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Thermal analysis of Si-IGBT based power electronic modules in 50kW traction inverter application

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ABSTRACT

Estimation of accurate IGBT junction temperature is crucial for reliability assessment. The well-known RC lumped approach can help predict junction temperature. However, this method suffers from inaccuracy while characterizing the thermal behaviour of several IGBT modules mounted to the liquid-cooled heatsink. Specifically, the thermal challenge originates from the thermal cross-coupling and module-to-module heat spreading and the converter cooling condition. This article demonstrates a methodology to study the impact of heat spreading, thermal interface material, and massive size liquid cold-plate on the overall thermal behaviour. A case study of 50 kW traction inverter is chosen to demonstrate the benefit of early assessment of electro-thermal simulation before making costly prototype design. Power loss is initially estimated using an analytical loss model and later the estimated power loss is used in FEA (Finite Element Analysis) thermal model. This paper also compares the performance of single-phase and two-phase liquid cooling and various thermal interface materials (TIM) to determine which type of cooling system and TIM is most suitable for real applications. Simulation results suggest that combination of two-phase liquid cooling and TIM can improve the thermal performance and reduce junction temperature by 4.5%, 4.2%, 4.6% for the traction power load 30 kW, 40 kW, and 50 kW, respectively. The proposed methodology can be used as useful reference guidance for thermal design and modelling of IGBT based power converter applications.

1. Introduction

IGBT (insulated gate bipolar transistor) based power module is still relevant in traction applications mainly due to its ability to handle high current/voltage and high power [1–3]. There is a promise of emerging wideband gap devices such as SiC/GaN in various converter applications. However, packaging challenges and manufacturing costs are key barriers to the mass penetration of SiC power module. In addition, the reliability of SiC-based power module is still under question to replace mature Si IGBT-based power modules, particularly in high power applications. The attractive solution for meeting the design requirement of high current is multi-die integration at the packaging level [4–6]. Miniaturization of chips has been an overwhelming trend due to the advancement of semiconductor technologies. Thus, reaching high power density with these reduced die sizes in power modules appears as a thermal challenge from the design point of view. Heat generation is evident due to device on-resistance and switching characteristics. A significant amount of heat is generated due to handling high currents in the IGBT module. The critical concern is tackling such high heat load within the small active area of the IGBT chip. Thus, high power density and associated thermal issues are now compounded into electro-thermal problems. To be more specific, electrical design aims for decreased

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packaging parasitics to avoid unwanted voltage or current overshoot. Thermal design, on the other hand, aims to achieve a low thermal resistance package while also reducing the coefficient of thermal expansion (CTE) mismatch between IGBT module constituent materials. Thermal stress caused by power losses reduces the lifetime of IGBT modules and speeds up their failure rate. Several IGBT module failures due to thermo-mechanical stress have been reported in the literature [7–9].The lifetime of IGBT module is mainly determined from its operating junction temperature. The mathematical lifetime model of IGBT module is described in [10–13] . Therefore, the thermal behaviour is of significant interest to enhancing the performance and lifetime of the power semiconductor module. This issue needs to be carefully addressed in the early design stage. A well-designed high-fidelity simulation can ensure the electrical and thermal design where electro-thermal interaction is present and if left untreated, can potentially lead to the severe failure of the power module. The simulation-driven traction inverter design can reduce the cost and time associated with the cumbersome hardware-driven design, testing and redesign. The early simulation can inform the designer about the overall temperature distribution of traction inverter since real test hardware set up is costly and problematic, particularly embedding thermocouple in critical locations where temperature identification is measurement challenge. This paper presents the simulation-driven development process of a Si IGBT power module-based traction inverter exploiting the commercial finite element method (FEM).

High power density traction inverter requires a new approach to cope with the stringent reliability requirements. The junction temperature of Si IGBT must be kept below 125 °C to avoid temperature induced failures. To maintain a safe junction temperature, serious attention needs to be paid in achieving high cooling performance because it not only deals with the high thermal load but also determines the size and weight of the converter. However, strong literature is not available where an entire traction inverter has been developed following thermal modelling of Si IGBT power module with liquid-cooled heatsink structure. This could suggest that the simulation process of power module in high-power converter application with liquid-cooled heatsink structure is cumbersome or the impact of thermal crosstalk and heat spreading effect in the chip beneath area has been either neglected or oversimplified. Second, very few literatures have thoroughly investigated the Si-based IGBT power module thermal performance in high power density traction inverter application.

Several approaches can perform electro-thermal analysis. Classical electrothermal models [14–16] use thermal equivalent RC type network, and usually RC type network can be synthesized from the module manufacturer datasheets. However, sometimes, these models are oversimplified and non-reflective in the physical representation of module layout, what is worse, these can even be physically meaningless, and non-relatable with the multi-die heat source, baseplate size, and thermal spreading in module to module and integrated cooling system.

Analytical models are often used to derive the compact thermal model. These exploit various mathematical treatment. One popular approach is a separation of variables [17], and other is Fourier series solution [18–20]. Another method is based on Green's function to solve heat equation [21]. It is relatively computationally less costly than the numerical or experimental measurement-driven approach and is quite useful for design optimization. However, the analytical model is not straightforward due to complexity arising from various influence factors such as module geometric layout, cooling system and chip to chip thermal coupling, and module to module heat spreading. Numerical methods like finite element method (FEM) [22–26], and finite difference method (FDM) [27–29] are drawing attention for the simulation and thermal analysis of complex geometries of module layout. The promise of FEA driven design is exploitable in identifying hot spot, temperature distribution within module mounted to liquid cooled heatsink. The use of multi-layered multi-die in a compact structure makes thermal design of IGBT power modules a particular concern in high-power density converter applications, and the trend toward more chip integration and paralleling the module to meet increasing current density drives the adoption of detailed thermal analysis. However, evaluating a packaged module's thermal design with a hardware test setup is costly and time consuming, and there are sometimes measurement challenges in predicting temperature at critical locations such as chip solder and baseplate solder, where thermal stress induced solder failures are common due to extreme loading.

There have been several recent research reported on electro-thermal modelling of traction inverter and some of them have also addressed the modelling techniques. In [30], an electro-thermal modelling methodology was established to derive thermal coupling resistance at junction-to-case level in multichip power modules. However, the method did not address the thermal coupling from case-to-ambient if the heatsink is integrated to the power modules. In [31], a methodology was established for modelling a single half-bridge power module, which was adaptable to operating conditions. In [32], double sided cooling was implemented for a single inverter leg only considering a SiC based power module. However, none of the existing methods has comprehensively considered the entire thermal coupling of three half-bridge power module integrated on the liquid heatsink.

In [33], an experiment driven thermal model was established for a high power density 100 kW SiC traction inverter and evaluated for 105 °C ambient temperature operation. Another study regarding liquid cooled heatsink using water/ethylene glycol/oil was presented for traction inverter [34]. Chip level electrothermal stress calculation method for half-bridge IGBT power module was demonstrated in [35]. However, ignoring thermal coupling effects from other power module might result in under estimation of junction temperature in IGBT power module. An efficient thermal model is required to improve the lifetime of the power module. In [36], a detailed step by step strategy has been outlined to reduce the temperature swing across the power module while guaranteeing the stability of the converter operation. A very high-power density 150 kW T-type traction inverter was studied using non-metallic impingement cooler and integrated to the direct baseplate. However, this urges for not only advanced machining tools to produce non-metallic impingement cooler but also requires a dedicated mechanical process which can add cost and time.

