A Review on the Design Considerations for Next-Generation e-Motorbike Drive-train Inverter

Jaydeep Saha[1], He Bin[2], Sai Srinivas Manohar[1], Rahul S. Bhujade[1], Tang Gongyue[2], Sanjib Kumar Panda[1]
[1]Department of Electrical & Computer Engineering (ECE), National University of Singapore (NUS)
[2]Institute of Microelectronics (IME), Agency for Science, Technology & Research (A*STAR), Singapore

***Abstract*—Though e-motorbikes comprise a considerable proportion of electric vehicles (EVs), it's drive-train design is rarely presented in the literature. This paper focuses on reviewing the important design considerations for drive-train inverters of next-generation e-motorbikes. A compilation of state-of-the-art e-motorbikes' specifications reveals that the inverter requirements are diverse in terms of power with a thrust towards enhanced efficiency and power density. A review of the power-electronic design of this inverter is presented to elicit the topology choices, battery-pack design based on DC-link voltage choice, as well as the benefits of using new wide-bandgap devices and latest ceramic capacitors. An overview of the inverter's cooling system design shows the merits of liquid-cooling for compact inverter design.**

***Index Terms*—Efficiency, Electric Vehicle, Inverter, Liquid-cooling, Power Density, Wide-Bandgap Devices.**

I. INTRODUCTION

The pledges by governments of several countries towards reduction in pollutant emission have led to higher motivation towards reducing vehicular pollution through transportation electrification, and a high growth of electric vehicles (EVs) has been projected for this decade [1]. EV drive-trains have been predominantly researched upon with respect to the 4-wheeler cars segment (with typically 75-200 kVA power range drive-trains), while accounting for the demand in majority of the western countries [2]–[4]. However, 2-wheeler segment electrification has become one of the spotlights of this decade, mainly due to their rising demand in the congested cities of developing nations (mostly in Asia) [2], [5]–[7].

U.S. DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability) initiative of U.S. Department of Energy (DoE) has set steep research and development targets for the EV drive-train inverter [8]. For $\sim$100 kW EV drive-trains (representative of the 4-wheeler segment), it aims to achieve an inverter design having volumetric power density of 100 kW/L at a cost of \$2.70/kW. The mean drive-train inverter power density demonstrated by on-road EVs worldwide till FY 2020/21 was $<$15 kW/L [9], which could meet the U.S. DRIVE 2020 target of 13.4 kW/L, but is far behind the 2025 target. The major reason for low power density is the requirement for higher cooling system's volume to absorb the high conduction and switching losses associated with Si-based IGBTs and MOSFETs, which was used for most EV drive-train inverters developed in the last decade. Few high-end EV manufacturing companies who already made the transition to SiC-based drive-train inverters have benefited largely and have enhanced power density, for example, Tesla model Y has achieved $\sim$60 kW/L inverter and Porsche Taycan houses a $\sim$40 kW/L inverter [9]. Though 100 kW/L can be achieved by 2025 through disruptive power-electronics, packaging and cooling technologies, such a sophisticated inverter design will be limited to a few high-end EV companies. The mean drive-train inverter power density of on-road EVs, through use of wide-bandgap (WBG) devices may be capable of reaching the Chinese SAE target of 40 kW/L [9] by 2025. As the 2-wheeler EV industry, especially in developing economies, is quite cost sensitive, 40 kW/L WBG based inverter development by 2025 would be a more reasonable target for this EV segment.

Though the drive-train inverter design considerations for 2-wheeler e-motorbikes are fundamentally similar to those of 4-wheeler EVs, a review on the specific requirements of next-generation e-motorbike drive-train inverter design is not available in contemporary literature. To address the aforementioned lack of information, this paper provides a specific overview on various aspects of e-motorbike drive-train inverter design considerations for the near future, to benefit both academic and industrial research and development. Section II provides a compilation of drive-train specifications of recently developed e-motorbikes at various power capabilities. Section III reviews the design considerations for the power-electronic board, that involves suitable inverter topology selection, evaluating the battery-pack that forms the DC-link preceding the inverter, as well as, the adoption of WBG devices and new-generation ceramic capacitors. Section IV discusses the inverter's cooling system design considerations and highlights the advantages of liquid-cooling for highly power dense inverter designs. Finally, Section V provides a succinct conclusion.

II. STATE-OF-THE-ART E-MOTORBIKES

Though a considerable number of reviews on the EV drive-train and constituent inverter (also known as motor-control-unit or MCU) of 4-wheeler vehicle segment have been carried out [9]–[14], there is minimal literature available on the drive-train and inverter development specifically for e-motorbikes. Therefore, in this section, various specifications of the inverter-based drive-train are compiled for e-motorbikes (using data available on public domain) and presented through Tab. I.

The tabulated specifications of e-motorbikes are organized into three segments according to the nominal power of the drive-motor: (i) $\leq$5 kW, (ii) 5-15 kW, and (iii) $>$15 kW. Within a given power segment, the important drive-train specifications

This research is supported by A*STAR, Singapore, under its "RIE2025 MTC IAF-PP: Development of High Performance Electric Traction Module (HiPe-ETraM)", Grant No. M22K4a0044.

