harness due to doubling the battery voltage [28]. According to Fig. 1, utilizing 1.2 kV instead of 400 V in a 150 kW system, can reduce the weight per meter of copper by 63% due to the current reduction from 375 A to 125 A. Moreover, due to reduction of the wiring harness cross-section by more than three times, higher voltage cables usually show more flexibility for routing which facilitates packaging and manufacturing [29], [30].

Another concern is the weight of the cables which connect the charger to the EV. According to Occupational Safety and Health Administration (OSHA), the weight of the cable should be limited to a maximum of 22.7 kg for a single person to handle. With the conventional 400 V system, or even with an 800 V system, the cable's weight for an XFC exceeds the safety limit for 350 kW chargers. Utilizing 1 kV DC-bus voltage ensures that the charging cable's weight remains within the standards [31].

B. MOTORS

There is an emphasis on the power to volume ratio of the electric motors in EVs. 50 kW/L is set by the US Department of Energy (DoE) as the electric motor power density target for 2025 [32]. By increasing the motor's rated voltage, its power density can be improved since higher-voltage motors are smaller, faster, and more efficient [33].

C. FAST CHARGING

Off-board chargers, without the space and weight limitations of their onboard counterparts, have enabled fast charging of EVs. With the ongoing trend in increasing range and decreasing charging time of EVs, XFCs were introduced to enable even higher-power charging of EVs. The goal of XFCs is to recharge the EV battery from 0% to 80% in a comparable

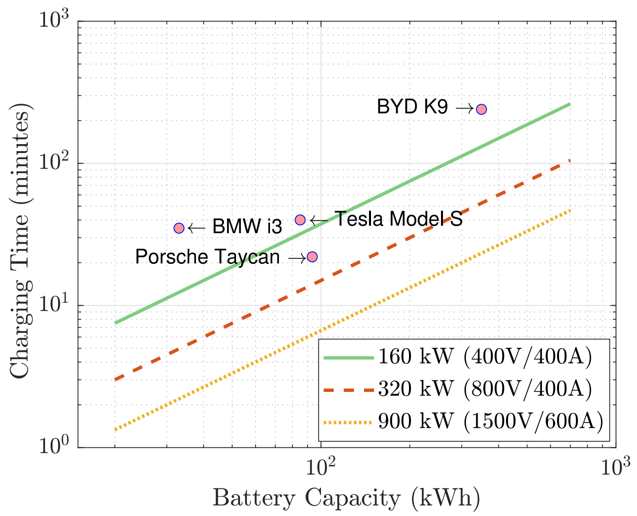


FIGURE 2. Charging times versus battery capacity with different charging powers.

time to the refueling time of ICEVs. The main characteristics of XFCs are 800-1000 V output voltage range and charging power of 350 kW or more. Higher-power charging mostly benefits long-distance travels and public transportation [4], [10].

The standards of DC chargers have been revised in order to enable fast chargers. CHAdeMO and CCS standards have introduced new voltage/power classes for EV chargers. While CHAdeMO has defined 1 kV, 400 kW charging level, CCS has a maximum 920 V, 350 kW level [10]. As the latest update, CHAdeMO in collaboration with China Electricity Council (CEC) have announced the codevelopment of a 900 kw charging standard. The new protocol will increase the maximum allowed output DC voltage to 1500 V, and output current to 600A [34]. This can be considered as a solution not only for passenger EVs, but also for other types of electrified transportation, like electric buses, trucks, and aircrafts.

While the typical charging time of an EV using a 50 kW charger is about 80 minutes, the shift to higher voltages can reduce it to about 15 minutes [35]. Fig. 2 depicts charging time in some commercial passenger EVs and buses, and compares them with feasible charging times using high voltage XFCs. According to Fig. 2, an electric bus with a charging time of 4 hours using an 80 kW charger, can be charged in 25 minutes using a 900 kW charger, or in 70 minutes using a 320 kW charger. The charging time of Tesla Model S will also reduce to half using an 800 V charger. This can be considered as a huge step toward equal recharging/refueling time in EVs and ICEVs. However, it should be noted that other than charger system, battery technology and cooling systems need to progress as well in order to enable high-power charging levels.

D. BATTERIES

Utilizing higher voltage batteries doesn't affect the total number of cells in a battery pack. However, the configuration of series and parallel cells changes [29]. Therefore, there are some challenges that need to be addressed. High current in a battery pack can impact pack hardware, busbars, fuses, disconnect switches, and tabs which results in increasing battery pack cost and weight [36]. On the other hand, there are some issues to be addressed regarding the battery thermal management and cooling systems for enabling XFC [37]. Consequently, additional cost and complexity would be predictable for the future battery management and cooling systems.

Battery safety includes multiple aspects that needs to be considered in the production of EV. Electrical safety considerations to prevent high-voltage exposure and shock, mechanical safety considerations to prevent liquid and gas leakage from a damaged cell, thermal safety considerations, and functional safety consideration. As the number of series cells increases, electrical and functional safety considerations become stricter [38], [39]. 800 V batteries require an accurate cell monitoring and balancing. Battery management system (BMS) is in charge of monitoring the cells and ensuring that they are not overcharged or undercharged. It also makes sure that the cells have an almost equal state of charge (SOC) [40]. Although passive and active balancing techniques have been used widely in the industry, active topologies offer more efficient and flexible systems in EVs.

Centralized, distributed, and modular categories classify the BMSs based on the number of cells that each controller handles. With more than 100 series li-ion cells inside the vehicles with 800 V system, the sophistication of cell diagnostics reporting has increased. Distributed battery pack system allows for higher cell count packs with separate battery monitors. Typically, each of the battery management ICs is able to monitor maximum 16 cells in series. One concern regarding these multiple monitoring modules in high-voltage batteries is the connection and communication among each of them. Wired and wireless communications are the two options available for EV battery designers. Wireless communication has the advantages of lower weight and complexity, smaller footprint, less isolation components, and easier maintenance. Since the cost and size are two of the most important criteria in EVs, there has been a trend to move towards wireless link within the battery. On the other hand, the wired communication is more secure and noise-tolerant and can be used easier in harsh automotive environments. [41], [42]. Moreover, the potential errors as well as error detection approaches is different in wired and wireless communications. In [42] a comparison of these errors is presented.

Fault tolerance is another essential requirement of the BMS system like many other components inside the EV. If fault-tolerance is not ensured, an open circuit between the cell and the BMS PCB or disconnection of the communication path between the ICs can result in the malfunction of EV or hazardous events. Therefore, redundant communication protocols in BMS circuitry are essential to ensure safety and health of the battery, especially in higher-voltage EVs with higher number of series cells [38].

In order to estimate the state of charge and state of health of the battery, machine learning approach has become popular recently. A review of the most recent studies in this regard is presented in [43]. Different methods like Feedforward neural network, Radial basis function neural network, Extreme learning machine, Support vector machine, Recurrent neural network, Hamming neural networks, and Bayesian network are presented and compared in the mentioned study. An essential requirement is the collection and preparation of the data to train the algorithm with the realistic situation that happens in traction applications.

E. DV/DT ISSUE

High-frequency transitions inside an inverter are unavoidable in order to control the traction motor. However, due to these fast transitions and the existence of parasitic inductances and capacitances, considerable EMI issues emerge in both conducted and transmitted emissions. Due to the typical size and frequency of the inverter, the noise is mainly emitted through the lines and cables. At the inverter output, voltage spikes may reduce the motor lifetime by da maging the windings, insulation, bearing balls, or rollers. High *dv/dt* also increases the eddy current and skin effect losses in the cores and the windings, respectively. [44]–[46]. These issues are even more serious in the modern inverters which use new IGBTs and MOSFETs with faster transitions. IEC and NEMA have suggested a maximum *dv/dt* of 500 $V/\mu s$ in typical motor drive applications [46].

An increase in battery voltage leads to the increase of *dv/dt* value. As wide bandgap (WBG) devices are gaining more attention in power electronics, the aforementioned issues can be aggravated due to faster transitions. While *dv/dt* filters can be used to reduce the destroying effects of fast transitions on the motor side, these transitions also affects other electrical devices and circuits, like the gate drivers [47].

F. OTHER

As mentioned in Section I, higher voltage levels inside a traction drive affects the efficiency of power electronic converters, such as the inverter, due to changing conduction and switching losses. Higher voltage and lower current reduce conduction losses. On the other hand, switching losses increase as a result of increasing the DC input voltage [18]. Moving to higher voltages also affects selection of the sensors, especially current and voltage sensors. Higher galvanic isolation is needed which may increase cost of the sensors.

Fig. 3 summarizes the comparison of a 400 V EV drive versus its 800 V counterpart. Although high DC-link voltage offers several attractive advantages, higher EMI, higher switching losses, and more complex BMS are several non-negligible drawbacks. Multilevel inverters can compensate the two first drawbacks by utilizing low-voltage switches and reducing *dv/dt* transitions. Consequently, the next sections of this paper deal with a review and comparison of multilevel topologies in traction applications, their advantages, disadvantages, and the future trends.