Another study is found in [37] regarding electro-thermal model application for estimating junction temperature for an asymmetric half-bridge converter of a switched reluctance motor drive system. This work considered different power losses in devices with same phase bridge. Another extended study of improved power loss model in electro-thermal modelling method application is found in [38]. This work considered electro-magnetic physics which accounted for device parasitic (collector, emitter, gate) and power module external terminals. The improved parasitic extraction offered exact current sharing which was critical for estimating an accurate power loss. However, this study only considered half-bridge module and neglected the thermal coupling influence from other power module and the heatsink. In [39], a new hybrid IGBT power modules combining both Si and SiC was demonstrated for traction application. This work also elaborately described the thermal modelling technique. However, the study has been restricted to half-bridge power module.

A technology of fibre optic sensor-based temperature measurement is demonstrated for power modules in [40]. However, the studied converter used AC and DC power cyclic testing on the specific device and only estimated the junction temperature swing. The technique seems difficult to be embedded in other critical locations such as chip solder and thus poses challenges to gain its wide acceptability in converter thermal analysis. In [41], component level reliability assessment in real field operation was carried out for SiC based 20 kW inverter by considering the electro-thermal model. However, the electro-thermal model used in this work was simplistic and derived based on fixed boundary temperature conditions and did not consider the heatsink. Only device to device thermal coupling might not be sufficient enough to capture the electro-thermal interactions happening in critical locations such as chip solder and baseplate solder.

In [42], a better refined lumped thermal model was applied to evaluate the solder degradation in real time for single half-bridge Si-IGBT based inverter topology. However, the work did not demonstrate the thermal interaction between other chips and ignore the influence of lateral heat transfer coming from other devices. Another thermal model based on thermal coupling between different dies of SiC were demonstrated and experimentally evaluated in [43]. However, this thermal model focused on only junction temperature estimation and considered the heatsink at a constant temperature of 60 °C but did not show any detail thermal interaction at the critical layers of power modules due to different loading dynamics, ambient temperature dynamics, flow rate variation and thermal interface material impact etc.

The benefits of lumped RC circuit thermal network extracted from 3D FEA thermal simulation is challenging to be realistically implemented in real field converter operation such as condition monitoring (tracing solder degradation) of Si IGBT/ SiC MOSFET based power module. There is a serious need for fast and easily implementable thermal model. A computationally fast 2D average thermal model is proposed in [44]. However, several factors limit this method such as neglecting thermal coupling in critical layers and module-to-module thermal coupling and the impact of TIM and integrated heat sink. Thermal imbalance between paralleling chips in single power module was studied and evaluated experimentally for the traction inverter in [45]. This work used separate heating and sensing the temperature on the other chips in parallel however, neglected other power module and loading conditions and heatsink operating conditions such as flow rate variation and Thermal Interface Material (TIM) which might impact the overall accuracy of the proposed thermal model accuracy.

From the presented literature review, it is quite evident that none of the above-mentioned methods have considered whole inverter structure (thermal influence from three half-bridge power module), TIM layer, cooling system. In order to address the challenges of the prior works, this article presents a physics-based novel computer simulation that is tailored to the heat dissipation structure of Si IGBT power modules in an entire traction inverter application.

In this paper, the thermal simulation is investigated extensively for the Si based IGBT power module in traction application. Additionally, this paper presents a detailed methodology to build up a thermal model for the Si IGBT module that considers thermal coupling, thermal spreading, thermal interface material, and cooling system. The main aim of this study is to investigate the detailed thermal design of Si-based IGBT power semiconductor module in the high-power traction converter application. FEA is used to investigate the thermal crosstalk module to module, heat spreading in chip beneath layers and the impact of the cooling system. In terms of the novelty, this article has made the following contributions compared with the previous works [33-34, 38-39,45].

1) Research scenario: The research extends to simulation of single half-bridge power module to three half-bridge power modules, thus taking into account the effect of thermal interaction and realistic cooling system (TIM layer + heatsink)
2) Improvement: Compared to the previous research [33-34,38-39,45], an improved technique for junction temperature prediction with better accuracy and reduced junction temperature has been proposed by considering more accurate representation of inverter physical structure in FEA simulation.
3) Capturing modelling challenges: A modelling and simulation method has been developed to evaluate the thermal behaviour based on an accurate physical structure of the IGBT module, and demonstrated a design example of 50 kW traction inverter by taking into account of thermal behaviour influencing factors such as, thermal cross-coupling and module-to-module heat spreading and the converter cooling condition etc.
4) Applicability: A capability for conducting virtual thermal analysis of the whole traction inverter instead of building the hardware prototype has been developed to realise traction inverter and conducting experimental measurement to obtain junction temperature of the IGBT modules.

To illustrate the modelling method, firstly, the geometric structure of the stacked Si IGBT power module package is built in Solidworks, and secondly, the material properties are applied in FEA simulation, all the power dissipating sources are identified and the thermally critical components in the module are modelled exploiting COMSOL Multiphysics. Detailed analysis is shown to reduce the localised hot spot and junction temperature in the traction inverter with the suitable TIM and liquid cooling combination.

This paper is organized in such a way that Section 2 describes the model development, Section 3 deals with the simulation results and analysis, Section 4 deals with discussion and finally, conclusions are presented in Section 5.

2. Thermal modelling

This section describes the underlying theory and assumptions for FEA thermal model of traction inverter using COMSOL Multiphysics. This section elaborates on the IGBT module structure, material properties, traction inverter parameters, power loss estimation approach, construction of FEA thermal model and steady-state thermal analysis.

2.1. IGBT module description

The power converter considered in this study is a traction inverter with a power rating of 50 kW, rated DC-link voltage of 800 V, an output current of 70A, and a power factor 0.85. Fig. 1 describes the typical IGBT module-based traction inverter, which consists of 240 V battery pack, DC-link and inverter. Table 1 summarizes the traction converter parameter. The inverter is operated at the standard pulse width modulation (PWM) technique which uses 20 kHz switching frequency. The inverter uses three half-bridge power electronic switch from the Semikron manufactured SKM75GB123D. The voltage and current rating of this Si IGBT module is 1200 V/75A and the overall dimension is 34mm*94mm*30.5 mm. Three half-bridge modules are integrated to realize the inverter drive and mounted on liquid cold plate. The inverter has total six IGBT switches and six antiparallel diodes. The geometric structure of the inverter mounted on liquid cold plate is shown in Fig. 2 (a). The internal structure of IGBT stack layer is illustrated in Fig. 2(b). FEA thermal model set up is illustrated in Fig. 2(c). Table 2 lists the material properties of the IGBT power module as well as the geometric structure details. Each half-bridge module's internal structure is made up of two IGBT chips and two antiparallel diodes. Chips are soldered to direct bonded copper (DBC) substrates, which are then soldered to a copper baseplate. The thermal grease layer connects the copper baseplate to the liquid cold plate.

Multidomain physics are dominant in stacked Si IGBT power module. This paper focuses on investigating the temperature distribution across the package integrated with liquid-cooled heatsink. Temperature is the key parameter in design simulation because its impact is significant on electrical and mechanical characteristics at the module level. The important figure of merit in thermal analysis is junction temperature, which helps determine the device's reliability. To initiate the detailed thermal analysis, power loss estimation is starting step. The power loss estimation can be performed based on power loss model.