TABLE I

DRIVE-TRAIN SPECIFICATIONS OF STATE-OF-THE-ART E-MOTORBIKES FOR REVEALING THEIR INVERTER REQUIREMENTS

Company, Model, Nation	Motor type	Rated, Max. power	Max. torque	Battery type	Voltage	Energy	Inverter info.	Max. power
e-motorbikes with nominal power of motor-load $\leq$5 kW								
Onyx, RCR, USA	Hub-motor	3 kW, 5.4 kW	180 Nm	-	72 V	3.44 kWh	-	7.5 kW
Maeving, RM1, UK	Hub-motor	3 kW, 4.4 kW	160 Nm	Samsung Li^+	50.4 V	2.03 kWh	-	>4.4 kW
Honda, Benly e II, Japan	EF07M AC	3 kW, 4.2 kW	15 Nm	Honda Li^+	50.4 V	2x1.1 kWh	air-cooled	>4.2 $kW_{\Re}$
Kymco, Like EV, Taiwan	BLDC	3.2 kW, >4 kW	124 Nm	Li-ion	50 V	<1 kWh	-	>4 kW
Ather, 450X, India	PMSM	3.3 kW, 6.2 kW	26 Nm	Li^+ IP67	60 V	3.7 kWh	Si-based	>6.2 kW
Vespa, Electrica, Italy	DC-motor	3.6 kW, 4 kW	200 Nm	Li-ion	48 V	4.2 kWh	-	>4 kW
Vmoto, CPX, Australia	BLDC-hub	4 kW, 4.8 kW	171 Nm	Li-ion	60 V	2.7 kWh	-	>4.8 kW
Ion Mob., M1-S, Singapore	PMSM	5 kW, 12.5 kW	45 Nm	Li^+ NMC	72 V	4.3 kWh	Si-based	>12.5 kW
Treeletrik, T-90, Malaysia	-	5 kW, >6 kW	-	Li-ion	84 V	3.8 kWh	-	>6 kW
Niu, RQi, China	PMSM	5 kW, 7.5 kW	-	Panason. Li^+	72 V	2x3.5 kWh	-	>7.5 kW
e-motorbikes with nominal power of motor-load in the range of 5-15 kW								
Ola, S1 pro, India	IPMSM	5.5 kW, 8.5 kW	58 Nm	Li^+ IP67	-	4 kWh	Si-based	>8.5 kW
Cake, Kalk INK, Sweden	IPMSM	5.8 kW, 11 kW	42 Nm	Li^+ (18650)	51.8 V	2.6 kWh	-	>11 kW
Frison, M8000, France	Hub-motor	7.2 kW, 11 kW	148 Nm	Li-ion	72 V	7.2 kWh	-	>11 kW
Metacycle, Sondors, USA	PMSM-hub	8 kW, 14.5kW	175 Nm	Li-ion	72 V	4 kWh	-	>14.5 kW
Eccity, 125+, France	BLDC	8 kW, 12 kW	-	Li-ion	74 V	5.4 kWh	-	>12 kW
Yamaha, E01, Japan	PMSM	-, 8.1 kW	30 Nm	Li-ion	87.6 V	4.9 kWh	-	>8.1 kW
KTM, Freeride, Austria	IPMSM	9 kW, 18 kW	42 Nm	Sony Li^+	260 V	3.9 kWh	liq.-cooled	>18 kW
Nerva, Exe, Spain	-	9 kW, 12 kW	∼50 Nm	BYD LFP	76.8 V	2x2.9 kWh	-	>12 kW
Dayi, E-oidin pro, China	BL-AMR	10 kW, 12 kW	-	CATL Li^+	84 V	10 kWh	-	>12 kW
Edison, Volta s150, Korea	Brush-less	-, 11 kW	-	Li^+ (LFP)	-	3.2 kWh	liq.-cooled	>11 kW
BMW, CE04, Germany	$PMSM_{l.c.}$	15 kW, 31 kW	62 Nm	40 Li^+ cells	148 V	8.9 kWh	WBG-based	43.5 $kW_{\Re}$
e-motorbikes with nominal power of motor-load >15 kW								
Tarform, Luna, USA	PMSM	41 kW, 55 kW	160 Nm	Li-ion	-	11.2 kWh	-	>55 kW
Energica, Experia, USA	PMaSynRM	60 kW, 75 kW	115 Nm	Li-polymer	306 V	22.5 kWh	liq.-cooled*	>75 $kW_{\Re}$
Livewire, ONE, USA	$PMSM_{l.c.}$	-, 75 kW	114 Nm	Samsung Li^+	254 V	15.5 kWh	liq.-cooled	>75 $kW_{\Re}$
Newron, EV-1, USA	$PMSM_{l.c.}$	-, 75 kW	240 Nm	Li-ion	350 V	13 kWh	-	>75 kW
Zero, SR/S, USA	IPMSM	-, 82 kW	190 Nm	Z-Force Li^+	102 V	17.3 kWh	SiC-based**	>82 $kW_{\Re}$
ARC, Vector, UK	PMSM	-, 87 kW	173 Nm	Samsung Li^+	399 V	16.8 kWh	-	>87 $kW_{\Re}$
Evoke, 6061-GT, China	$PMSM_{l.c.}$	90 kW, 120 kW	221 Nm	Li^+ NMC	336 V	29.7 kWh	Evoke SiC	120 $kW_{\Re}$
Triumph, TE-1, UK	$PMSM_{l.c.}$	90 kW, 130 kW	109 Nm	WAE Li^+	360 V	15 kWh	Helix $SiC_{l.c.}$	150 $kW_{\Re}$
Lightning, LS218, USA	$IPMSM_{l.c.}$	-, 150 kW	227 Nm	Sil. Li^+	380 V	20 kWh	liq.-cooled	>150 kW
Verge, TS-ultra, Estonia	Hub-less	-, 150 kW	1200 Nm	Li-ion	-	20.2 kWh	-	150 kW
Damon, Hypersp., Canada	$PMSM_{l.c.}$	-, 160 kW	200 Nm	Li-ion	450 V	21.5 kWh	liq.-cooled	2x80 $kW_{\Re}$

Note: BLDC = Brush-less direct-current; PMSM = Permanent Magnet Synchronous Motor; IPMSM = Interior Permanent Magnet Synchronous Motor; Li^+ = Li-ion; LFP = LiFePO4/C; subscript $_{l.c.}$ refers to liquid-cooled; subscript $_{\Re}$ signifies drive-train inverter control includes regenerative braking.

* Drive-train inverter shares liquid-coolant with the electric-motor [permanent magnet assisted synchronous reluctance machine (PMaSynRM)].