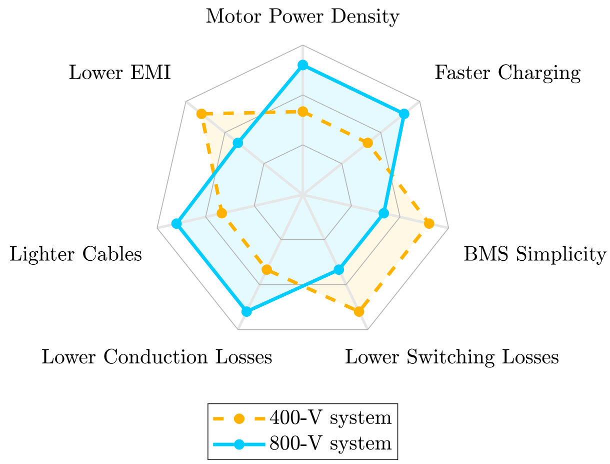


FIGURE 3. Advantages and drawbacks of increasing DC-link voltage in electric vehicles.

IV. MULTILEVEL INVERTERS TOPOLOGIES IN TRACTION DRIVES

In the past decades, many conventional two-level voltage source inverters are replaced by their multilevel counterparts, mostly in medium to high-voltage applications in order to gain lower current and voltage THD, lower EMI and common-mode voltage, higher efficiency, and lower voltage stress on devices [48], [49]. Moreover, some multilevel topologies benefit from modularity and fault-tolerance [49], which makes them even more interesting in particular applications. On the other hand, the capacitor voltage balancing, suppressing circulating currents, and reduced reliability due to higher number of devices and capacitors are the challenges that need to be addressed when approaching multilevel inverters [50]–[52].

A. CURRENT STATUS OF MULTILEVEL INVERTERS IN DIFFERENT APPLICATIONS

1) ELECTRICAL RAILWAY AND ELECTRIC LOCOMOTIVES

Utilization of multilevel inverters in traction drives was first proposed in 1988, where a three-level GTO-based neutral point clamped (NPC) was proposed as an efficient substitute for two-level inverters of locomotives' induction motors [53]. This topology has been implemented in a back-to-back structure and tested successfully by Siemens AG for the TRANSRAPID propulsion system in Emsland [54].

In 2016, a six-level NPC inverter, using selective harmonic elimination (SHE) technique was designed and implemented as a traction inverter for the railway with an input DC voltage of 1500 V. It is shown that the efficiency of the implemented inverter has increased by at least 5% comparing to the conventional inverters [55]. Another application of multilevel converters in railway traction drives is proposed by [56], where modular multilevel converters (MMC) are used to store the regenerative energy of the train in low-voltage supercapacitor cells which resulted in a more efficient energy storage system comparing to two-level designs. In [57], an MMC-based railway power supply system is proposed. Improved power quality, increased modularity, and scalability make this configuration superior comparing to the conventional traction supply system.

2) ELECTRIC SHIPS

Multilevel inverters have been suggested as an option in ships, where high power quality, high power density, and fault tolerance are mandatory [49]. Load commutated inverters and cycloconverters, which are the dominant solutions in ship propulsion system due to high efficiency and low size, suffer from poor input current quality which will disturb the on-board ship power system [60]. Due to these power quality issues, medium-voltage DC power system has become more attractive for ship application [49]. Medium-voltage DC-link inside the ship enables the utilization of multilevel inverters for the propulsion. In comparison to other solutions in ships, multilevel inverters offer higher power quality, lower insulation stress, and lower over-voltage on motor terminals [61].

3) ELECTRIC VEHICLES

In low-power, low-voltage electrified transportation, such as passenger EVs, multilevel inverters have been the topic of several studies as well. In [63], MMC inverter is recommended for EV in order to eliminate the need for BMS. One battery cell is connected to each module of the inverter. Consequently, the voltage balancing of cells is ensured without using a BMS. However, in practice, either large number of modules or a step-up transformer is required in order for this topology to be used in commercial EVs.

In [64] a dual PMSM motor is driven using a dual T-type NPC (TNPC) converter which resulted in over 90% current reduction in DC-link capacitors. In [65], a method is presented to allow low frequency output currents in an MMC inverter, with low capacitor voltage ripple. This is suitable for variable frequency drive applications like traction application. A 23-level asymmetrical CHB (ACHB) using only one DC source is presented in [66], where a high-frequency transformer is used in order to provide isolated voltage sources.

In an effort to reduce the number of components in multilevel inverters, a new topology, called nested neutral point clamped (NNPC), was proposed in [67]. Fewer diodes and floating capacitors compared to NPC and FC topologies respectively, makes it an interesting option regarding the size and cost of the inverter. Three-level T-type inverter is also introduced which benefits from fewer components and low losses. However, this topology requires high-voltage switches [68].

A multi-source inverter topology based on three-level NPC and T-type inverters is proposed in [69] for hybrid and plug-in hybrid EVs. Unlike conventional multilevel structures, the two input voltage sources of the proposed multi-source inverter are independent. This configuration has resulted in a higher-efficient powertrain and a smaller DC/DC boost converter. In [70], an NPC inverter with multi-battery input is proposed which is capable of balancing the state of charge (SOC) of the battery packs by controlling the flow of energy from the batteries to the load. Different topologies of multilevel inverters for multiphase drives (MPD) have also been investigated in the literature [71].

In spite of the studies that have been conducted in this area, all commercial EV drives are based on conventional two-level inverters [22]. However, due to the discussion in Section III, there is a trend toward higher DC-link voltage in EVs which makes multilevel inverters more attractive for use in commercial products.

4) OTHER APPLICATIONS

In 1998, cascaded H-bridge (CHB) multilevel inverter was suggested as a suitable choice for military combat vehicles and heavy-duty trucks, since they facilitate using higher voltage motors with low-voltage switching devices [62]. In electric aircraft application, a high efficiency 9-level interleaved flying capacitor (FC) multilevel inverter utilizing GaN switches is proposed in [58]. The use of multilevel structures at aircrafts with high DC bus voltage can reduce partial discharge occurance [59].

B. ESSENTIAL REQUIREMENTS AND CRITICAL ISSUES IN TRACTION INVERTERS

As mentioned before, there are various multilevel topologies with different characteristics that make them suitable for different applications. The selection of the best topology of multilevel converters depends on the application and its specific requirements. Traction drive application, likewise any other application, has its own specific requirements. The following subsections deal with a review of the most important requirements of traction drives which affect the selection of the best topology.

1) COST AND SIZE

Since cost and size are the two important challenges for EVs, in 2017, the US DoE has updated its requirements of EV electrical components. For the inverter and the boost converter if applicable, the 2025 targets for cost and size are 2.7$/kW and 100 kW/L respectively, which show 18% and 87% change compared to the 2020 targets [32]. Consequently, the cost and size of different topologies have to be considered prior to selection.

The capacitors are the most voluminous and heaviest parts in the inverter. Moreover, low-frequency operation of traction drives increases voltage ripple in floating capacitors of the multilevel structure, necessitating higher capacities [22]. As a result, the topologies with more floating capacitors are more voluminous than others. From the cost point of view, since diodes and switches are usually more expensive than capacitors, topologies with a large number of semiconductors are more expensive, especially in large number of levels.

2) IMPACTS ON THE BATTERIES

An essential concern that needs to be considered in BEVs, is the impact of the inverter topology and control scheme on the batteries. The input current of the inverter is usually drawn from the battery pack. The current waveform and its harmonic contents can affect the reliability, loss, and lifetime of the batteries. Generally, the input current of multilevel inverters can have lower current distortion compared to two-level structures [72]. However, the amount of RMS current reduction depends on both the structure and the modulation technique. As an example, fundamental selective harmonic elimination (SHE), reduces the input RMS current [73] at the cost of larger capacitors to ensure voltage balancing among the levels. A comparative review of the well-known and advanced modulation and control techniques for multilevel traction inverters is presented in [74].

Some studies in the literature have investigated the impacts of multilevel structures on battery. Since higher RMS currents increase the battery loss and decrease its lifetime, EV inverters need additional measures in order to reduce the RMS current that is drawn from the batteries. This issue happens in both two-level and multilevel inverters. Presence of medium frequency currents in multilevel inverters necessitates the use of energy storage components with higher capacity than film capacitors. Electrolytic capacitors and supercapacitors can effectively reduce the battery RMS losses in this case [73]. In [75], supercapacitor modules are connected to cells of a MMC inverter and have resulted in the reduction of battery RMS currents. In another study, ultracapacitors are integrated in the NPC multilevel conditioning inverter of the motor drive for large vehicles [76]. Due to the elimination of the DC/DC converter, a special modulation technique is required in order to ensure proper operation of the drive at different ultracapacitor states of charges.

In [73], the impact of placing supercapacitor and electrolytic capacitors in parallel with battery modules in CHB multilevel inverter is simulated and verified. It is shown that the battery ohmic loss in different drive cycles can reduce by up to 40%. It is also mentioned that the added energy storage components increase the weight and cost of the powertrain. However, a more comprehensive study is also required to consider the economic benefits of the extension of battery lifetime due to lower losses.

To compare different topologies from their influences on batteries perspective, the input side of each structure must be considered. In those topologies that require isolated supplies, the structure of battery has to be changed. Multiple isolated battery modules are required instead of a single battery pack. Therefore, the BMS and its communication also need to conform to new requirements. In other topologies, the battery structure can remain unchanged.

3) ISSUES RELATED TO FLOATING CAPACITORS

Other than cost and weight, an increased number of floating capacitors is also discouraging since they increase the complexity of the control system. The voltage balancing of these capacitors requires plenty of isolated voltage sensors and complex control [77]. Additionally, floating capacitors need to be charged prior to inverter operation in order to ensure equal voltage sharing on devices. Low reliability of the capacitors will also reduce the total reliability of the inverter.