2.2. Power loss model

In thermal analysis, power loss is the most important input. Conduction loss and switching loss are the two types of power loss in Si chips, and they can be estimated using either experimental measure-

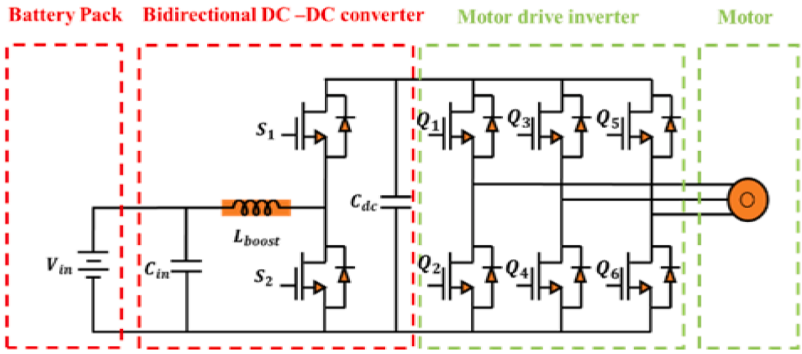

Fig. 1. Typical IGBT module based traction motor inverter.

Table 1
Parameters of traction inverter shown in Fig. 1.

Converter Parameter	Value
Rated Traction Inverter Power P_{out}	50kW
Output Power factor $p.f$	0.85
DC bus voltage V_{DC}	800 VDC
Rated load current I_{load}	70A
Fundamental frequency f	50 Hz
Switching frequency f_{sw}	20kHz
IGBT Module	1200 V/75A

ment or datasheet-driven loss parameters. Because the main goal of this work is to conduct early-stage thermal analysis rather than the development of an accurate loss model, power dissipation can be calculated using the datasheet in this paper.The total average power in Si IGBT devices can be determined by using (1) and (3) [46]. Similarly, power losses in Diode can be estimated by using (2) and (4). The conduction loss of the Si chip mostly relies on the drain current, power factor, etc. The switching loss can be estimated simply by multiplying the switching frequency by the turn-on and turn-off energy.

$$P_{cond,I} = \left(\frac{1}{2\pi}+\frac{m*pf}{3\pi}\right)*V_{CE,I}*I_{load}+\left(\frac{1}{8}+\frac{m*pf}{3\pi}\right)*R_{dson,I}*I_{load}^{2} \quad (1)$$

$$P_{cond,D} = \left(\frac{1}{2\pi}-\frac{m*pf}{3\pi}\right)*V_{CE,D}*I_{load}+\left(\frac{1}{8}-\frac{m*pf}{3\pi}\right)*R_{dson,D}*I_{load}^{2} \quad (2)$$

$$P_{sw,I} = \left(E_{on,I}+E_{off,I}\right)*f_{sw} \quad (3)$$

$$P_{sw,D} = E_{on,D}*f_{sw} \quad (4)$$

where $P_{cond,I}$, $P_{cond,D}$ denote the IGBT and Diode conduction losses respectively, pf denotes the power factor, $V_{CE,I}$, $V_{CE,D}$ denote the IGBT and Diode collector-emitter saturation voltage drop, respectively, $R_{dson,I}$, $R_{dson,D}$ denote the on-resistance of IGBT and Diode, respectively. I_{load}, f_{sw}

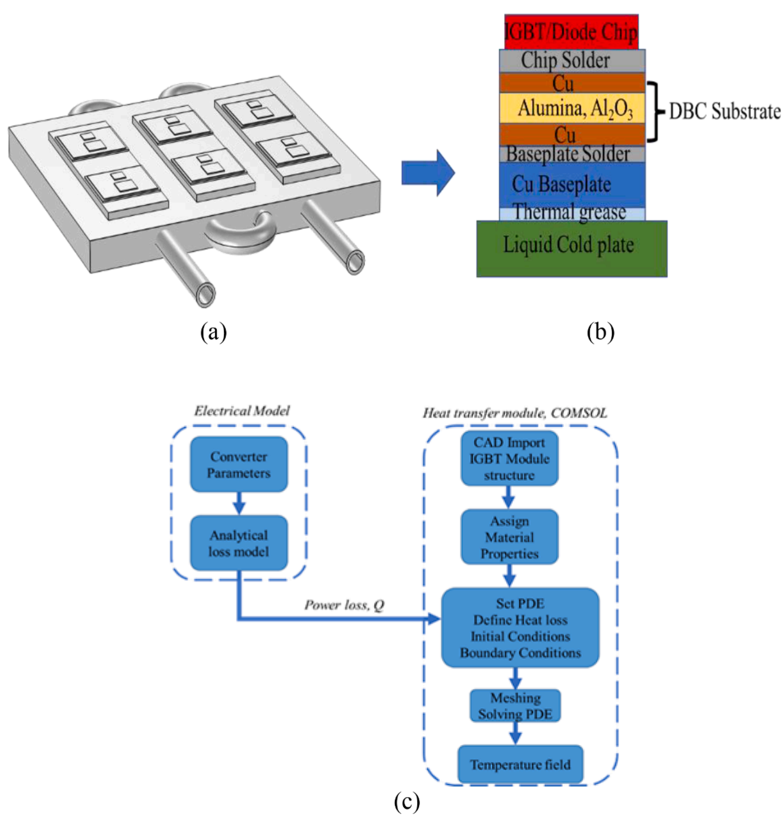

Fig. 2. FEA CAD Structure of (a) IGBT Module based traction Inverter mounted on Liquid Cold plate (b) Structure details of IGBT module material layer (c) FEA Thermal Model set up.

Table 2
Dimensions and constituent material properties of power module.

Component layer	Material	Dimension (L(mm)*W(mm)*H(mm))	Density ρ (kg.m^{-3})	Specific heat capacity c_p(J.kg^{-1}.K^{-1})	Thermal Conductivity k (W.m^{-1}.K^{-1})
IGBT Chip	Si	9 × 9*0.4	2329	700	130
FRD Chip	Si	6 × 6*0.4	2329	700	130
Chip Solder	60Sn-40Pb	9 × 9*0.053 6 × 6*0.053	9000	150	50
DBC Substrate	Cu	28×25×0.35	8700	385	400
	Al_2O_3	30×27×0.636	3900	900	27
	Cu	28×25×0.35	8700	385	400
Substrate Solder	60Sn-40Pb	28×25×0.103	9000	150	50
Baseplate	Cu	91×31×3	8700	385	400
Thermal grease	Thermal Grease (Shinetsu X-23–7762-S)	91×31×0.1	1180	1044	2.5
Heatsink	Al	305×127×17.4	2700	900	201

denote the operating load current and switching frequency of the inverter.

$P_{sw,I}$, $P_{sw,D}$ denote the IGBT and Diode switching losses respectively, $E_{on,I}$, $E_{off,I}$ denote the IGBT turn-on and turn-off energy, respectively. $E_{on,D}$ denotes the diode turn-off energy.

Junction temperature is one of the key parameters that influences the electrical characteristics of the device. The device's on-resistance and switching energy are affected by the device's operating temperature while converter in loading condition. Table 3 summarizes the power losses of traction inverter at the various operating load.

2.3. FEA thermal model

FEA heat transfer module is introduced to investigate the thermal behaviour in multichip IGBT power module. The obtained power losses are the input to the FEA thermal model. The following governing equation used in [47–50] can be formulated to model the heat transfer problem in IGBT power modules.

$$k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+Q=\rho c_p\frac{\partial T}{\partial t} \tag{5}$$

Where, for IGBT power module, c_p is the material-specific heat capacity, ρ is the density, k is the thermal conductivity, T is the operating temperature, which is a function of space and time and Q is the heat generation rate.