** Highly efficient and power dense three-phase inverter with high switching frequency (relative to contemporaries) and max. current limit of 900 A.

of the most recent e-motorbike model (having sufficient electrical specifications released) of each company are recorded. It should also be noted that most of the companies listed in Tab. I have announced that they will be releasing the specifications of several new-generation e-motorbikes in financial year 2023/24 (which will be made available commercially soon after). Some observations from Tab. I are listed down as follows:

1) Various variants of Li-ion is the dominant battery technology adopted by drive-trains of different peak/nominal power requirements; battery-packs with higher voltages (than the usual 60-72 V) are being used for e-motorbikes in the 8-15 kW and >15 kW power-range segments.
2) Though quite limited information regarding topolgy and semiconductor devices of inverters is available, some reveal the use of WBG devices; silicon-carbide (SiC) is the dominant WBG device for high-power e-motobike drive-train inverters (with >75 kW peak-power capability and connected to >300 V battery-packs).
3) Some drive-train inverters in medium and high power segments reveal liquid-cooling; most of the high-power variants (manufactured mostly in developed countries with high-end price range) have regenerative deceleration control and other advanced controls within inverter.
4) The battery (source) and motor (load) side information of a given drive-train helps to estimate the intermediate inverter's basic specifications like voltage, power, etc.
5) The drive-train inverter must be capable of supplying the peak/maximum power demanded by motor (load); if this peak motor power has to be supplied for >1 s by the inverter, then it becomes the maximum continuous load power which should be the rated power of inverter.
6) It can be inferred from the e-motorbike drive-trains' trend towards higher DC-link voltages and adoption of WBG-based constituent inverters that the manufacturers' push is towards higher efficiency and power density (similar to 4-wheeler EV segment [11]–[14]).

III. POWER-ELECTRONIC DESIGN

As presented through Fig. 1, the typical contemporary e-motorbike drive-train shows the constituent inverter (or MCU), which is one of the most critical components of the drive-train and controls the power transfer from the battery to the motor (and in reverse direction as well if regenerative deceleration control is possible). The design strategy and operational principle used for the inverter determines its efficiency, power density, cost, etc., which are discussed further in this section.

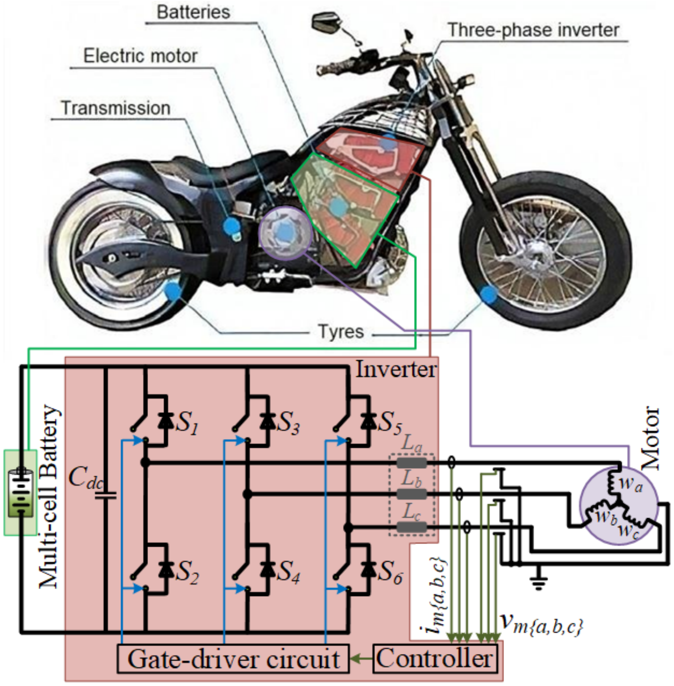

Fig. 1. Simplified schematic of the typical state-of-the-art e-motorbike drive-train with the most common inverter topology.

A. Inverter topology

The circuit topology is the most fundamental design decision to be made while designing any inverter for a given application, and the decision is influenced by the electrical specifications, efficiency and power density targets and cost constraints. The most common motor types used in EV drives are Brush-less Direct-current (BLDC) motor and Permanent Magnet Synchronous Motor (PMSM), mainly due to their high efficiency, low maintenance and affordability. For driving these motors, three-phase inverters with three output terminals are commonly used. Multilevel-inverters are not customary for BLDC based EV drive-trains due to common-usage in drive-trains with lower voltage and power, and thus the literature is brief [15]–[17]. Whereas, considerable amount of literature is available on multilevel-inverters for PMSM based EV drive-trains due to better feasibility of the multilevel topologies at higher voltage and power ranges (compared to the typical BLDC drive-trains) [18]–[22]. Z-source inverters have also been researched (mainly for PMSM drive applications) for boosted DC-AC conversion with the objective of reducing the conduction losses in the drive-train [12], [23]–[25], but suffers from lower power density due to bulky passive devices.

A majority of the EV industry (except the luxury segment) is not only cost sensitive, but also has targets for high reliability with low maintenance, less complexity and compact design. Thus, multilevel/Z-source inverters are not preferable choices for EV drive-trains and the conventional three-phase inverter topology with six active-switches is preferred, especially for the e-motorbike drives [12], [14]. Some of the companies and their inverter manufacturers (listed in Tab. I) have mentioned terms like *simple*, *reliable* and *conventional* while referring to the inverter's topology as a part of their publicly available documents/statements, which point towards the utilisation of six-switch inverter topology. A minority of the e-motorbikes have mentioned that their MCU topology consists of 2 six-switch inverters in parallel. In practice, six-switch topology is the most common inverter configuration for EV motor-drive application and there is abundant literature for their operation in both BLDC [26]–[29] and PMSM [30]–[35] based drives.