4) ISOLATED DC SOURCES

Isolated DC sources are available in BEVs from the battery packs. Consequently, CHB multilevel inverter is also a choice for BEVs. However, additional measures are required to ensure the equal share of battery packs in feeding the motor. On the other hand, modularity and scalability, which are demanded in many industrial applications as well as traction drives [49], can be obtained using CHB or MMC inverters. In large automotive electric drives, CHB inverters can be a suitable choice because of the large number of battery cells [78].

Voltage balancing of the isolated battery modules is a critical issue that needs to be considered when CHB inverter is used. This issue happens in both charging and discharging modes. Since the battery modules are isolated from each other, conventional BMSs cannot ensure voltage balancing and equal current in the separate battery modules. Therefore, there is an essential need to a secure and reliable BMS, designed for this specific structure. This will increase the complexity and cost of the BMS.

5) FAULT-TOLERANCE AND RELIABILITY

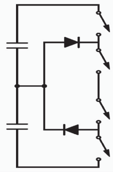
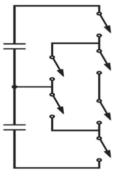
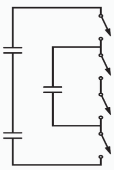
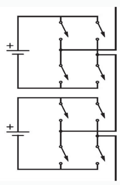
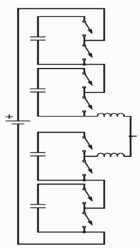
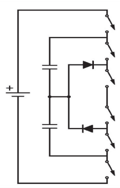
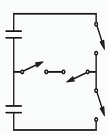
Another comparison criterion is fault-tolerance capability and reliability in different topologies. Since various failures may occur inside the propulsion system of an electrified vehicle, continuity of operation is of great importance [79]. Therefore, fault-tolerance is identified as one of the requirements of the propulsion system of EVs including motor drive in ISO 26 262, mainly in limp-home mode [49].

Considering the increased number of capacitors and semiconductor devices in multilevel converters, the reliability of multilevel inverters seems to be low. However, intrinsic fault tolerance in some multilevel topologies increases the reliability of these inverters [51]. A comparison of reliability has been conducted in [80] between FC, NPC, and CHB structures. The large number of capacitors has resulted in the highest failure rate for FC structure, while CHB has the highest reliability between the three.

6) CHARGING/DISCHARGING SPEED

Multilevel topologies help to have the inverter/charger operate at higher voltage and current levels which helps to use higher power inverters/chargers. This is due to the fact that the voltage stress on the switches decrease as the number of levels goes higher. However, this is not applicable to the T-type inverter in which the voltage stress on the switches is same as the DC input voltage.

TABLE 3. A Comparison of Well-Known Multilevel Inverter Topologies for Traction Application

Topology	Leg Schematic	Advantages	Disadvantages
Neutral Point Clamped (NPC)		• No floating capacitors • Good dynamic response • Simple design • Low cost and compact in 3-level structure	• Increased cost and reduced reliability as number of levels increase due to drammatical increase in number of diodes • Unequal loss in switches
Active Neutral Point Clamped (ANPC)		• No floating capacitors in 3-level structure • Good dynamic response • Simple design • Equal loss in switches • Low cost and compact in 3-level structure	• Increased number of floating capacitors as levels increase • More complex control than NPC • Different voltage rating of power switches at higher levels
Flying Capacitor (FC)		• Cost efficient in higher level structures	• High number of floating capacitors • Complex control • High stored energy in capacitors • High voltage ripples at low frequencies • Voluminous and heavy • Requires plenty of voltage sensors • Low reliability
Cascaded H-Bridge (CHB)		• High reliability • Modular • No floating capacitors • Simple control	• Isolated DC sources are needed which is not provided in grid-connected traction applications • More power switches
Modular Multilevel Converter (MMC)		• High reliability • Modular • Scalable	• Large number of capacitors • Complex control • Pre-charging circuits for the capacitors • High voltage ripples at low frequencies • Voluminous and heavy • Requires lots of voltage sensors
Nested Neutral Point Clamped (NNPC)		• Fewer capacitors comparing to FC • Fewer diodes comparing to NPC	• All of the issues related to floating capacitors • Unequal voltage sharing on switches at levels higher than 4
T-type Multilevel Inverter		• No floating capacitors • No diodes • Simple control	• Higher voltage stress on switches • Low efficiency at high frequency operation due to high switching losses • Not suitable for high voltage, high power traction drives

7) MODULATION AND CONTROL TECHNIQUES

Selection of proper modulation and control techniques is essential to meet the requirements of electrified transportation. While this paper deals with comparison of topologies, [74] presents a comparative investigation of modulation and control techniques for multilevel traction drives.

Based on the above criteria, a comparison of the most well-known multilevel inverter topologies in traction application can be found in Table 3.

Other than mentioned topologies, new multilevel inverter structures have been developed and proposed in the literature. Although some of the proposed topologies offer the benefit of fewer semiconductors and capacitors, they are not mature enough in terms of control, modulation, voltage balancing techniques, fault-tolerance, and reliability. Consequently, due to the strict requirements of traction inverters, these topologies have not been implemented and tested in the literature for this particular application. Table 4 lists some of the

TABLE 4. New Multilevel Structures; Advantages and Drawbacks [81]

Topology	Advantages	Drawbacks
Switched Capacitor Unit Based Inverter [82]	• Small number of semiconductors in high levels • Modular structure and equal load sharing among sources	• Isolated DC sources are needed • Large number of capacitors
Developed Cascaded Cell Based Inverter [83]	• Switching frequency can be as low as fundumental frequency • High modularity and simplicity	• Isolated DC sources are needed • Unequal power sharing among cells • Unequal voltage rating of switches
Cascaded Power Circuit Cell Based Inverter [84]	• Equal power sharing among switches • High modularity and simplicity • Non-isolated DC sources	• Unequal voltage rating of switches
Cascaded Innovative Cell Based Inverter [85]	• High modularity • Low switching losses	• Unequal power sharing • Requires isolated voltage sources
Hybrid Topology Based Inverter [86]	• Equal power sharing • Suitable for all voltage levels • Switching frequency can be as low as fundamental frequency	• Unequal voltage stress on switches • Complex control • Requires isolated voltage sources
Highly Efficient and Reliable Configuration Based Cascaded Inverter [87]	• High modularity and Simplicity • Equal power sharing • Low conduction and switching losses	• Requires isolated voltage sources
Single Source Switched Capacitor Inverter [88]	• Capacitor voltage self balancing is provided • Reduced number of switches	• High complexity • High switching losses • Larger number of capacitors
Cross Connected Source Based Inverter [89]	• High simplicity • Switching frequency can be as low as fundamental frequency • Suitable for all voltage levels	• Requires asymmetric voltage sources • Requires bidirectional switches • Unequal power sharing
Staircase cascaded Inverter [90]	• High Modularity and Simplicity • Low conduction losses • Suitable for all voltage levels	• Unequal voltage stress on switches • Unequal power sharing • Requires bidirectional switches
Reduced Switch Based CHB Inverter [91]	• High simplicity in high-level structures • High efficiency	• Requires isolated voltage sources • Requires bidirectional switches • Unequal power sharing • Unequal voltage stress on switches
Cascaded Unit Based Inverter [92]	• High Modularity • Switching frequency can be as low as fundamental frequency	• Unequal voltage stress on switches • Unequal power sharing • Requires isolated voltage sources

new topologies with some of their specific advantages and drawbacks.

V. COMPARISON OF MULTILEVEL INVERTERS VS. 2-LEVEL INVERTERS FOR TRACTION DRIVES

Although many papers have investigated different topologies, modulation, and control techniques of multilevel inverters in traction applications, there are not many studies comparing different aspects of multilevel inverters and two-level inverters in this specific application. This section deals with a comparison of these two structures in terms of 7 criteria; Efficiency, cost, power density, power quality, reliability, fault tolerance, and cooling system.

A. EFFICIENCY

The efficiency of a traction inverter not only affects the power consumption and battery discharge rate, but also impact the thermal design of the system. A more efficient inverter topology can be manufactured in a smaller footprint since the heatsink and cooling system size can be reduced. Consequently, an important criterion in the comparison between the two-level and multilevel inverters are efficiency.

A CHB multilevel inverter using low-voltage Si MOSFETs is compared with two-level IGBT and SiC MOSFET based inverters [93]. For a realistic comparison, the inverter structures are used in a verified EV model, with less than 2% error in estimating the energy consumption. Efficiency maps of the three

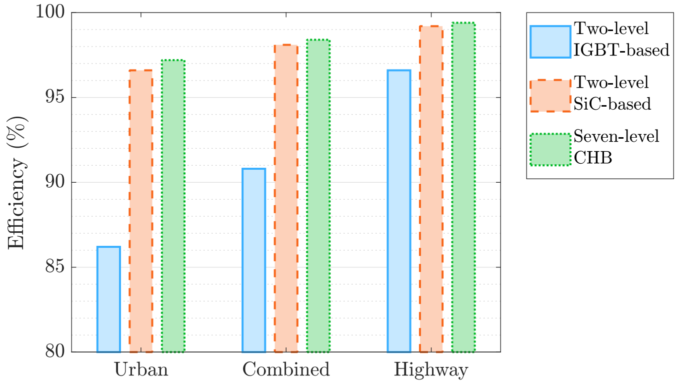


FIGURE 4. Comparison of efficiency between two-level and multilevel structures [93].

options, which have been verified using ANSYS Simplorer, are used to model the inverter inside the EV model. The first difference of the three inverter structures appears in the low-speed range of the motor, where the minimum efficiency of the inverter has increased from 70% in IGBT-based two-level inverter to 92% in the MOSFET-based CHB inverter.