Additionally, a convective boundary condition is applied at the bottom of the liquid cold plate. Newton's law of cooling suggests that the amount of heat dissipated due to the movement of a fluid (such as air, water/glycol) can be found using Eq. (6).

$$Q=hA\left(T_S-T_f\right) \tag{6}$$

Where h is convective heat transfer coefficient, A is the surface area convection takes place, T_S is the surface temperature and T_f is the bulk fluid temperature away from the surface.

Heat transfers from the chip to the liquid cooling system, which includes heat spreading through various material layers in the packaged Si Module, are considered adiabatic from all sides except the bottom side, where the liquid-cooled heatsink is mounted in this study in order to have a good thermal approximation. In this work, IGBT and diode act as heat source, DBC substrate and Cu Baseplate work as heat spreaders, TIM provides the solid connection between the IGBT module and liquid cooling system where pipe describes fluid flow path. To remove the heat from the baseplate, coolant is usually pumped through the pipe at a set rate. The combined effect of heat transfer in solids and fluids is used to dissipate heat. This problem can be solved using conjugate heat transfer. This necessitates massive computational resources. This study has simplified cooling system by employing an effective heat transfer coefficient.

Table 3
Power Losses of Traction Inverter @ Various Power Load.

Rated Converter Power	Total loss per IGBT switch	Total loss per Diode	Total loss of the Inverter (Six IGBT+ Six Switch)
30kW	131.24W	26.03W	943.67W
40kW	145.06W	28.55W	1041W
50kW	161.25W	31.43W	1156W

2.4. Mesh sensitivity study

In COMSOL, a thermal model is created based on the structure of the IGBT module shown in Fig. 2(a). The proposed thermal model makes use of a half-bridge IGBT power module with two IGBT switches and two diodes. The entire traction inverter is modelled using three half-bridge power modules, with the cooling system modelled using a liquid cold plate embedded in the IGBT power modules via a thermal grease layer. Initially a 3-D geometry model representing IGBT power module mounted on liquid cold plate is built in Solid works, and later FEA thermal analysis is conducted by COMSOL. To investigate the mesh sensitivity, nine different meshes have been used. These include extremely coarse, extra coarse, coarser, normal, fine, finer, extra fine, and extremely fine. The predicted temperature with different element size is compared in Fig. 3. As seen in Fig. 3, the temperature is almost same for every case, and it is nearly 104 °C at every element size. It can be pointed that mesh size does not affect the temperature distribution. For numerical simplicity, we have applied coarse mesh in the baseplate and cold plate in this study whereas fine mesh is applied in thin layers of IGBT module such as chips, solder layers, and DBC.

2.5. Steady-state thermal analysis

Thermal simulations in the FEM environment were used to better

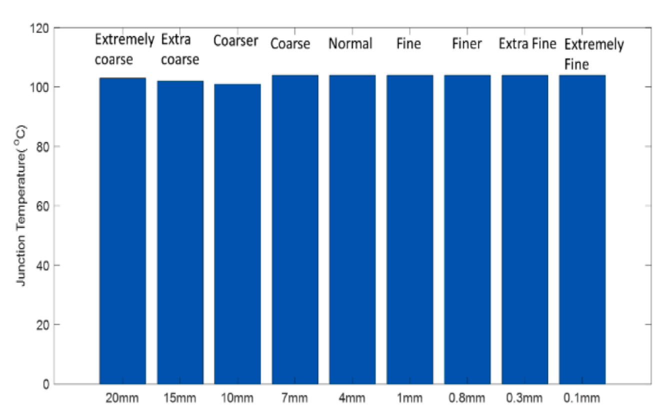

Fig. 3. Predicted junction temperature for the various mesh.

understand the cooling capability. COMSOL is used to create the FEA thermal model. The built thermal model takes advantage of the constant power loss across each Si IGBT switch and diode, which is calculated using the analytical loss model in Eqs. (1)-(4). The power losses are estimated for the traction inverter operating at a power rating of 30 kW, 40 kW and 50 kW. The operating condition of traction inverter is emulated with 70A rms load current, 800-V dc-link voltage and switching frequency of 20 kHz. The power losses of IGBT are estimated as 131.24 W, 145.06 W, 161.25 W for power load of 30 kW,40 kW and 50 kW, respectively. Similarly, the power losses for diode are 26.03 W, 28.55 W, 31.43 W for power load of 30 kW,40 kW and 50 kW respectively. Two case studies are set by changing the liquid cooling system configuration. First case exploits a single-phase cooling system, and the second case exploits a two-phase liquid cooling system. A series of simulations are performed by changing the flow velocity of coolant. For problem simplification and avoiding huge computational load, CFD has not been employed in this work. A complete thermal treatment has been applied to the model.

In order to establish accurate numerical thermal model, estimation of equivalent heat transfer coefficient (htc) is necessary. Based on the previous study [51], an equivalent heat transfer coefficient can be estimated for both single-phase and two-phase liquid cold plate cooling.

From the following expression, dimensionless Nusselt number can be calculated as

$$Nu = 0.023\, Re^{0.8} Pr^{0.4} \tag{7}$$

Where Re is Reynold Number and Pr is Prandtl Number. The equivalent heat transfer coefficient can be estimated as

$$htc = \frac{Nu * k}{D_h} \tag{8}$$

Where Nu is the Nusselt number, k is the thermal conductivity of the cooling liquid, D_h is the hydraulic diameter

In order to calculate the heat transfer coefficient, the fluid flow rate, tube diameter, and fluid thermo-physical properties were taken into account. The cold plate has a base size of 196mm×196mm×10 mm. Two types of working fluid are considered in this study: Water/Glycol (50/50) and R-134a Refrigerant. The material properties of coolant are given in Table 4. To achieve thermal solution, a convective boundary condition is set to all along the walls of the inner tubes of the cold plate and inlet fluid temperature is set to 20 °C.

This section discusses the steady-state thermal analysis in the FEM environment. The steady-state thermal analysis results for a traction load profile of 30 kW and 50 kW (considering single-phase cooling) are presented in Figs. 4 and 5. When the fluid velocity is 8 L/min, the junction temperature is at its highest. At a fluid velocity of 18 L/min, the lowest junction temperature is observed. The steady-state temperature distribution for two-phase cooling, on the other hand, shows that a temperature reduction of the same magnitude can be achieved at 8 L/min. The steady-state thermal analysis results for two phase cooling are presented in Fig. 6. The reduction of junction temperature differs in all cases due to the high heat convective coefficient resulting from two-phase flow. It can be concluded that increasing flow rate for two-phase flow does not show significant temperature reduction compared to single phase cooling.

Table 4
Material properties of coolants.

Material	Water/Glycol (50/50) [52]	R-134a Refrigerant [53]
Density (kg/m^3)	1069	1234
Specific heat capacity (J/kg/k)	3323	1153.8
Thermal conductivity (W/m/k)	0.3892	0.08
Kinematic viscosity (m^2/s)	2.58e-6	1.2e-7

3. Results and analysis

This section analyses the results obtained in the FEA simulations using two different cooling techniques: single-phase cooling (which employs water/glycol as coolant), and two-phase cooling (which employs R-134a as the coolant). Additionally, it discusses the effect of TIM on temperature distribution.