TABLE II
CASE STUDY: BATTERY-PACK DESIGNS AT DIFFERENT VOLTAGES

Bat. voltage	72 V Battery-Pack		300 V Battery-Pack	
Manufacturer	Panasonic	A-123 Syst.	Panasonic	A-123 Syst.
Cell type	Cylindrical	Pouch	Cylindrical	Pouch
Cell voltage	3.6 V	3.3 V	3.6 V	3.3 V
Cell energy	11.52 Wh	64.35 Wh	11.52 Wh	64.35 Wh
Series cells	20	22	84	91
Paral. strings	43	7	11	2
Total cells	860	154	924	182
Pack weight	41.7 kg	76 kg	44.8 kg	90 kg
Pack volume	15.1 L	40 L	16.2 L	48 L
Pack energy	10 kWh	10 kWh	10 kWh	10 kWh
Cont. power	10 kW	10 kW	10 kW	10 kW
Peak power	∼12 kW	∼100 kW	∼12 kW	∼100 kW

B. Battery Considerations and DC-link voltage

As observed from Tab. I, majority of e-motorbike drive-trains in ≤5 kW range have battery voltages ≤72 V, whereas, most drive-trains in 5-15 kW range posses batteries with voltages <100 V. It is not preferable to have a DC-DC boost converter (having bulky inductor) due to space-constraints and high-power density requirement of the drive-train, and thus the DC-link voltage seen by the inverter would be ≈ the battery's terminal voltage. This is in contradiction with the considerable volume of research performed in the past decade which recommends higher DC-link voltages for enhancing efficiency and power density [3], [8], [10]–[12]. Few years back, there were safety/insulation related concerns regarding the charger socket for off-board charging which gets connected to the same DC-link (whose voltage is proposed to be increased); however, that issue is resolved with the introduction of new generation chargers (due to the advent of fast-charging) and appropriate standards [36]. In fact, similar to the drive-train inverter, higher DC-link voltage is also conducive for fast-charging due to the same reason of reduction in conduction losses; thus, there is no dearth of motivation to push for higher DC-link voltages.

As higher DC-link voltage implies higher battery voltage for most e-motorbikes, an investigation is done to understand if the battery-pack poses any challenge to increment of DC-link voltage. A case study is carried out for the battery-pack design of an e-motorbike drive-train with 10 kW continuous power (R&D of most companies focused on 5-15 kW segment) at two voltages (72 V and 300 V) and with two types of cells. As presented in Tab. II, Panasonic cylindrical-cell based battery-pack (most common) has limited current capability which limits maximum power capability to ∼12 kW [37]; whereas, A-123 System's pouch-cell based battery-pack has maximum power capability of ∼100 kW, due to very high cell discharge current pulse capability of ∼400 A safely for 10 s [38]. It can be observed that while using the commonly used cells (with voltages in the range of 2.5-4 V), the higher voltage battery-packs have a low ratio of parallel to series cells which is detrimental for the battery's reliability and ease of packaging [12]. A solution to have higher battery-pack voltage at 10 kW continuous power delivery would be to use cells with higher voltage, similar to the strategy used in BMW CE04 (Tab. I).

C. Wide-bandgap devices and Soft-switching

Silicon-carbide (SiC) and Gallium-nitride (GaN) are the WBG device segments that have shown tremendous development in the last decade. Their applications can be found recently in the EV industry [77], for instance, emerging EV fast-charging as found in papers [39]–[45], and more extensively for EV drive-trains as in [46]–[53]. Various companies like Tesla, BMW, Porsche, etc. have reported their state-of-the-art EV drive-trains constituting SiC-based inverters [54]–[56], and an all-GaN light-EV has been developed/demonstrated jointly by Nagoya University and Toyota Advanced Power Electronics Research Division [57]. For e-motorbike inverter development, GaN is the only WBG device choice for DC-link voltages $<$150 V (considering the voltage blocking utilization factor), whereas, both SiC and GaN are feasible choices for DC-link voltages $>$150 V. It should be noted that GaN technology is not matured yet and has limitations in power carrying capability, whereas, the lowest SiC-MOSFET blocking voltage is 650 V with compact six-switch modules (ideal for compact drive-train inverter development) available only $>$1 kV.

Soft-switching in general helps to minimize switching losses in devices, and zero-voltage-switching (ZVS) is the most effective method for commonly available SiC and GaN devices. Two broad categories of ZVS soft-switching strategies applied to drive-inverters are: (i) through auxiliary resonant circuitry that influences the commutation/switching [58]–[60], and (ii) through variable switching-frequency based modulation alone [61]–[63]. The first technique leads to slight deterioration of power density due to packaging of additional components, whereas, the second method requires devices with higher peak current carrying capability and induces higher harmonics in the motor windings if additional capacitive filter is not used. Additionally, ZVS is difficult to implement in the GaN-based inverters due to shorter switching times and susceptibility to higher currents [64], [65]. Due to these reasons, soft-switching techniques are not commonplace in EV inverters and further investigation is required to minimize the switching losses of predominantly hard-switched EV drive-train inverters.

D. New-generation Capacitors for DC-link

DC-link voltage is kept stable through the use of capacitors (taking up a considerable volume in the inverter), which help in filtering out the high-frequency current ripple generated due to the switching action of the inverter's active devices. Over the last few years, polymer-film and ceramic capacitors have become preferable choices over the conventional electrolytic capacitors, due to their high current carrying capability, higher frequency operation (ideal for WBG devices), high reliability, high power density, etc. Lead-lanthanum-zirconate-titanate (PLZT) based ceramic capacitors have been recently introduced which offer higher capacitance density (compactness), higher lifetime, low parasitics (ESR and ESL) and minimum limitation on $\mathrm{d}V/\mathrm{d}t$ (for fast switching), which give the best characteristics among ceramic capacitors and aid in the development of highly compact, WBG based drive-train inverters [14], [66]–[68]. As several of these capacitors need to be arranged to suffice the DC-link capacitance requirement, careful packaging is needed to minimize current asymmetry among parallel branches and parasitic layout inductance.

IV. Cooling System Design

The root cause of most semiconductor device failures is unbounded thermal stress [69]–[71], whereas higher junction temperature leads to increased semiconductor losses [72]–[74], which necessitate a cooling system (a.k.a. thermal management system) that occupies a considerable volume in an inverter. Thus, the cooling system's architecture directly affects the efficiency and power density of drive-train inverter. In fact, higher junction temperature causes higher losses (pushing towards higher heat-sink volume), but also enhances heat-flow due to higher junction-to-ambient temperature difference (pushing towards lower heat-sink volume); this trade-off can be resolved through heat-sink design optimization.