In higher speeds, multilevel inverter's efficiency still higher than two-level IGBT-based inverter by 2%-3%. The EV model has been simulated in different standard driving cycles with different characteristics. In highway driving cycles, MOSFET-based multilevel structure has improved the efficiency by 2%-3%, since the speed is high in most of driving cycle points. On the other hand, for urban driving cycles, the efficiency has been improved by approximately 10% due to the lower speed of the vehicle and motor. It should be noted that the SiC two-level inverter has similar conduction loss with Si multilevel inverter, while the switching loss is slightly more in the former [93]. The results of the mentioned study are shown in Fig. 4. Additionally, due to lower output current THD with multilevel inverters, motor efficiency also benefits from this structure [94], leading to increased system efficiency.

In another research, MMC inverter for EVs is evaluated from the efficiency point of view [95]. In the proposed structure, each of the submodules is connected to a battery cell. Consequently, the SOC of each cell can be controlled separately using proper control and modulation technique, eliminating the need for a BMS. A loss model has been developed for MMC, which is then verified using simulation and experimental results. In a comparison of MMC and two-level inverter, the former has shown 3%-5% efficiency improvement in the constant torque region, at 20 kHz maximum switching frequency.

In all of the aforementioned studies, the switching devices for the multilevel topology are MOSFETs. An important factor in the efficiency increase of low-speed operating points is the physical behavior of MOSFET [96]. However, with the increasing DC-link voltage in traction applications, multilevel IGBT-based inverters using IGBT modules are also an alternative to two-level inverters, especially in heavy-duty applications. By comparing same-technology IGBTs with different rated voltages, it can be resulted that a series connection of two low-voltage IGBTs in a multilevel inverter will have lower power loss than a single high-voltage IGBT in a two-level structure. Although the conduction loss increase in the former structure, the sum of switching losses will decrease in a way that the total efficiency usually increases. Consequently, the higher the switching frequency, the more superior the multilevel inverter is [97].

Although the above results are for EVs, it can be extended to heavy-duty electrified transportation as well. Multilevel MOSFET-based inverters can increase efficiency significantly in urban electric buses or trains since they operate at low speeds for a considerable portion of the time. On the other hand, efficiency increase in intercity transportation is less significant due to the constant, and close to nominal speed.

B. POWER QUALITY

As mentioned before, the value of output voltage THD reduce considerably by using multilevel inverters. The amount of THD reduction depends on the operating point of the traction inverter which determines the modulation and frequency indexes. However, it can be seen that in a typical operating condition, output voltage THD reduces by a factor of 2-3 by using a three-level multilevel inverter [98]. However, the amount of current THD reduction in drive application is less significant due to the fact that the motor acts as a current filter.

Moreover, high *dv/dt* transitions in two-level inverters cause voltage spikes, arcing, leakage currents, and sparks which can cause the bearing balls or rollers to fail. The problem of high *dv/dt* is not limited to damaging the motor. The interference from long power cables inside the vehicle can be coupled to low-voltage circuits in the vehicle. Current trend toward higher-voltage DC-link will intensify this issue. Although using shielded cables can mitigate radiated EMI, it can't decrease the conducted emissions [44]. EMI filters and ferrite ring cores can be used in order to reduce the damaging effects of this high frequency interference in traction inverters [44], [99]. However, it is well-known that passive components increase the cost, volume, and weight of the traction system. Multilevel inverters can decrease *dv/dt* and reduce or eliminate common-mode (CM) voltages on the motor side which results in reduced EMI, increased motor lifetime, and eliminating the need to use different types of filters [100]. For example, a 5-level NPC inverter reduces the maximum *dv/dt* and CM voltage value by four times, considering constant switching speed.

C. COST

Cost reduction, as an important objective of the future electrified transportation, plays an important role in selection of the inverter structure. Utilizing multilevel inverters affect the cost of traction drive. However, based on the side-effects of these converters, changes are not limited to the inverter. In what follows, cost alterations in the inverter and other devices are discussed.

TABLE 5. Multilevel vs Two-Level Inverter Cost Comparison Based on [93]

Costs	Two-level Inverter	7-Level CHB Inverter
Switches	296.6	203.4
Gate Drivers	39	234
Capacitors	30.3	0
Heatsink	17.3	16.2
Controller	150	300
Battery	5760	5310
Contactor	74	180
Overhead Cost	133.3	188.6
Sum	6500.5	6433.3

TABLE 6. Multilevel vs Two-Level Inverter Cost Comparison Based on [97]

Costs	Two-level Inverter	Three-Level NPC Inverter
Switches	204	216
Fast Diodes	0	72
Capacitors	90	90
Heatsink	400	400
Controller	150	300
Gate Drivers	60	120
Filter	842	640
Sensors	80	90
Sum	1726	1678

A cost comparison is made between a two-level IGBT-based traction inverter and a CHB inverter in [93]. Other than the inverter cost, the cost saving in the battery by using the multilevel structure is considered. Since the multilevel inverter has found to be more efficient in the same research, the vehicle is capable of maintaining same driving range with a lower battery capacity. The results of the comparison is shown in Table 5. It can be seen that although the inverter cost is higher in case of CHB structure, overal system cost has been slightly reduced by using multilevel inverter.

Another comparison has been made in [97] between a conventional two-level inverter with a three-level NPC inverter. The switching devices in both inverters are IGBTs. The prices of IGBTs, fast diodes, voltage sensors, heat sink, gate drivers, control system, DC-link capacitors, and filters can be seen in Table 6. This comparison doesn't include battery price, therefore it can be valid for grid-connected electrified transportation. It can be seen that reduced filter cost has resulted in a 3% lower system cost in case of three-level NPC inverter.

D. FAULT-TOLERANCE

While the common solution for fault-tolerant two-level inverters is to add a fourth leg, multilevel inverters usually offer inherent fault-tolerance due to higher number of semiconductor devices and redundant switching states for voltage space vectors [101].

In multilevel inverters, the faulty cell or switch can be bypassed using a bidirectional switch in order for the operation to continue with a reconfigured modulation without adding any auxiliary cell or switch to the inverter. A fault diagnosis technique, capable of detecting and locating the short-circuit and open-circuit faults is proposed for CHB inverter in [102]. The proposed method can detect the fault in six cycles using the output phase voltage data. Special modulation schemes for fault-tolerant FC [103], NPC [104]–[106], and MMC [107] topologies are also investigated in the literature.

Although multilevel inverters offer intrinsic fault-tolerance, the voltage and current ratings of the devices should be selected in a way that the healthy cells or devices can tolerate the DC voltage after bypassing the faulty cell or device, at least with a derated operation.

E. RELIABILITY

At first glance, it seems that a larger number of power devices, drivers, and capacitors in multilevel structures compared to two-level inverters leads to a large difference between the reliability of the two options. However, the intrinsic fault-tolerant capability of most of the multilevel inverters reduces the gap. This issue has been investigated in [51] for two, three, and five-level inverters. It is resulted that by including one fault-tolerant capability, the gap between $R(t)$ function of three structures remains below 0.2 for 0-25000 hours of operation. Moreover, by including multiple fault-tolerant capability, the reliability of multilevel topologies surpasses two-level inverter. Moreover, since cabling, control electronics, and fan failures have a higher failure rate than semiconductors, the higher efficiency of multilevel inverters increase reliability by reducing the temperature inside the system [97].

F. COOLING SYSTEM

Increased efficiency of multilevel inverters offers a simpler and lighter cooling system. Additionally, due to the power loss division among multiple switching devices, the cooling system benefits from a more uniform loss distribution comparing to the conventional inverters. Two-level inverters can achieve this advantage through using parallel switches to divide the power loss.

G. POWER DENSITY

The power density of the multilevel inverter structure depends on the selected topology. As mentioned in Section IV, topologies with floating capacitors have lower power density comparing to the other multilevel inverters. However, other topologies show an increased inverter power density due to the smaller cooling system.

In addition to the inverter, the power density of the drive system benefits even more. With the decrease of output voltage THD and EMI, the volume and the weight of the filters reduce. Smaller required battery capacity also contributes to the power density increase of the system.

A comparison of all the aforementioned criteria between two-level and three-level traction inverters is shown in Fig. 5.

VI. FUTURE TRENDS OF MULTILEVEL INVERTERS IN TRACTION DRIVES

While many papers have investigated the use of multilevel inverters for traction applications, utilizing these inverters have not been expanded to all types of electric transportation.

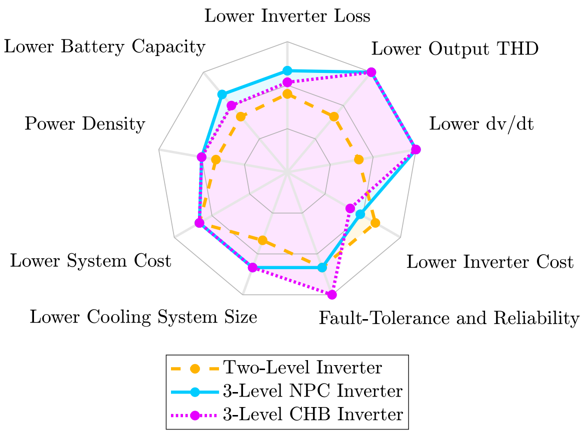


FIGURE 5. Comparison of different criteria in conventional two-level, three-level NPC, and three-level CHB inverters.