3.1. Effect of liquid cold plate

One of the main goals of the thermal analysis is to keep the temperature of the IGBT junction below the safe thermal limit. To investigate the effect of a liquid cold plate on temperature distribution, the effective heat transfer coefficient for single-phase cooling was varied from 4381 to 8381 $Wm^{-2}K^{-1}$. To emulate the two-phase cooling, an effective heat transfer coefficient is varied from 9145 to 14,638 $Wm^{-2}K^{-1}$. The inlet fluid flow rate is swept from 8 to 18 L/min. The predicted junction temperature of IGBT is enlisted in Tables 5 and 6 for single phase and double phase liquid cooling respectively. Figs. 7 and 8 illustrate the steady-state thermal analysis results of inverter (mounted on both single-phase and two-phase liquid cold plate system) considering the various flow rate. For single phase cooling, junction temperature reduction is noticeable. It is clear from the computed results for single phase cooling that temperature reduction of 14 °C, 15 °C, 17 °C is achievable at the highest inlet velocity of 18 L/min comparing to the results obtained at fluid velocity of 8 L/min. The computed result shown in Table 6 clearly indicates that employing a high heat transfer coefficient derived at the inlet velocity of 18 L/min reduce the junction temperature by 7 °C, 8 °C, 9 °C for the traction inverter load of 30 kW, 40 kW and 50 kW respectively. It is worth to note that an increase of heat transfer coefficient above 6059 $Wm^{-2}K^{-1}$ has not significant impact on junction temperature reduction. As a result, it can be concluded that single phase cooling is still sufficient for junction temperature reduction in the studied IGBT power module cooling, but double phase cooling can achieve a higher heat transfer coefficient at low flow rate. For single phase cooling, a high flow rate is required to achieve a high heat transfer coefficient, which was found to be nearly 18 L/min in this study. Overall heat transfer coefficient 9145 $Wm^{-2}K^{-1}$ can be achieved at the flow rate of 8L/min for two-phase cooling. Ultimately IGBT module thermal resistance is the dominant factor in cooling perspective. Thus, choice of IGBT module (low R_{thjC} IGBT module from electronic package) is an important factor in thermal analysis of traction inverter.

The better cooling performance obtained by the proposed method can be justified by exploring the similar work of [54]. Itxaso et al. developed a two-phase liquid cold plate prototype and conducted a comparison study with the single-phase cooling technology from an experimental and numerical perspective. The experimental study specifically points out that the leverage of two-phase cooling over single phase cooling is significant. This highlights the benefit of two-phase cooling in improving the performance and reliability of traction power converter without making massive changes in cold plate configuration.

3.2. Effect of TIM

As part of thermal management, a liquid cold plate is an important component of traction drive. The thermal interface material (TIM) is used to connect the IGBT module to a liquid cold plate via a via material. As a result, the conductivity of TIM is critical in thermal analysis. A series of simulations were conducted and presented to better understand the effect of TIM on junction temperature. All simulation cases are performed with varying TIM. The thermal conductivities of TIM, k_{TIM} are considered 2.5, 4.4, and 13 $W.m^{-1}.K^{-1}$ respectively. The material properties of TIMs are shown in Table 7. The computed junction

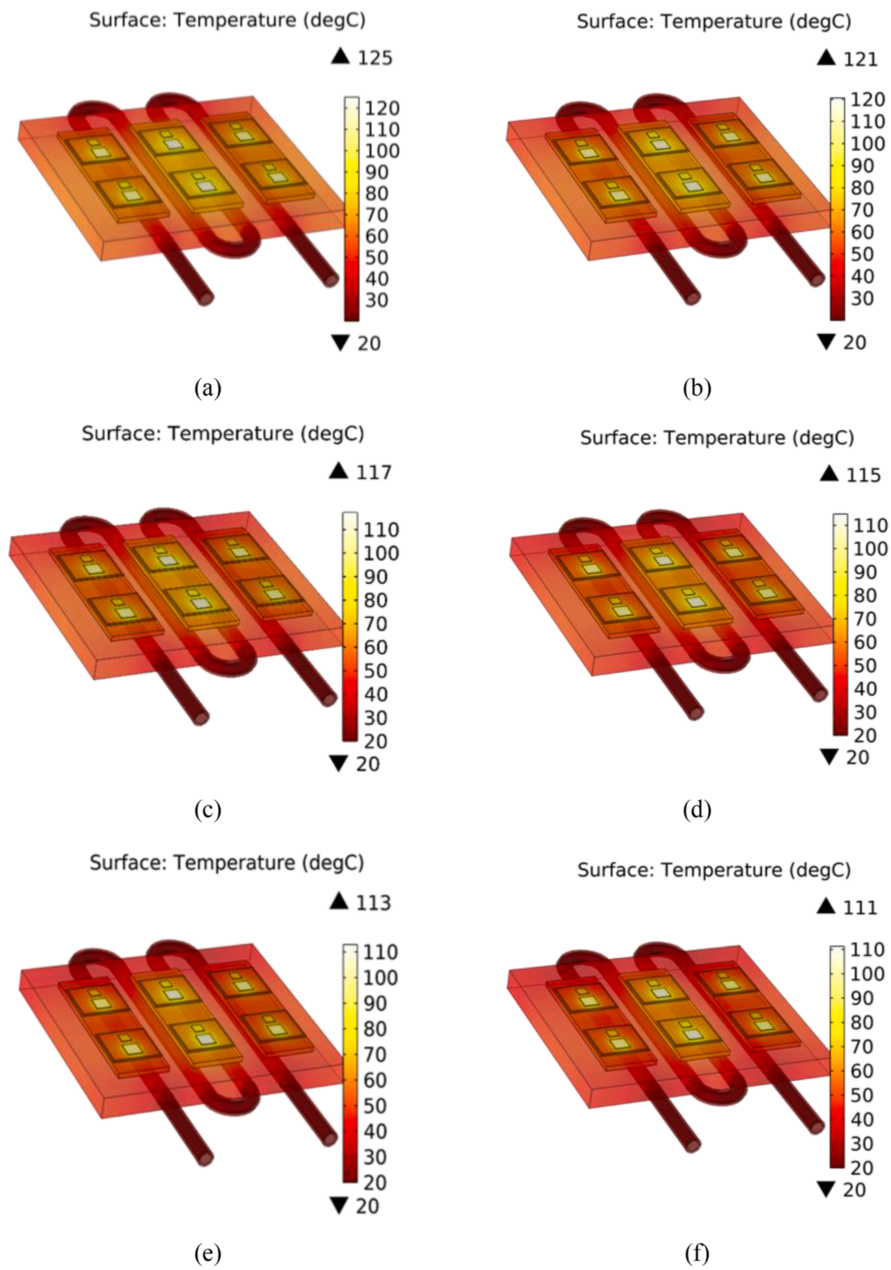

Fig. 4. Steady-state thermal analysis results for Inverter (mounted on single phase liquid cold plate) operating at 30 kW load for various flow rate of (a) 8 L/min (b) 10 L/min (c) 12 L/min (d) 14 L/min (e) 16 L/min and (f) 18 L/min, respectively.

temperature is enlisted in Table 8. Fig. 9 shows the predicted junction temperature for the varying TIM under the variable power load of 30 kW, 40 kW and 50 kW, respectively.