The choice of cooling methodology is dependent on the case-to-heat-sink heat-flux, wherein liquid-cooling is preferred for heat-flux $\geq$500 W/cm^2 [75]. Liquid-cooling is the only option for compact semiconductor modules, especially for the WBG devices/modules with low contact area and heat-flux $\geq$1000 W/cm^2; thus, most EV inverter manufacturers in the last decade have water ethylene-glycol (WEG) based liquid-cooling and moved away from forced air-cooling. The last few years' trend is towards double-sided cooling of modules, which is widely adopted by leading EV companies like Toyota, Chevrolet, BMW, Audi, Tesla, Porsche, Honda, etc. [9], with highest power density ($\sim$90 kW/L) achieved in Hitachi's SiC-module for Porsche Taycan GTS having direct-water-cooled double-sided pin fins. Additive printing techniques enhance the thermal performance of heat-sinks through optimizing heat transfer surfaces (thereby reducing weight and removing unnecessary interfaces), introduction of microchannel coolant flow, etc. [76]. For e-motorbikes' drive-train inverters, liquid-cooling highly improves power density and slightly improves efficiency; but the design technology has to be carefully chosen while considering the cooling system's budget constraint.

V. Conclusion and Trends

This paper provides the first specific review (in academic literature) on design considerations for e-motorbike drive-train inverter. Firstly, due to the lack of literature on e-motorbike drive-train, a compilation of contemporary e-motorbike drive-train specifications is presented to reveal the expectations from inverter. Secondly, an investigation on the power-electronic design considerations for the e-motorbike drive-train inverter reveals that: (i) conventional six-switch topology is (and will be) preferred; (ii) though higher DC-link voltage is theoretically preferable for enhancing efficiency, battery-pack design with higher cell voltage is required; (iii) WBG devices are being adopted for more efficient and power dense design, but incorporation of soft-switching still needs evaluation; (iv) new generation PLZT based DC-link capacitors are preferred, especially for WBG based inverter designs. Further, a study on thermal management system's design suggests: (i) liquid cooling to be the preferable choice for inverter designs, especially for WBG based inverter designs with higher case-to-heat-sink heat-flux; (ii) additive printing techniques can further enhance the cooling system's design but is constrained by budget.

References

[1] *Global EV Outlook 2022: Securing supplies for an electric future*, International Energy Agency (IEA), OECD Publishing, Paris, May 2022. [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2022

[2] T Eccarius, C.C. Lu, "Powered two-wheelers for sustainable mobility: A review of consumer adoption of electric motorcycles," *Internat. J. of Sustain. Transport.*, vol. 14(3), pp. 215-231, Jan. 2020.

[3] *U.S. DRIVE*, Vehicle Technologies Office, U.S. Department of Energy. [Online]. Available: https://www.energy.gov/eere/vehicles/us-drive

[4] *Our Roadmaps*, Advanced Propulsion Centre UK. [Online]. Available: https://www.apcuk.co.uk/media-type/roadmaps/

[5] *Electric Scooters Market Size, Share & Trends Analysis Report By Battery (Lithium-ion, Lead-acid), By Drive Type (Belt Drive, Hub Motor), By End-use (Personal, Commercial), By Region, And Segment Forecasts, 2023-2030*, Grand View Research (GVR), San Francisco, USA, 2023. [Online]. Available: https://www.grandviewresearch.com/industry-analysis/electric-scooters-market

[6] *Global Electric Vehicles Outlook, 2022*, Frost & Sullivan, North America, Jun. 2022. [Online]. Available: https://store.frost.com/global-electric-vehicles-outlook-2022.html

[7] J. Aarhaug, N. Fearnley, K.J. Hartveit, E. Johnsson, "Price and competition in emerging shared e-scooter markets," *Research in Transport. Econom.*, vol. 98, May 2023.

[8] "Electrical and electronics technical team roadmap," U.S. DOE Vehicle Technology Office, Washington DC, USA, Tech. Rep., Oct. 2017.

[9] M. Liu, A. Coppola, M. Alvi and M. Anwar, "Comprehensive Review and State of Development of Double Sided Cooled Package Technology for Automotive Power Modules," *IEEE Open J. Power Electron.*, vol. 3, pp. 271 289, 2022.

[10] S. E. Schulz, "Exploring the High-Power Inverter: Reviewing critical design elements for electric vehicle applications," *IEEE Electrific. Mag.*, vol. 5, no. 1, pp. 28-35, Mar. 2017.

[11] J. Reimers, L. Dorn-Gomba, C. Mak and A. Emadi, "Automotive Traction Inverters: Current Status and Future Trends," *IEEE Trans. Vehic. Tech.*, vol. 68, no. 4, pp. 3337-3350, Apr. 2019.

[12] I. Aghabali, J. Bauman, P. J. Kollmeyer, Y. Wang, B. Bilgin and A. Emadi, "800-V Electric Vehicle Powertrains: Review and Analysis of Benefits, Challenges, and Future Trends," *IEEE Trans. Transport. Electrific.*, vol. 7, no. 3, pp. 927-948, Sept. 2021.

[13] A. Poorfakhraei, M. Narimani and A. Emadi, "A Review of Multilevel Inverter Topologies in Electric Vehicles: Current Status and Future Trends," *IEEE Open J. Power Electron.*, vol. 2, pp. 155-170, 2021.

[14] I. Husain et al., "Electric Drive Technology Trends, Challenges, and Opportunities for Future Electric Vehicles," *Proc. of the IEEE*, vol. 109, no. 6, pp. 1039-1059, June 2021.

[15] V. Viswanathan and J. Seenithangom, "Commutation Torque Ripple Reduction in the BLDC Motor Using Modified SEPIC and Three-Level NPC Inverter," *IEEE Trans. Power Electron.*, vol. 33, no. 1, pp. 535-546, Jan. 2018.