Low-voltage EVs, buses, and trucks are using two-level structures in their drive system. However, based on the previous sections, multilevel inverters are being more attractive due to their special specifications. This section investigates the future trends in this area.

A. DC-LINK VOLTAGE AND BATTERIES

Fig. 3 depicted a comparison of different issues in 400 V and 800 V EVs. Considering all the aforementioned benefits and challenges, moving toward higher DC-link voltages seems inevitable, especially for enabling fast charging and higher power density. For passenger EVs, 800-1000 V voltage level results in a charging time comparable to the refueling time of ICEVs. Consequently, it seems that this voltage level will be established in future passenger EVs in order to satisfy the costumers' demand for fast charging. The situation is different for heavy-duty vehicles like electric buses. Typical recharging time for those vehicles is more than several hours due to high battery capacity. Even XFCs will not decrease the charging time to refueling time. Accordingly, DC-link voltages up to 1500 V in heavy-duty applications are not far-fetched. Also, in future all-electric aircrafts, 3 kV maximum DC voltage system seems to be utilized due to the high required power for the electric motors.

Higher-voltage DC-link may be obtained in two ways; Increasing battery voltage or increasing the voltage ratio of the boost converter, if applicable. While increasing battery voltage seems to be simply adding more cells in series, it increases the complexity and requires more efficient and reliable balancing circuits. Technology developments for BMS seem likely. Issues like higher required isolation, more voltage levels, more complex balancing circuits, and noise immunity need to be addressed to have a reliable battery pack.

Regarding battery production, the shortage in lithium and cobalt might cause changes in production materials. The shortage in cobalt seems to be more concerning. Therefore, alternatives like lithium phosphate are being developed for future use in this industry [108]. While plenty of other battery technologies exist today, utilizing them in EV industry requires large investments on each technology [109]. In terms of battery power density, the continuous increase in the past decade is expected to continue in future years, enabling light and heavy duty battery based vehicles with longer maximum range.

B. INVERTER TOPOLOGY

Large number of required DC sources is a discouraging factor for CHB inverter, especially in applications with more than one motors. However, heavy-duty electric transportation, like electric trucks and buses which utilize high capacity batteries with a larger number of parallel battery cells, provide more isolated DC voltages. Consequently, CHB inverters can be more useful in these cases. New topologies which are being proposed for this application should fulfill the mentioned criteria in order to be a good fit for this application.

A possible research topic in this regard is determining the optimum number of levels of the multilevel topology. Different numbers of levels, from 3 to 23, are proposed for this application in the literature. However, a comprehensive comparison in terms of efficiency, cost, power density, and reliability is required in order to make a fair decision on the required number of levels.

C. WBG DEVICES

WBG devices offer several advantages in traction inverters. High-temperature operation and fast switching transitions facilitate achieving the power density goal for traction inverters by 2025. Tesla Model 3 benefits from high-frequency SiC MOSFETs manufactured by STMicroelectronics. Moreover, Toyota and Mitsubishi Electric have SiC-based two-level inverters under development with increased efficiency and power density [110], [111]. GaN devices are also encouraging due to the zero reverse recovery losses which results in even higher efficiency compared to SiC-based inverters [112]. However, higher *dv/dt* caused by fast transitions increases the EMI inside the drive system. Moreover, the price of WBG devices is still a discouraging factor. An investigation of the multilevel inverters using WBG devices can be a topic for future research.

The higher possible operating frequency of WBG-based inverters results in a reduction in the size of floating capacitors in FC and MMC structures which can reduce the drawbacks of floating capacitors considerably. As a result, utilizing the state of the art switching devices can affect the selection of best topology and modulation scheme for multilevel inverters.

D. MULTILEVEL POWER MODULES

Although Tesla Model S and Model 3 use discrete semiconductor switches, utilizing power modules which contain several power semiconductors in a single package is common in two-level EV inverters. These power modules provide higher power density, higher reliability, and more simplicity compared to discrete switches. However, there are not many power module options when it comes to low-power multilevel structures. Therefore, the designer's options are limited to discrete switches, especially when WBG MOSFETs are going to be used. In order to achieve higher power density and lower system footprint with multilevel structures, multilevel power modules seem essential in future.

E. CONTROL AND MODULATION TECHNIQUES

In addition to the selection of the best available topology, control and modulation techniques need to be selected and improved according to the traction drives requirements. Ensuring equal capacitor voltage sharing requires plenty of voltage sensors and communication lines, especially in high-level multilevel inverters. Large number of sensors decreases the reliability and increase the cost of the drive system. Consequently, development of sensorless techniques seems to be a possible trend in this regards. Another issue that complicates the controller stage is the large number of voltage vectors in multilevel inverters. Due to the need to share the power loss between semiconductors equally, selection among the redundant voltage vectors and transition between them is of great importance.

Model-predictive control (MPC) technique shows perfect match with the multilevel traction inverters requirements. Reference tracking, voltage balancing, power loss sharing, and overcurrent protection can all be included in a single cost function with proper weighting factors. However, large computation time, especially in high-level inverters, need to be overcome by either simplification techniques or utilizing higher-speed processors.

F. COOLING DESIGN AND PCKAGING

Higher efficiency of multilevel inverters reduces heat dissipation inside the powertrain. Moreover, the total amount of power loss is distributed in more number of devices as the number of levels goes higher. This allows the designer to choose smaller heatsink and simpler cooling methods to reduce the size of the inverter. However, an increased number of devices and capacitors, and larger required clearances in the PCBs are acting in the opposite way. These issues need to be addressed since inverter size reduction is crucial in order to meet the DoE requirements.

Additionally, thinner cables in high-voltage inverters show more flexibility which makes the manufacturing process much easier. the electrical connections will also be smaller and more reliable due to reduced currents.

G. MULTILEVEL ON-BOARD CHARGERS AND INTEGRATION

While the focus of this paper was mainly on the traction inverter, multilevel structues can also be beneficial for the on-board charger since low-voltage switches can be used in this stage. The integration of the multilevel inverter with the on-board charger system is another research topic that can eliminate the need to use a separate charger. This will help reducing the total price and weight of the vehicle.

Moreover, modular structures, like CHB and MMC, enable direct connection of battery cells to each bridge. In the extreme case, if each cell is connected to one bridge, the inverter can act as a battery management system which can eliminate the need to a separate BMS system. In the case of multi-motor traction systems, the integration of several inverters into a single package can also be a research topic. Different multilevel inverters sharing a single DC-link can reduce the size of DC-link capacitors using coordinated modulation schemes.

Another possible research area in this regards is the integration of the motor with the inverter. While integrated motor/inverters exist in case of two-level structures, multilevel inverter topologies can facilitate the integration since their output has higher waveform quality and can be connected to the motor terminals directly.

VII. CONCLUSION

Improving the specifications of inverters plays a key role in achieving the goals which are set for the power density and cost of traction drives by the US DoE. Higher-voltage DC-link inside a traction drive system offers several advantages. Lighter cables, more efficient motors, and faster charging are the main motivations of moving toward higher-voltage battery modules. However, an increase in electromagnetic interference and higher voltage stress on power semiconductors are two main drawbacks of increasing DC-link voltage. Multilevel inverter topologies, offering reduced voltage stress on the switches and reduced EMI in the system, can be a substitute for two-level inverters.

Multilevel inverters operate at higher efficiency, especially when the motor is operating at low speeds, like urban cycles for EVs. In a comparison of cost, multilevel inverters are usually more expensive than their two-level counterparts. However, considering the savings in the cost of battery, filters, and heatsink results in an almost equal price for the two structures. Lower *dv/dt* reduces the EMI in the drive system. In terms of reliability, although the high number of components in multilevel inverters lowers the reliability, the intrinsic fault-tolerance of multilevel structures compensate the lower reliability.

A comparison of different multilevel topologies was conducted in this paper. Requirements of traction application establish the criteria for selection between the various options. Topologies with a large number of floating capacitors, like FC and MMC, are discouraging since capacitors are bulky, unreliable, and add complexity to the control circuit. On the other hand, NPC topology is not cost-efficient if the number of levels goes higher than 3. CHB topology can be used in battery electric vehicles, trucks, and buses since isolated DC sources are provided from the batteries.

Finally, future trends were investigated in the last section. Higher DC-link voltage, higher-voltage battery modules and battery management systems, utilizing WBG devices and multilevel power modules, control and modulation techniques, packaging and cooling system design, and system integration are the topics that require further studies with the advent of multilevel inverters in electrified transportation, especially electric vehicles.

REFERENCES

[1] "Sources of greenhouse gas emissions." 2019. [Online]. Available: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

[2] A. Adib *et al.*, "E-mobility - advancements and challenges," *IEEE Access*, vol. 7, pp. 165226–165 240, 2019.

[3] A. Tomaszewska *et al.*, "Lithium-ion battery fast charging: A review," *eTransp.*, vol. 1, 2019, Art. no. 100011.