An increase of high thermal conductivity TIM can only reduce the Si average temperature by 5 °C, 5 °C and 6 °C for the converter load of 30 kW, 40 kW, and 50 kW respectively. This means the use of appropriate TIM of high thermal conductivity can reduce junction temperature by 4.5%, 4.2%, 4.6% for the traction load of 30 kW, 40 kW, and 50 kW, respectively. Computed results clearly show that junction temperature can be reduced by employing high thermal conductivity TIM. It is worth pointing that the low thermal conductivity TIM can raise the junction temperature, which can be detrimental for IGBT health and thus reduce the reliability of the IGBT.

3.3. Effect of loading condition

A simulation study is established to further justify the use of two-phase liquid cooling solution. Two case study is set up. First case considers loss profile of dynamic load, and second case considers loss profile of complex mission profile. The test IGBT module is cooled by both single-phase and two-phase coolant. Power loss profiles for dynamic load condition and complex mission profile are shown in Figs. 10 and 11 respectively. Temperature reduction can be achieved up to 13.25 °C for IGBT by two phase liquid cooling compared to single phase liquid cooling.

To examine the performance of the proposed two-phase cooling solution, the results obtained from the FEA method are compared in Figs. 11 and 12 under the dynamic load and complex mission profile. Temperature reduction can be achieved up to 6.1 °C for IGBT by two phase liquid cooling compared to single phase liquid cooling. These results clearly demonstrate that the two-phase coolant shows superior performance than the single-phase coolant. As shown in Figs. 11 and 12, the temperature estimated from the two-phase coolant is lower than that of single-phase coolant.

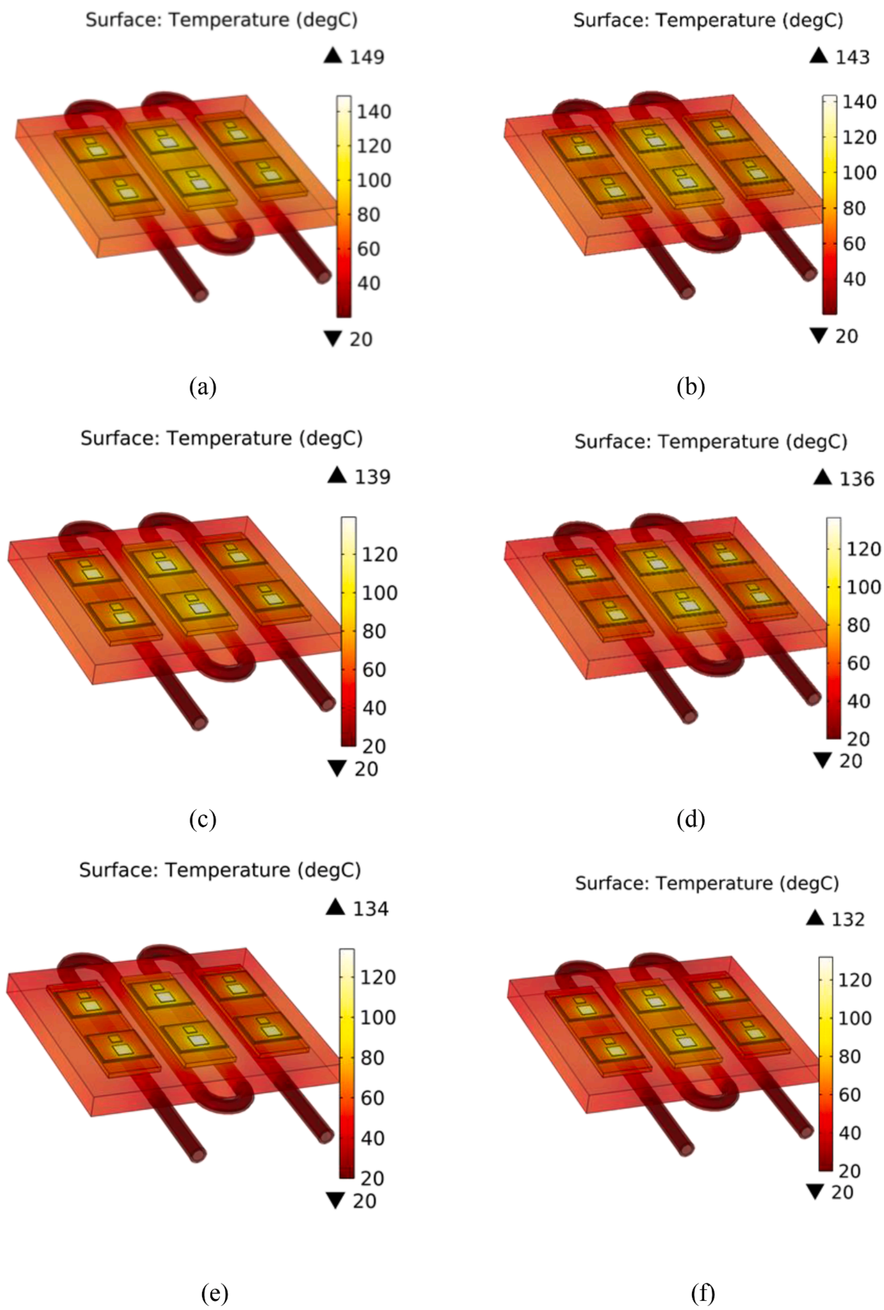

Fig. 5. Steady-state thermal analysis results for Inverter (mounted on single phase liquid cold plate) operating at 50 kW load for various flow rate of (a) 8 L/min (b) 10 L/min (c) 12 L/min (d) 14 L/min (e) 16 L/min and (f) 18 L/min, respectively.

4. Discussion

It is worthwhile to note that stringent thermal requirements are needed to meet while designing high power traction inverter. Since the most failures in power modules are temperature driven, it is highly recommended to keep the junction temperature within a safe operating envelope (for Si-IGBT power module the thermal limit is typically 150 °C while for SiC MOSFET based power module the thermal limit is 175 °C). The ideal approach is to predict the junction temperature before hardware prototyping of the converter. If the thermal requirement is needed to be changed, it is much easier to conduct the simulation at the early design cycle. Table 9 presents a summary of the estimated junction temperatures by the electrothermal loading studied in recent literatures [33,34,38-39,45]. This work deals with the total three-phase inverter power of 50 kW. Compared with the other studies, the proposed thermal model also predicted similar results but provided reduced junction temperature, which shows the accuracy of the proposed method.