[16] I. Shchur and V. Turkovskyi, "Multilevel DC Link Inverter Fed BLDC Motor Drive with Modular Battery/Supercapacitor HESS for Electric Vehicle," *IEEE Problems of Automated Electrodrive. Theory and Practice (PAEP)*, Kremenchuk, Ukraine, 2020, pp. 1-6.

[17] B. Chokkalingam, A. Yusuff, M. Tariq and T. Bhekisiph, "Torque-Ripple Mitigation for BLDC using Integrated Converter Connected Three-Level T Type NPC-MLI," *International Conference on Electrical, Electronics and Computer Engineering (UPCON)*, Aligarh, India, 2019, pp. 1-6.

[18] B. Xu, Q. Jiang, W. Ji and S. Ding, "An Improved Three-Vector-Based Model Predictive Current Control Method for Surface-Mounted PMSM Drives," *IEEE Trans. Transport. Electrific.*, vol. 8, no. 4, pp. 4418-4430, Dec. 2022.

[19] X. Jin, S. Liu, W. Shi, H. Yang and R. Zhao, "Optimal Vector Sequences for Simultaneous Reduction of the Switching Loss, Zero-Sequence Circulating Current, and Torque Ripple in Two Parallel Interleaved Inverter-Fed PMSM Drives," *IEEE Trans. Transport. Electrific.*, vol. 7, no. 3, pp. 1493-1505, Sept. 2021.

[20] L. Liu, H. Li, S. H. Hwang and J. M. Kim, "An Energy-Efficient Motor Drive With Autonomous Power Regenerative Control System Based on Cascaded Multilevel Inverters and Segmented Energy Storage," *IEEE Trans. Ind. Appl.*, vol. 49, no. 1, pp. 178-188, Jan.-Feb. 2013.

[21] H. Yao, Y. Yan, T. Shi, G. Zhang, Z. Wang and C. Xia, "A Novel SVPWM Scheme for Field-Oriented Vector-Controlled PMSM Drive System Fed by Cascaded H-Bridge Inverter," *IEEE Trans. Power Electron.*, vol. 36, no. 8, pp. 8988-9000, Aug. 2021.

[22] H. Yao, Y. Yan, Y. Cao, P. Song and T. Shi, "A Variable Duty Cycle-Based Predictive Control for PMSM Fed by Cascaded H-Bridge Inverter," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 10, no. 4, pp. 4195-4206, Aug. 2022.

[23] A. Battiston, E. H. Miliani, S. Pierfederici and F. M. Tabar, "Efficiency Improvement of a Quasi-Z-Source Inverter-Fed Permanent-Magnet Synchronous Machine-Based Electric Vehicle," *IEEE Trans. Transport. Electrific.*, vol. 2, no. 1, pp. 14-23, March 2016.

[24] F. Guo, L. Fu, C. H. Lin, C. Li, W. Choi and J. Wang, "Development of an 85-kW Bidirectional Quasi-Z-Source Inverter With DC-Link Feed-Forward Compensation for Electric Vehicle Applications," *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5477-5488, Dec. 2013.

[25] M. Reza et al., "High Gain Quasi-Switched Boost Inverter With Optimal Performance Parameters," *IEEE Trans. Transport. Electrific.*, vol. 6, no. 2, pp. 554-567, Jun. 2020.

[26] F. Naseri, E. Farjah and T. Ghanbari, "An Efficient Regenerative Braking System Based on Battery/Supercapacitor for Electric, Hybrid, and Plug-In Hybrid Electric Vehicles With BLDC Motor," *IEEE Trans. Vehic. Tech.*, vol. 66, no. 5, pp. 3724-3738, May 2017.

[27] P. H. Kumar and V. T. Somasekhar, "An Enhanced Fault-Tolerant and Auto-reconfigurable BLDC Motor Drive for Electric Vehicle Applications," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 4, no. 1, pp. 368-380, Jan. 2023.

[28] S. R. Meher, S. Banerjee, B. T. Vankayalapati and R. K. Singh, "A Reconfigurable On-Board Power Converter for Electric Vehicle With Reduced Switch Count," *IEEE Trans. Vehic. Tech.*, vol. 69, no. 4, pp. 3760-3772, Apr. 2020.

[29] B. Saha, B. Singh and A. Sen, "SMO Based Position Sensorless BLDC Motor Drive Employing Canonical Switching Cell Converter For Light Electric Vehicle," *IEEE Trans. Ind. Electron.*, 2023.

[30] S. He et al., "Digital Collaborative Development of a High Reliable Auxiliary Electric Drive System for eTransportation: From Dual Three-Phase PMSM to Control Algorithm," *IEEE Access*, vol. 8, pp. 178755-178769, 2020.

[31] W. Hu, C. Ruan, H. Nian and D. Sun, "Zero-Sequence Current Suppression Strategy With Common-Mode Voltage Control for Open-End Winding PMSM Drives With Common DC Bus," *IEEE Trans. Ind. Electron.*, vol. 68, no. 6, pp. 4691-4702, Jun. 2021.

[32] K. Kumar and S. B. Santra, "Performance Analysis of a Three-Phase Propulsion Inverter for Electric Vehicles Using GaN Semiconductor Devices," *IEEE Trans. Ind. Appl.*, vol. 54, no. 6, pp. 6247-6257, Nov.-Dec. 2018.

[33] M. Wu, X. Sun, J. Zhu, G. Lei and Y. Guo, "Improved Model Predictive Torque Control for PMSM Drives Based on Duty Cycle Optimization," in *IEEE Trans. Ind. Magnet.*, vol. 57, no. 2, pp. 1-5, Feb. 2021.

[34] P. Dost and C. Sourkounis, "On Influence of Non Deterministic Modulation Schemes on a Drive Train System With a PMSM Within an Electric Vehicle," *IEEE Trans. Ind. Appl.*, vol. 52, no. 4, pp. 3388-3397, July-Aug. 2016.