[4] A. Meintz *et al.*, "Enabling fast charging-vehicle considerations," *J. Power Sour.*, vol. 367, pp. 216–227, 2017.

[5] D. Ronanki, A. Kelkar, and S. S. Williamson, "Extreme fast charging technology-prospects to enhance sustainable electric transportation," *Energies*, vol. 12, no. 19, 2019, Art. no. 3721.

[6] H. Tu, H. Feng, S. Srdic, and S. Lukic, "Extreme fast charging of electric vehicles: A technology overview," *IEEE Trans. Transp. Electrific.*, vol. 5, no. 4, pp. 861–878, Dec. 2019.

[7] J. De Santiago *et al.*, "Electrical motor drivelines in commercial all-electric vehicles: A review," *IEEE Trans. Veh. Technol.*, vol. 61, no. 2, pp. 475–484, Feb. 2012.

[8] "Tribute to tomorrow. Porsche concept study mission E.: Dr Ing. h.c. F. Porsche AG," [Online]. Available: https://www.porsche.com/microsite/mission-e/international.aspx

[9] "The charging process: Quick, comfortable, intelligent and universal," [Online]. Available: https://newsroom.porsche.com/en/products/taycan/charging-18558.html

[10] C. Suarez and W. Martinez, "Fast and ultra-fast charging for battery electric vehicles-a review," in *Proc. IEEE Energy Convers. Congr. Expo.,* 2019, pp. 569–575.

[11] C. Hampel, "Lucid air to sport a 900-volt system," Feb. 2020. [Online]. Available: https://www.electrive.com/2020/02/06/lucid-air-to-sport-a-900-volt-system/

[12] "Chevrolet pressroom - United States - Spark EV," [Online]. Available: https://media.chevrolet.com/media/us/en/chevrolet/vehicles/spark-ev/2016.tab1.html

[13] P. Harrop, "Electric vehicles go high voltage," Jun. 2019. [Online]. Available: https://www.idtechex.com/en/research-article/electric-vehicles-go-high-voltage/17347

[14] H. M. Group, "Hyundai motor invests in ionity to democratize high-power EV charging network," Sep. 2019. [Online]. Available: https://www.hyundai.news/eu/brand

[15] "Gm reveals new ultium batteries and a flexible global platform to rapidly grow its ev portfolio," Mar. 2020. [Online]. Available: https://media.gm.ca/

[16] H. Schefer, L. Fauth, T. H. Kopp, R. Mallwitz, J. Friebe, and M. Kurrat, "Discussion on electric power supply systems for all electric aircraft," *IEEE Access*, vol. 8, pp. 84 188–84 216, 2020.

[17] D. Ronanki and S. S. Williamson, "A simplified space vector pulse width modulation implementation in modular multilevel converters for electric ship propulsion systems," *IEEE Trans. Transp. Electrific.*, vol. 5, no. 1, pp. 335–342, Mar. 2019.

[18] A. Bubert, K. Oberdieck, H. Xu, and R. W. De Doncker, "Experimental validation of design concepts for future EV-traction inverters," in *Proc. IEEE Transp. Electrific. Conf. Expo.*, 2018, pp. 795–802.

[19] A. Choudhury, P. Pillay, and S. S. Williamson, "Comparative analysis between two-level and three-level DC/AC electric vehicle traction inverters using a novel DC-link voltage balancing algorithm," *IEEE Trans. Emerg. Sel. Topics Power Electron.*, vol. 2, no. 3, pp. 529–540, Sep. 2014.

[20] "Traction systems for locomotives and highspeed applications," 2018. [Online]. Available: https://library.e.abb.com/public/

[21] "Retrofit traction solutions," 2018. [Online]. Available: https://library.e.abb.com/public/

[22] J. Reimers, L. Dorn-Gomba, C. Mak, and A. Emadi, "Automotive traction inverters: Current status and future trends," *IEEE Trans. Veh. Technol.*, vol. 68, no. 4, pp. 3337–3350, Apr. 2019.

[23] "Power electronic solutions for public transport; trams, trolleybuses, metro, ebuses." 2018. [Online]. Available: https://medcom.com.pl/en/downloads

[24] M. Kane, "Dana SiC inverter offers up to 195 kw/l at up to 900 V," Dec. 2019. [Online]. Available: https://insideevs.com/news/386996/dana-sic-inverter-900-v/

[25] "High-voltage traction inverter: electric vehicle," May 2018. [Online]. Available: https://www.eaton.com/us/en-us/catalog/emobility/high-voltage-inverter.html

[26] "Newsroom," Sep. 2019. [Online]. Available: https://www.delphi.com/newsroom/press-release/delphi-technologies-new-industry-leading-800-volt-sic-inverter-cut-ev

[27] N. LePan, "How much copper is in an electric vehicle?" Mar. 2019. [Online]. Available: https://www.visualcapitalist.com/how-much-copper-is-in-an-electric-vehicle/

[28] D. VanderWerp, "Porsche Taycan's 800-volt architecture enables slimmer wiring, faster charging, less heat," Sep. 2019. [Online]. Available: https://www.caranddriver.com/news/a28903284/porsche-taycan-ev-800-volt-charging-performance/

[29] C. Jung, "Power up with 800-V systems: The benefits of upgrading voltage power for battery-electric passenger vehicles," *IEEE Electrific. Mag.*, vol. 5, no. 1, pp. 53–58, Mar. 2017.

[30] K. Küpper *et al.*, "Tension 12 V to 800 V, efficient powertrain solutions," Oct. 2014. [Online]. Available: http://siar.ro/wp-content/uploads/2016/01/2.-Kupper-K.-AVL-Tension-12-V-to-800-V-2015.compressed.pdf

[31] A. Burnham *et al.*, "Enabling fast charging-infrastructure and economic considerations," *J. Power Sour.*, vol. 367, pp. 237–249, 2017.

[32] "US drive electrical and electronics technical team roadmap," Oct. 2017. [Online]. Available: https://www.energy.gov/eere/vehicles/downloads/us-drive-electrical-and-electronics-technical-team-roadmap

[33] K. Wand, "High performance 800v e-motor for automotive application," *AVL Trimerics GmbH*, Nov. 10, 2016. [Online]. Available: https://www.profemag.ch/de/downloads/category/35-awt-2016?download=513:2016

[34] J. Boyd, "China and Japan push for a global charging standard for EVs." Dec. 2018. [Online]. Available: https://spectrum.ieee.org/energywise/transportation/efficiency/a-global-charging-standard-for-evs

[35] V. Reber, "New possibilities with 800-volt charging," *Porsche Eng. Mag.*, vol. 1, pp. 10–15, 2016.

[36] S. Ahmed *et al.*, "Enabling fast charging-a battery technology gap assessment," *J. Power Sour.*, vol. 367, pp. 250–262, 2017.

[37] M. Keyser *et al.*, "Enabling fast charging-battery thermal considerations," *J. Power Sour.*, vol. 367, pp. 228–236, 2017.

[38] D. Tatman, "Functional safety considerations in battery management for vehicle electrification," *Texas Instrum.*, Sep. 2020. [Online]. Available: https://www.ti.com/lit/sliy006

[39] Z. B. Omariba, L. Zhang, and D. Sun, "Review of battery cell balancing methodologies for optimizing battery pack performance in electric vehicles," *IEEE Access*, vol. 7, pp. 129 335–129352, 2019.

[40] M. Ahmad, "Battery management systems 101: Powertrain electrification," Jan. 2019. [Online]. Available: https://www.embeddedcomputing.com/application/automotive/electric-vehicles-powertrain/a-primer-on-battery-management-system-bms-for-powertrain-electrification

[41] T. Vogt, "Wired vs. wireless communications in EV battery management," *Texas Instrum.*, Oct. 2020. [Online]. Available: https://www.ti.com/lit/pdf/SLYY197.

[42] T. Urban, "Functional safety-relevant wireless communication in automotive battery management systems," *Texas Instrum.*, 2021. [Online]. Available: https://www.ti.com/lit/ug/sluucf5/sluucf5.pdf

[43] C. Vidal, P. Malysz, P. Kollmeyer, and A. Emadi, "Machine learning applied to electrified vehicle battery state of charge and state of health estimation: State-of-the-art," *IEEE Access*, vol. 8, pp. 52 796–52 814, 2020.

[44] "Innovative filter solutions for e-mobility," Jul. 2015. [Online]. Available: https://www.tdk-electronics.tdk.com/en/373562/tech-library/articles/applications---cases/applications---cases/innovative-filter-solutions-for-e-mobility/1311962

[45] S. Guttowski, S. Weber, E. Hoene, W. John, and H. Reichl, "EMC issues in cars with electric drives," in *Proc. IEEE Symp. Electromagn. Compatibility. Symp. Record*, vol. 2, 2003, pp. 777–782.

[46] T. G. Habetler, R. Naik, and T. A. Nondahl, "Design and implementation of an inverter output LC filter used for dv/dt reduction," *IEEE Trans. Power Electron.*, vol. 17, no. 3, pp. 327–331, May 2002.

[47] A. K. Morya *et al.*, "Wide bandgap devices in AC electric drives: Opportunities and challenges," *IEEE Trans. Transp. Electrific.*, vol. 5, no. 1, pp. 3–20, Mar. 2019.

[48] J. I. Leon, S. Vazquez, and L. G. Franquelo, "Multilevel converters: Control and modulation techniques for their operation and industrial applications," *Proc. IEEE*, vol. 105, no. 11, pp. 2066–2081, Nov. 2017.