5. Conclusion

This article presents a systematic approach to study, analyse, and characterize the thermal design for Si IGBT power module-based traction inverter. The detailed thermal design for a 50 kW Si IGBT-based inverter with an overall junction temperature less than 125 °C is presented to illustrate the FEA thermal model considering the cooling system. Variable heat transfer coefficients and various TIMs were investigated using FEA thermal design. The proposed method can be used to estimate the temperature distribution across the traction inverter and predict the junction temperature. The overall simulation results for the single-phase and two-phase liquid cooling systems show that when

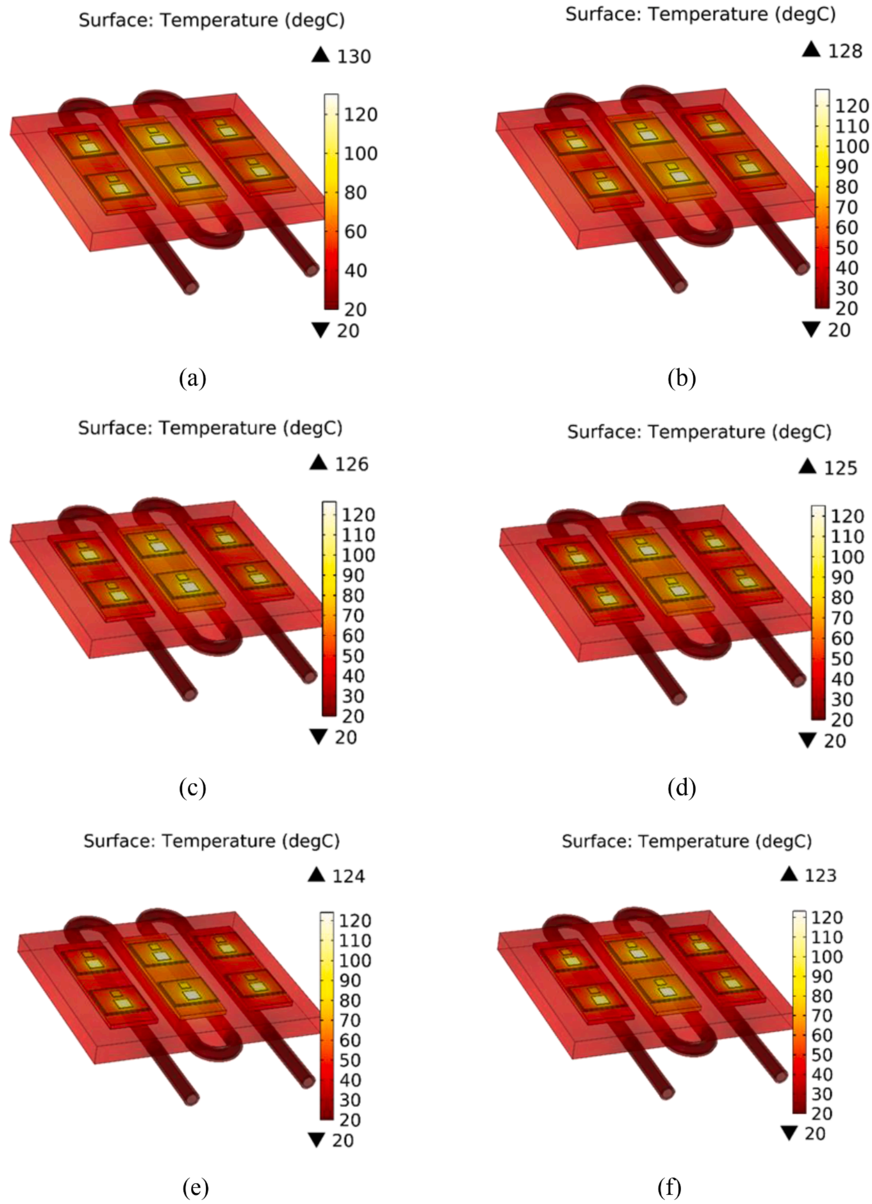

Fig. 6. Steady-state thermal analysis results for Inverter (mounted on two phase liquid cold plate) operating at 50 kW load for various flow rate of (a) 8 L/min (b) 10 L/min (c) 12 L/min (d) 14 L/min (e) 16 L/min and (f) 18 L/min, respectively.

Table 5
Predicted junction temperature for single phase liquid cooling.

Power Load		30kW	40kW	50kW
Flow Rate, L/min	Heat Transfer Coefficient, $h,\ Wm^{-2}K^{-1}$	T_{jIGBT} [°C]	T_{jIGBT} [°C]	T_{jIGBT} [°C]
8	4381	125	136	149
10	5237	121	131	143
12	6059	117	128	139
14	6855	115	125	136
16	7628	113	123	134
18	8381	111	121	132

Table 6
Predicted junction temperature for two phase liquid cooling.

Power Load		30kW	40kW	50kW
Flow Rate, L/min	Heat Transfer Coefficient, $h,\ Wm^{-2}K^{-1}$	T_{jIGBT} [°C]	T_{jIGBT} [°C]	T_{jIGBT} [°C]
8	9145	110	119	130
10	10,409	108	117	128
12	11,570	107	116	126
14	12,652	106	115	125
16	13,671	105	114	124
18	14,638	104	113	123

fluid flow rate is a design constraint, two-phase cooling can be a promising solution for lowering cooling system costs. Using a two-phase cooling system with a low flow rate, the same junction temperature can be achieved. The acceptable cooling performance can be achieved at the 8 L/min for two-phase cooling, while single phase cooling needs 18 L/min. This means two orders of magnitude reduction of flow rate can be achieved using two-phase liquid cooling compared to a single-phase liquid cooling. Comparing TIMs, it has also been found that the TIM in thermal liquid paste performs better than thermal grease. It can be concluded that combination of right kind of TIM and two-phase cooling can reduce junction temperature by 4.5%, 4.2%, 4.6% for the traction power load of 30 kW, 40 kW, and 50 kW respectively. This simulation-

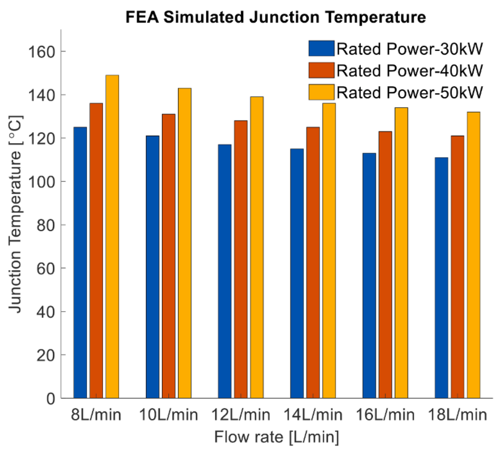

Fig. 7. Steady-state thermal analysis results for Inverter (mounted on single phase liquid cold plate) operating at 30,40 & 50 kW load for various flow rate of (a) 8 L/min (b) 10 L/min (c) 12 L/min (d) 14 L/min (e) 1 L/min and (f) 12 L/min, respectively.

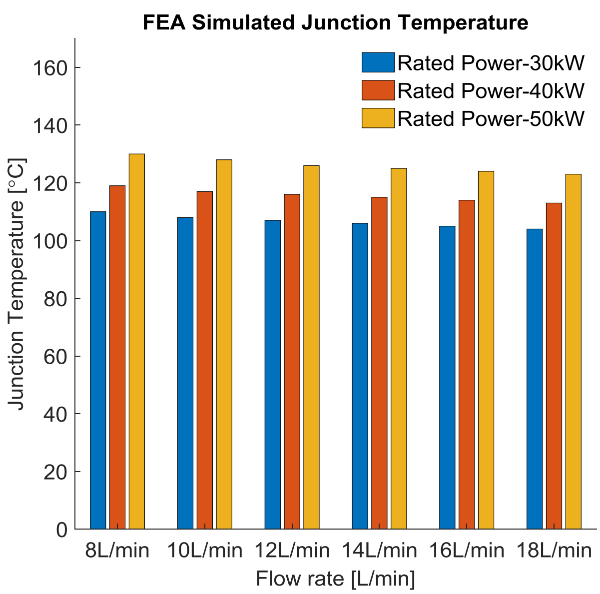

Fig. 8. Steady-state thermal analysis results for Inverter (mounted on two phase liquid cold plate) operating at 30,40 & 50 kW load for various flow rate of (a) 8 L/min (b) 10 L/min (c) 12 L/min (d) 14 L/min (e) 16 L/min and (f) 18 L/min, respectively.