[35] C. Sain, P. K. Biswas, P. R. Satpathy, T. S. Babu and H. H. Alhelou, "Self-Controlled PMSM Drive Employed in Light Electric Vehicle-Dynamic Strategy and Performance Optimization," *IEEE Access*, vol. 9, pp. 57967-57975, 2021.

[36] *IEC 61851-25:2020*, International Electrotechnical Commission (IEC) TC69, Ed. 1.0, Switzerland, Dec. 2020. Accessed: Jun. 2023. [Online]. Available: https://webstore.iec.ch/publication/31531

[37] *NCR-18650B: Lithium-ion / NNP + HRL Technology*, Panasonic Energy Company, Hamburg, Germany. Accessed: Jun. 2023. [Online]. Available: https://www.imrbatteries.com/content/panasonic_ncr18650b-2.pdf

[38] *Lithium Ion Cells: A123 14Ah Lithium Iron Nano-phosphate Prismatic Cell*, Altertek, UK. Accessed: Jun. 2023. [Online]. Available: https://www.altertek.com/products/lithium-ion-pouch-cylindrical-cells/a123-li-ion-cells

[39] L. Zheng et al., "SiC-Based 5-kV Universal Modular Soft-Switching Solid-State Transformer (M-S4T) for Medium-Voltage DC Microgrids and Distribution Grids," *IEEE Trans. Power Electron.*, vol. 36, no. 10, pp. 11326-11343, Oct. 2021.

[40] L. Zheng, R. P. Kandula and D. Divan, "Multiport Control With Partial Power Processing in Solid-State Transformer for PV, Storage, and Fast-Charging Electric Vehicle Integration," *IEEE Trans. Power Electron.*, vol. 38, no. 2, pp. 2606-2616, Feb. 2023.

[41] J. Saha, D. Hazarika, N. B. Y. Gorla and S. K. Panda, "Machine-Learning-Aided Optimization Framework for Design of Medium-Voltage Grid-Connected Solid-State Transformers," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 9, no. 6, pp. 6886-6900, Dec. 2021.

[42] J. Saha, N. Kumar and S. K. Panda, "Adaptive Grid-Supportive Control for Solar-Power Integrated Electric-Vehicle Fast Charging Station," *IEEE Trans. Energy Conv.*, 2023.

[43] J. Saha, N. Kumar and S. K. Panda, "A Futuristic Silicon-Carbide (SiC) Based Electric-Vehicle Fast Charging/Discharging (FC/dC) Station," *IEEE J. Emerg. Sel. Top. Power Electron.*, 2022.

[44] J. Lu, L. Zhu, G. Liu and H. Bai, "Device and System-Level Transient Analysis in a Modular Designed Sub-MW EV Fast Charging Station Using Hybrid GaN HEMTs + Si MOSFETs," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 7, no. 1, pp. 143-156, March 2019.

[45] S. Mukherjee, J. M. Ruiz and P. Barbosa, "A High Power Density Wide Range DC–DC Converter for Universal Electric Vehicle Charging," *IEEE Trans. Power Electron.*, vol. 38, no. 2, pp. 1998-2012, Feb. 2023.

[46] Z. Wang, Y. Xu, P. Liu, Y. Zhang and J. He, "Zero-Voltage-Switching Current Source Inverter Fed PMSM Drives With Reduced EMI," *IEEE Trans. Power Electron.*, vol. 36, no. 1, pp. 761-771, Jan. 2021.

[47] X. Ding et al., "Analytical and Experimental Evaluation of SiC-Inverter Nonlinearities for Traction Drives Used in Electric Vehicles," *IEEE Trans. Vehic. Tech.*, vol. 67, no. 1, pp. 146-159, Jan. 2018.

[48] Z. Zeng, X. Zhang, F. Blaabjerg, H. Chen and T. Sun, "Stepwise Design Methodology and Heterogeneous Integration Routine of Air-Cooled SiC Inverter for Electric Vehicle," *IEEE Trans. Power Electron.*, vol. 35, no. 4, pp. 3973-3988, April 2020.

[49] X. Wen, T. Fan, P. Ning and Q. Guo, "Technical approaches towards ultra-high power density SiC inverter in electric vehicle applications," *CES Trans. Elec. Mach. and Syst.*, vol. 1, no. 3, pp. 231-237, Sept. 2017.

[50] K. H. Ming, J. Saha, S. K. Panda and L. A. Poh, "Multi-Objective Design Optimization of SiC-Based Electric Vehicle Drive-train Inverter," *IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, Jaipur, India, 2022, pp. 1-6.

[51] J. Liu, "GaN Semiconductors Driving More Efficient Automotive Traction Inverters [Expert View]," *IEEE Power Electron. Mag.*, vol. 8, no. 4, pp. 48-53, Dec. 2021.

[52] P. Han, P. Liu, Q. Huang, Z. Chen and A. Q. Huang, "A 650 V, 2.1 mohm GaN Half-bridge Power Module for 400V EV Traction Inverter Application," *IEEE Energy Conversion Congress and Exposition (ECCE)*, Detroit, MI, USA, 2022, pp. 1-6.

[53] D. Cittanti, E. Vico, E. Armando and R. Bojoi, "Analysis and Conceptualization of a 400V 100 kVA Full-GaN Double Bridge Inverter for Next-Generation Electric Vehicle Drives," *IEEE Transport. Electrific. Conf. & Expo (ITEC)*, Anaheim, CA, USA, 2022.

[54] Z. Ye, *Tesla Model Y Innovation - Gen-4 Traction Drive Unit Teardown*, Inventchip Technology. Accessed: Jun. 2023. [Online]. Available: www.inventchip.com.cn/uploads/files/20230410/1681093675599128.pdf

[55] *Marelli supplies the inverter for the new BMW CE 04 electric scooter*, Magneti Marelli, Corbetta, Italy, Feb. 2023. Accessed: Jun. 2023. [Online]. Available: https://www.marelli.com/public/uploads/2022/02/Press-Release_Marelli_Inverter-for-BMW_ENG.pdf

[56] *Power electronics insights report*, Advanced Propulsion Centre (APC), Coventry, UK, Feb. 2023. Accessed: Jun. 2023. [Online]. Available: http://www.apcuk.co.uk/wp-content/uploads/2023/02/Power-Electronics-Value-Chain-Insight-report.pdf

[57] *All GaN Vehicle for future*, Nagoya University, Japan. Accessed: Jun. 2023. [Online]. Available: https://www.gan-vehicle.jp/

[58] P. Korta, L. V. Iyer and N. C. Kar, "Soft–Switching EV Traction Inverter Exploiting Full Potential of Wide Bandgap Devices," *IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society*, Singapore, 2020, pp. 4703-4708.