[49] D. Ronanki and S. S. Williamson, "Modular multilevel converters for transportation electrification: Challenges and opportunities," *IEEE Trans. Transp. Electrific.*, vol. 4, no. 2, pp. 399–407, 2018.

[50] N. S. Hasan, N. Rosmin, D. A. A. Osman, A. H. Musta'amal *et al.*, "Reviews on multilevel converter and modulation techniques," *Renewable Sustain. Energy Rev.*, vol. 80, pp. 163–174, 2017.

[51] F. Richardeau and T. T. L. Pham, "Reliability calculation of multilevel converters: Theory and applications," *IEEE Trans. Ind. Electron.*, vol. 60, no. 10, pp. 4225–4233, 2012.

[52] A. Choudhury and P. Pillay, "Space vector based capacitor voltage balancing for a three-level NPC traction inverter drive," *IEEE Trans. Emerg. Sel. Topics Power Electron.*, vol. 8, no. 2, pp. 1276–1286, Jun. 2020.

[53] J. K. Steinke, "Control strategy for a three phase AC traction drive with three-level GTO PWM inverter," in *19th Proc. 88 Record., IEEE Annu. Power Electron. Specialists Conf. (PESC)*, 1988, pp. 431–438.

[54] U. Henning, R. Hoffmann, and J. Hochleitner, "Advanced static power converter and control components for TRANSRAPID maglev system," in *Proc. Power Convers. Conf.*, 2002, pp. 1045–1049.

[55] M. Z. Youssef, K. Woronowicz, K. Aditya, N. A. Azeez, and S. S. Williamson, "Design and development of an efficient multilevel DC/AC traction inverter for railway transportation electrification," *IEEE Trans. Power Electron.*, vol. 31, no. 4, pp. 3036–3042, Apr. 2016.

[56] N. Mukherjee and P. Tricoli, "Modular multilevel converter based supercapacitor integration strategies and their comparative evaluation for railway traction drive systems," in *Proc. 17th Eur. Conf. Power Electron. Appl.*, 2015, pp. 1–10.

[57] X. He, J. Peng, P. Han, Z. Liu, S. Gao, and P. Wang, "A novel advanced traction power supply system based on modular multilevel converter," *IEEE Access*, vol. 7, pp. 165 018–165028, 2019.

[58] N. Pallo, T. Foulkes, T. Modeer, S. Coday, and R. Pilawa-Podgurski, "Power-dense multilevel inverter module using interleaved GaN-based phases for electric aircraft propulsion," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, 2018, pp. 1656–1661.

[59] L. Dorn-Gomba, J. Ramoul, J. Reimers, and A. Emadi, "Power electronic converters in electric aircraft: Current status, challenges, and emerging technologies," *IEEE Trans. Transp. Electrific.*, vol. 6, no. 4, pp. 1648–1664, Dec. 2020.

[60] S. Kouro *et al.*, "Recent advances and industrial applications of multilevel converters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 8, pp. 2553–2580, Aug. 2010.

[61] M. Spichartz, V. Staudt, and A. Steimel, "Modular multilevel converter for propulsion system of electric ships," in *Proc. IEEE Electric Ship Technol. Symp.*, 2013, pp. 237–242.

[62] L. M. Tolbert, F. Z. Peng, and T. G. Habetler, "Multilevel inverters for electric vehicle applications," in *Proc. Power Electron. Transp.*, 1998, pp. 79–84.

[63] M. Quraan, T. Yeo, and P. Tricoli, "Design and control of modular multilevel converters for battery electric vehicles," *IEEE Trans. Power Electron.*, vol. 31, no. 1, pp. 507–517, Jan. 2016.

[64] S. Bhattacharya, D. Mascarella, G. Joós, J.-M. Cyr, and J. Xu, "A dual three-level T-NPC inverter for high-power traction applications," *IEEE Trans. Emerg. Sel. Topics Power Electron.*, vol. 4, no. 2, pp. 668–678, Jun. 2016.

[65] A. J. Korn, M. Winkelnkemper, and P. Steimer, "Low output frequency operation of the modular multi-level converter," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2010, pp. 3993–3997.

[66] J. Pereda and J. Dixon, "23-level inverter for electric vehicles using a single battery pack and series active filters," *IEEE Trans. Veh. Technol.*, vol. 61, no. 3, pp. 1043–1051, Mar. 2012.

[67] M. Narimani, B. Wu, Z. Cheng, and N. R. Zargari, "A new nested neutral point-clamped (NNPC) converter for medium-voltage (MV) power conversion," *IEEE Trans. Power Electron.*, vol. 29, no. 12, pp. 6375–6382, Dec. 2014.

[68] M. Schweizer and J. W. Kolar, "Design and implementation of a highly efficient three-level t-type converter for low-voltage applications," *IEEE Trans. Power Electron.*, vol. 28, no. 2, pp. 899–907, Feb. 2013.

[69] L. Dorn-Gomba, P. Magne, B. Danen, and A. Emadi, "On the concept of the multi-source inverter for hybrid electric vehicle powertrains," *IEEE Trans. Power Electron.*, vol. 33, no. 9, pp. 7376–7386, Sept. 2018.

[70] S. Busquets-Monge *et al.*, "Multibattery-fed neutral-point-clamped dc-ac converter with soc balancing control to maximize capacity utilization," *IEEE Trans. Ind. Electron.*, vol. 67, no. 1, pp. 16–27, Jan. 2020.

[71] A. Salem and M. Narimani, "A review on multiphase drives for automotive traction applications," *IEEE Trans. Transp. Electrific.*, vol. 5, no. 4, pp. 1329–1348, Dec. 2019.

[72] R. A. Rana *et al.*, "Review of multilevel voltage source inverter topologies and analysis of harmonics distortions in FC-MLI," *Electron.*, vol. 8, no. 11, 2019, Art. no. 1329.

[73] A. Kersten, O. Theliander, E. A. Grunditz, T. Thiringer, and M. Bongiorno, "Battery loss and stress mitigation in a cascaded h-bridge multilevel inverter for vehicle traction applications by filter capacitors," *IEEE Trans. Transp. Electrific.*, vol. 5, no. 3, pp. 659–671, Sept. 2019.

[74] A. Poorfakhraei, M. Narimani, and A. Emadi, "A review of modulation and control techniques for multilevel inverters in traction applications," *IEEE Access*, vol. 9, pp. 24 187–24204, 2021.

[75] F. Ciccarelli, G. Clemente, and D. Iannuzzi, "Energy storage management control based on supercapacitors using a modular multilevel inverter topology for electrical vehicles," in *Proc. Int. Conf. Clean Elect. Power*, 2013, pp. 170–176.

[76] S. Lu, K. A. Corzine, and M. Ferdowsi, "A unique ultracapacitor direct integration scheme in multilevel motor drives for large vehicle propulsion," *IEEE Trans. Veh. Technol.*, vol. 56, no. 4, pp. 1506–1515, Jul. 2007.

[77] O. S. M. Abushafa, S. M. Gadoue, M. S. Dahidah, D. J. Atkinson, and P. Missailidis, "Capacitor voltage estimation scheme with reduced number of sensors for modular multilevel converters," *IEEE Trans. Emerg. Sel. Topics Power Electron.*, vol. 6, no. 4, pp. 2086–2097, Dec. 2018.

[78] L. Tolbert, F. Z. Peng, T. Cunnyngham, and J. N. Chiasson, "Charge balance control schemes for cascade multilevel converter in hybrid electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 49, no. 5, pp. 1058–1064, Oct. 2002.

[79] M. E. H. Benbouzid, D. Diallo, and M. Zeraoulia, "Advanced fault-tolerant control of induction-motor drives for EV/HEV traction applications: From conventional to modern and intelligent control techniques," *IEEE Trans. Veh. Technol.*, vol. 56, no. 2, pp. 519–528, Mar. 2007.

[80] O. Alavi, A. Hooshmand Viki, and S. Shamlou, "A comparative reliability study of three fundamental multilevel inverters using two different approaches," *Electronics*, vol. 5, no. 2, 2016, Art. no. 18.

[81] P. Omer, J. Kumar, and B. S. Surjan, "A review on reduced switch count multilevel inverter topologies," *IEEE Access*, vol. 8, pp. 22 281–22302, 2020.

[82] E. Babaei and S. S. Gowgani, "Hybrid multilevel inverter using switched capacitor units," *IEEE Trans. Ind. Electron.*, vol. 61, no. 9, pp. 4614–4621, Sep. 2014.

[83] E. Babaei, S. Laali, and Z. Bayat, "A single-phase cascaded multilevel inverter based on a new basic unit with reduced number of power switches," *IEEE Trans. Ind. Electron.*, vol. 62, no. 2, pp. 922–929, 2014.

[84] A. K. Sadigh, M. Abarzadeh, K. A. Corzine, and V. Dargahi, "A new breed of optimized symmetrical and asymmetrical cascaded multilevel power converters," *IEEE Trans. Emerg. Sel. Topics Power Electron.*, vol. 3, no. 4, pp. 1160–1170, Dec. 2015.

[85] M. R. J. Oskuee, M. Karimi, S. N. Ravadanegh, and G. B. Gharehpetian, "An innovative scheme of symmetric multilevel voltage source inverter with lower number of circuit devices," *IEEE Trans. Ind. Electron.*, vol. 62, no. 11, pp. 6965–6973, Nov. 2015.