Table 7
Material properties of different TIMs [55].

Material	Thermal Grease	Thermal Grease (Shinetsu X-23–7762-S)	Adhesive-Pad (Panasonic EYGT Graphite-Pad)
Density (kgm^{-3})	1180	2600	2100
Thermal conductivity ($W.m^{-1}.K^{-1}$)	2.5	4.4	13

Table 8
Predicted Junction temperature for various TIMs.

Power load	30kW	40kW	50kW
$k_{TIM}, W.m^{-1}.K^{-1}$	T_{jIGBT} [°C]	T_{jIGBT} [°C]	T_{jIGBT} [°C]
2.5	110	119	130
4.4	107	117	127
13	105	114	124

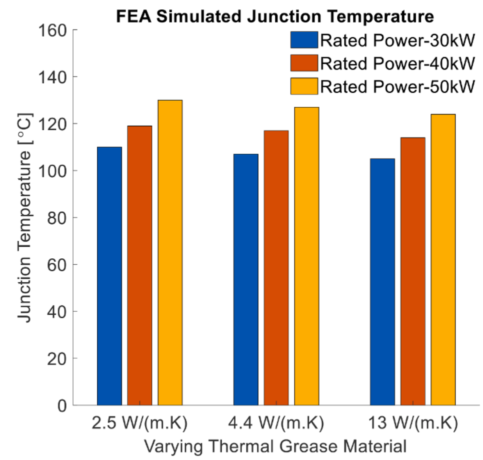

Fig. 9. Steady-state thermal analysis results for Inverter (mounted on two phase liquid cold plate) operating at 30,40 & 50 kW load for fixed flow rate of 8 L/min.

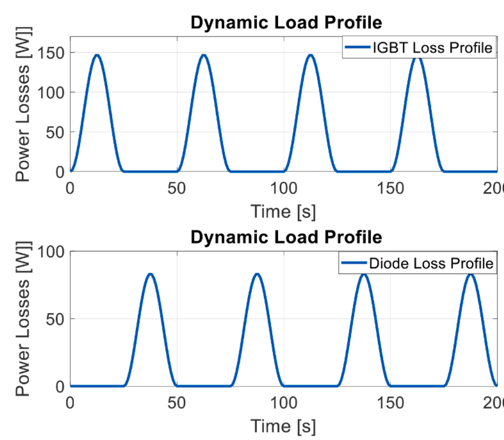

Fig. 10. Power loss profiles for one IGBT and one diode in a one of the switches of Inverter half-bridge leg under dynamic load profile.

based method presented in this work is beneficial for particularly where the high requirement of keeping the tolerable IGBT junction temperature and achieving homogenous temperature distribution across the traction inverter package of high-power rating and the requirement for detailed analysis to study the impact of heat spreading, thermal interface material, and massive size liquid cold-plate. The proposed method can help the designer by providing the means to achieve the electro-thermal design of the traction inverter and can reduce the cost of hardware prototype development for assessing cooling performance in converter system level application. The proposed modelling method can provide useful thermal design guidance allowing for both electrical and thermal characterization of any power-level traction inverter.

In future, the electro-thermal model will be extended and coupled to electromagnetic (to study device parasitic effect on thermal performance) and mechanical (for stress analysis in critical locations such as chip solder/baseplate solder), which are expected to bring greater benefits to power electronics engineer in relation to multiphysics based early design investigation.

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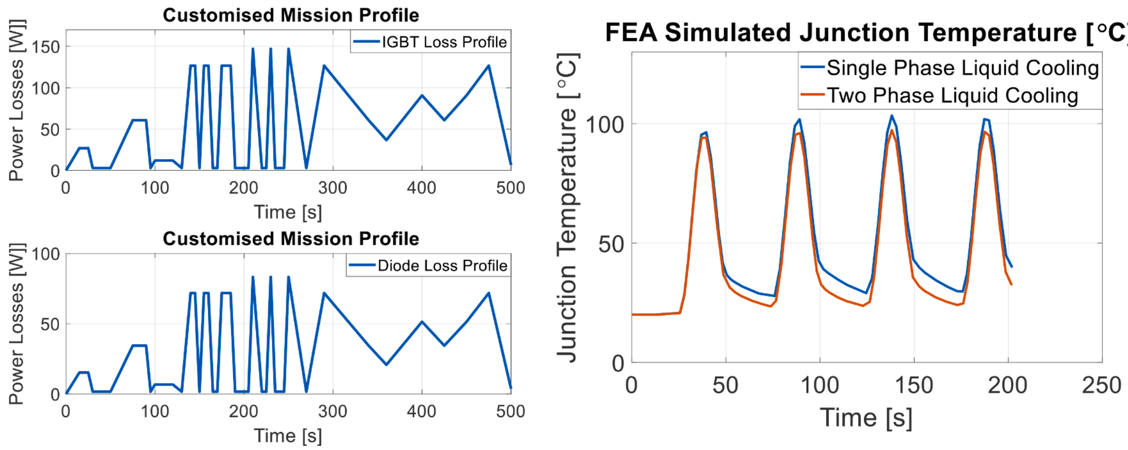

Fig. 11. Power loss profiles for one IGBT and one diode in a one of the switches of Inverter half-bridge leg under customised complex mission load profile. Junction temperature predicted by FEA method for single phase liquid cooling and two-phase liquid cooling under dynamic load profile.

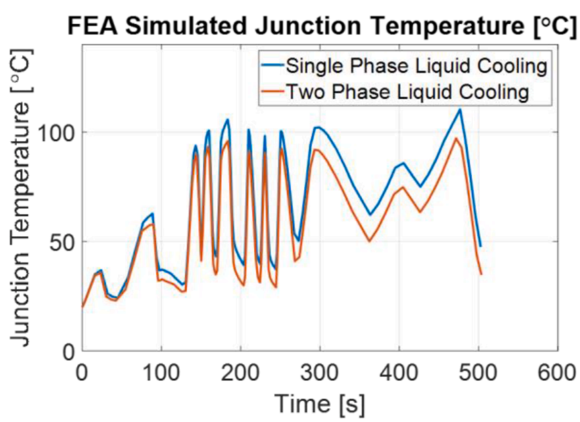

Fig. 12. Junction temperature predicted by FEA method for single phase liquid cooling and two-phase liquid cooling under dynamic load profile.

Table 9
Comparison of estimated junction temperature with state-of-the-art models.

Literature	Published Year	Power rating	Estimated Junction temperature
[33]	2022	100kW	145 °C
[34]	2022	168kW	140 °C
[38]	2019	255kW	140 °C
[39]	2021	375kW	150 °C
[45]	2022	375kW	145 °C
Current work	–	50kW	130 °C

CRediT authorship contribution statement

Mohammad Shahjalal: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Tamanna Shams:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Software, Visualization, Writing – original draft, Writing – review & editing. **Sadat Bin Hossain:** Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Md. Rishad Ahmed:** Investigation, Methodology, Formal analysis, Validation, Writing – original draft, Writing – review & editing. **Mominul Ahsan:** Methodology, Supervision, Formal analysis, Writing – original draft, Writing – review & editing. **Julfikar Haider:** Methodology, Supervision, Formal analysis, Writing – original draft, Writing – review & editing. **Rajib Goswami:** Methodology, Supervision, Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing. **Syed Bahauddin Alam:** Formal analysis, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Atif Iqbal:** Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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