[59] R. Li and D. Xu, "A Zero-Voltage Switching Three-Phase Inverter," *IEEE Trans. Power Electron.*, vol. 29, no. 3, pp. 1200-1210, Mar. 2014.

[60] N. He, M. Chen, J. Wu, N. Zhu and D. Xu, "20-kW Zero-Voltage-Switching SiC-mosfet Grid Inverter With 300 kHz Switching Frequency," *IEEE Trans. Power Electron.*, vol. 34, no. 6, pp. 5175-5190, June 2019.

[61] J. Chen, D. Sha, J. Zhang and X. Liao, "An SiC MOSFET Based Three-Phase ZVS Inverter Employing Variable Switching Frequency Space Vector PWM Control," *IEEE Trans. Power Electron.*, vol. 34, no. 7, pp. 6320-6331, July 2019.

[62] J. Chen, D. Sha and J. Zhang, "Current Ripple Prediction and DPWM-Based Variable Switching Frequency Control for Full ZVS Range Three-Phase Inverter," *IEEE Trans. Ind. Electron.*, vol. 68, no. 2, pp. 1412-1422, Feb. 2021.

[63] M. Haider et al., "Novel ZVS S-TCM Modulation of Three-Phase AC/DC Converters," *IEEE Open J. Power Electron.*, vol. 1, pp. 529-543, 2020.

[64] Q. Huang and A. Q. Huang, "Variable Frequency Average Current Mode Control for ZVS Symmetrical Dual-Buck H-Bridge All-GaN Inverter," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 8, no. 4, pp. 4416-4427, Dec. 2020.

[65] T. Liu, C. Chen, K. Xu, Y. Zhang and Y. Kang, "GaN-Based Megahertz Single-Phase Inverter With a Hybrid TCM Control Method for High Efficiency and High-Power Density," *IEEE Trans. Power Electron.*, vol. 36, no. 6, pp. 6797-6813, June 2021.

[66] *TDK Technical Guide 2021: CeraLink Capacitors*, TDK Electronics AG, Munich R&D, Germany. Accessed: Jun. 2023. [Online]. Available: https://www.tdk-electronics.tdk.com/download/2973492/332617d34954f4b618e1fff654b49dba/ceralink-technical-guide.pdf

[67] S. Chowdhury, E. Gurpinar and B. Ozpineci, "High-Energy Density Capacitors for Electric Vehicle Traction Inverters," *IEEE Transport. Electrific. Conf. & Expo (ITEC)*, Chicago, IL, USA, 2020, pp. 644-650.

[68] S. Chowdhury, E. Gurpinar and B. Ozpineci, "Capacitor Technologies: Characterization, Selection, and Packaging for Next-Generation Power Electronics Applications," *IEEE Trans. Transport. Electrific.*, vol. 8, no. 2, pp. 2710-2720, June 2022.

[69] S. Jones-Jackson, R. Rodriguez, Y. Yang, L. Lopera and A. Emadi, "Overview of Current Thermal Management of Automotive Power Electronics for Traction Purposes and Future Directions," *IEEE Trans. Transport. Electrific.*, vol. 8, no. 2, pp. 2412-2428, June 2022.

[70] K. Ma, J. Lin and Y. Zhu, "Statistical Characterization for Loss Distributions of Power Semiconductor Devices," *IEEE Trans. Power Electron.*, vol. 36, no. 7, pp. 7384-7388, July 2021.

[71] V. Samavatian, H. Iman-Eini, Y. Avenas and M. Samavatian, "Effects of Creep Failure Mechanisms on Thermomechanical Reliability of Solder Joints in Power Semiconductors," *IEEE Trans. Power Electron.*, vol. 35, no. 9, pp. 8956-8964, Sept. 2020.

[72] D. P. U. Tran, S. Lefebvre and Y. Avenas, "Discrete Power Semiconductor Losses Versus Junction Temperature Estimation Based on Thermal Impedance Curves," *IEEE Trans. Compon., Packag. and Manufac. Tech.*, vol. 10, no. 1, pp. 79-87, Jan. 2020.

[73] T. Van Do, J. P. F. Trovão, K. Li and L. Boulon, "Wide-Bandgap Power Semiconductors for Electric Vehicle Systems: Challenges and Trends," *IEEE Vehic. Tech. Mag.*, vol. 16, no. 4, pp. 89-98, Dec. 2021.

[74] A. Ranjbar, "Applications of Wide Bandgap (WBG) Devices in the Transportation Sector," in *Transportation Electrification: Breakthroughs in Electrified Vehicles, Aircraft, Rolling Stock, and Watercraft*, IEEE, 2023, pp.47-72.

[75] S.S. Murshed, C.N. De Castro, "A critical review of traditional and emerging techniques and fluids for electronics cooling" *Renew. and Sust. Ener. Rev.*, vol. 78, pp. 821-833, Oct. 2017.

[76] L. Lopera, R. Romina, Y. Mostafa, E. Mo, and E. Ali, "Current and potential applications of additive manufacturing for power electronics," *IEEE Open J. Power Electron.*, vol. 2, pp. 33–42, 2021.

[77] C. B. Saner, J. Saha and D. Srinivasan, "A Charge Curve and Battery Management System Aware Optimal Charging Scheduling Framework for Electric Vehicle Fast Charging Stations with Heterogeneous Customer Mix," *IEEE Trans. Intel. Transport. Syst.*, 2023.