[86] S. P. Gautam, L. Kumar, and S. Gupta, "Hybrid topology of symmetrical multilevel inverter using less number of devices," *IET Power Electron.*, vol. 8, no. 11, pp. 2125–2135, 2015.

[87] S. Jain and V. Sonti, "A highly efficient and reliable inverter configuration based cascaded multilevel inverter for PV systems," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 2865–2875, Apr. 2017.

[88] A. Taghvaie, J. Adabi, and M. Rezanejad, "A self-balanced step-up multilevel inverter based on switched-capacitor structure," *IEEE Trans. Power Electron.*, vol. 33, no. 1, pp. 199–209, Jan. 2018.

[89] R. Agrawal and S. Jain, "Multilevel inverter for interfacing renewable energy sources with low/medium-and high-voltage grids," *IET Renewable Power Gener.*, vol. 11, no. 14, pp. 1822–1831, 2017.

[90] H. Samsami, A. Taheri, and R. Samanbakhsh, "New bidirectional multilevel inverter topology with staircase cascading for symmetric and asymmetric structures," *IET Power Electron.*, vol. 10, no. 11, pp. 1315–1323, 2017.

[91] M. Jayabalan, B. Jeevarathinam, and T. Sandirasegarane, "Reduced switch count pulse width modulated multilevel inverter," *IET Power Electron.*, vol. 10, no. 1, pp. 10–17, 2017.

[92] C. I. Odeh, E. S. Obe, and O. Ojo, "Topology for cascaded multilevel inverter," *IET Power Electron.*, vol. 9, no. 5, pp. 921–929, 2016.

[93] F. Chang, O. Ilina, M. Lienkamp, and L. Voss, "Improving the overall efficiency of automotive inverters using a multilevel converter composed of low voltage si mosfets," *IEEE Trans. Power Electron.*, vol. 34, no. 4, pp. 3586–3602, Apr. 2019.

[94] H. Li and K. W. Klontz, "An investigation of current harmonic influence on induction motor in hybrid electric vehicle application," in *Proc. IEEE Int. Electric Mach. Drives Conf.*, 2017, pp. 1–6.

[95] M. Quraan, P. Tricoli, S. D"Arco, and L. Piegari, "Efficiency assessment of modular multilevel converters for battery electric vehicles," *IEEE Trans. Power Electron.*, vol. 32, no. 3, pp. 2041–2051, Mar. 2017.

[96] F. Chang, O. Ilina, O. Hegazi, L. Voss, and M. Lienkamp, "Adopting mosfet multilevel inverters to improve the partial load efficiency of electric vehicles," in *Proc. 19th Eur. Conf. Power Electron. Appl.*, 2017, pp. P.1–P.13.

[97] R. Teichmann and S. Bernet, "A comparison of three-level converters versus two-level converters for low-voltage drives, traction, and utility applications," *IEEE Trans. Ind. Appl.*, vol. 41, no. 3, pp. 855–865, May/Jun. 2005.

[98] B. Wu and M. Narimani, *High-Power Converters and AC Drives*. Hoboken, NJ, USA: Wiley IEEE Press, 2017.

[99] "New EMI filtering solution for electric vehicles." 2017. [Online]. Available: https://www.schaffner.com/media/news/details/article/new-emi-filtering-solution-for-electric-vehicles/

[100] H. Zhang, A. Von Jouanne, S. Dai, A. K. Wallace, and F. Wang, "Multilevel inverter modulation schemes to eliminate common-mode voltages," *IEEE Trans. Ind. Appl.*, vol. 36, no. 6, pp. 1645–1653, Nov./Dec. 2000.

[101] B. Mirafzal, "Survey of fault-tolerance techniques for three-phase voltage source inverters," *IEEE Trans. Ind. Electron.*, vol. 61, no. 10, pp. 5192–5202, Oct. 2014.

[102] S. Khomfoi and L. M. Tolbert, "Fault diagnosis and reconfiguration for multilevel inverter drive using ai-based techniques," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 2954–2968, Dec. 2007.

[103] X. Kou, K. A. Corzine, and Y. L. Familiant, "A unique fault-tolerant design for flying capacitor multilevel inverter," *IEEE Trans. Power Electron.*, vol. 19, no. 4, pp. 979–987, Jul. 2004.

[104] S. Li and L. Xu, "Strategies of fault tolerant operation for three-level PWM inverters," *IEEE Trans. Power Electron.*, vol. 21, no. 4, pp. 933–940, Jul. 2006.

[105] J. Li, A. Q. Huang, Z. Liang, and S. Bhattacharya, "Analysis and design of active NPC (ANPC) inverters for fault-tolerant operation of high-power electrical drives," *IEEE Trans. Power Electron.*, vol. 27, no. 2, pp. 519–533, Feb. 2012.

[106] S. Ceballos, J. Pou, E. Robles, J. Zaragoza, and J. L. Martin, "Performance evaluation of fault-tolerant neutral-point-clamped converters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 8, pp. 2709–2718, Aug. 2010.

[107] K. Shen *et al.*, "A modulation reconfiguration based fault-tolerant control scheme for modular multilevel converters," in *Proc. 28th Annu. IEEE Appl. Power Electron. Conf. Expo.*, 2013, pp. 3251–3255.

[108] The future of electric vehicle design. 2020. [Online]. Available: https://www.allaboutcircuits.com/uploads/articles/ON-Semiconductor-eBook-EV.pdf

[109] K. Baes, M. S. Kolk, A. Merhaba, F. Carlot, and Y. Ito, "Future of batteries; Winner takes all?" 2018. [Online]. Available: https://www.adlittle.com/en/insights/viewpoints/future-batteries

[110] S. Yano *et al.*, "Development of compact power control unit for HEVS," in *Proc. IEEE Energy Convers. Congr. Expo.*, 2017, pp. 584–588.

[111] "Toyota to trial new sic power semiconductor technology," Jan. 2015. [Online]. Available: https://global.toyota/en/detail/5692153

[112] N. Keshmiri, D. Wang, B. Agrawal, R. Hou, and A. Emadi, "Current status and future trends of GAN hemts in electrified transportation," *IEEE Access*, vol. 8, pp. 70 553–70 571, 2020.

AMIRREZA POORFAKHRAEI (Graduate Student Member, IEEE) received the bachelor's and master's degrees in electrical engineering from the Sharif University of Technology, Tehran, Iran, in 2014 and 2016, respectively. Since 2019, he has been currently working toward the Ph.D. degree with McMaster University, Hamilton, ON, Canada. His main research interests include traction motor drives, wireless power transfer, dc/dc and dc/ac converters.

MEHDI NARIMANI (Senior Member, IEEE) received the Ph.D. degree in electrical engineering from the University of Western Ontario, London, ON, Canada, in 2012.

He is currently an Assistant Professor with the Department of Electrical and Computer Engineering, McMaster University, Hamilton, ON, Canada. Prior joining McMaster University, he was a Power Electronics Engineer with Rockwell Automation Canada, Cambridge, ON, Canada. He has authored or coauthored more than 70 journal and conference proceeding papers, coauthored a Wiley-IEEE Press book, and holds more than four issued or pending U.S. and European patents. His research interests include power conversion, high-power converters, control of power electronics converters, and renewable energy systems.

ALI EMADI (Fellow, IEEE) received the B.S. and M.S. degrees in electrical engineering, with highest distinction, from the Sharif University of Technology, Tehran, Iran, in 1995 and 1997, respectively, and the Ph.D. degree in electrical engineering from Texas A&M University, College Station, TX, USA, in 2000. He is currently the Canada Excellence Research Chair Laureate of McMaster University, Hamilton, ON, Canada, the NSERC/FCA Industrial Research Chair in Electrified Powertrains, and Tier I Canada Research Chair in Transportation Electrification and Smart Mobility. Before joining McMaster University, he was the Harris Perlstein Endowed Chair Professor of engineering and the Director of the Electric Power and Power Electronics Center and Grainger Laboratories, Illinois Institute of Technology, Chicago, IL, USA, where he established the research and teaching facilities as well as courses in power electronics, motor drives, and vehicular power systems. He was the Founder, Chairman, and President of Hybrid Electric Vehicle Technologies, Inc., - a university spin-off company of Illinois Institute of Technology. He is currently the President and a Chief Executive Officer of Enedym Inc., Hamilton, ON, Canada, and Menlolab Inc., -two McMaster University spin-off companies. He is the Principal author or coauthor for more than 500 journal and conference papers and several books including *Vehicular Electric Power Systems* (2003), *Energy Efficient Electric Motors* (2004), *Uninterruptible Power Supplies and Active Filters* (2004), *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles* (2nd ed, 2009), and *Integrated Power Electronic Converters and Digital Control* (2009). He is also the Editor of the *Handbook of Automotive Power Electronics and Motor Drives* (2005) and *Advanced Electric Drive Vehicles* (2014). He is the Co-Editor of the *Switched Reluctance Motor Drives* (2018). He was the Inaugural General Chair of the 2012 IEEE Transportation Electrification Conference and Expo and has Chaired several IEEE and SAE conferences in the areas of vehicle power and propulsion. From 2014 to 2020, he was the Founding Editor-in-Chief of the IEEE TRANSACTIONS ON TRANSPORTATION ELECTRIFICATION.