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A Multiport Power Electronics Converter for Hybrid Traction Applications

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ABSTRACT Environmental concerns and energy efficiency have been driving the transportation innovation in the past decades. In this framework, hybrid city transport has been receiving the attention of the industry. The challenges for this application are the required high-power density, lower maintenance cost and the high-temperature environment due to the integration with the internal combustion engine. A multiport converter is proposed to realise the requirements of the automotive industry to achieve greater performance in driveline electrification. The platform suggests the combination of previously discrete power electronics converter modules into one physical package commonising parts such as the microcontroller, heatsink and busbars. This paper provides an overview of design considerations for engine start-stop within a series-parallel topology and how it is achieved using the multiport converter. Finally, a comparison between the multiport and discrete converter approach is made compared and findings presented, highlighting the advantages of the integrated solution.

INDEX TERMS Power electronics, converter, multiport system, electric drives.

I. INTRODUCTION

The electric transport sector is continuing to grow and assume increasing market share, driven, according by the International Energy Agency by two key factors [1]: i) ever increasing support for more environmentally friendly forms of transport, in the form of fuel economy standards coupled with incentives for zero emission vehicles that bridge the cost gap between electric and conventional vehicles and ii) technological enablers such as battery chemistry development and manufacturing techniques delivering substantial cost cuts; both important factors in counteracting increasingly prevalent problems of limited available hydrocarbon reserves and permanent environmental degradation [2].

Given its passenger carrying capability, one major point of growth in public road transport is driven by electrified busses, whereby the International Energy Agency claims that in 2018, there were approximately 460 000 electrified busses in operation around the world, up 100 000 from the year before [1]. In order to understand if the purchase and operation of these busses are to be commercially and financially viable, a lifecycle cost analysis has to be performed for the various applications of electrification technology within a bus. A study by Lajunen [3] showed, having compared 4 bus duty cycles including those from Finland and California that the cost over the lifetime, 12 years, of an electrified bus favoured Hybrid variants over its conventional and fully electric counterparts. A main contributor to this being the lower capital cost than a fully electric vehicle and a lower environmental cost than the internal combustion engine (ICE).

There is a growing electrical power requirement on vehicles, as referenced in [4], for the following reasons: the need for new and improved vehicle architectures, power conversion on demand, the use of precise electronics control and fast, high power motion onboard the vehicle. These requirements further the advent of driveline electrification in the automotive space with the integrated power electronic converters as the heart of the system since they offer improved

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power density with simplified integration for vehicle manufacturers [5]. Due to cost concerns, many electric vehicle functions in the past were realised actively avoiding power electronic components [4]. However, since the early 2000s until now, major strides in the development of power electronic converters pertaining to density, reliability, thermal performance and control algorithms have been achieved placing them as a viable solution to many of the challenges faced with on-vehicle power requirements in all aspects of vehicle design- powertrain, safety management, body and convenience [6]. This growth is set to increase with the electrification of vehicle drivetrains in the coming years as the demand for fully electric vehicles increases. With this increase comes further development in the power electronic converter space and the objective of reaching even higher power densities and efficiency [7].

When replacing a conventional drivetrain setup, it is imperative to improve performance but not to the detriment of reliability - especially in automotive applications. As part of the US Department of Energy's (DoE) efforts to achieve energy security, the Clean Cities program was launched. It encountered concerns from the consumer regarding idle reduction, whereby, turning the vehicle on and off would result in premature wear and consequently failure of the starter motor and battery.

Therefore, it is clear that the challenge faced with automotive electrification is in balancing performance and safety requirements against implementation cost, packaged within a design that optimises for power density and thermal performance [8]. Given the relationship between these three aspects, a high-level study of driveline topologies is first undertaken in order to identify the key component interfaces within a hybrid bus driveline.

Once the interaction between driveline components is understood, the contributors to electrical torque production-energy storage and power conditioning devices, are studied in isolation leading up to a specific application proposal of start-stop technology and its realisation within a multiport converter as given the strict requirement of power density and maintenance, an obvious advantage would be to integrate all the power electronics into a single object that can be cooled by the same coolant as the ICE.

This is presented as a case study where the design approach is considered for specific requirements of a London bus start-stop application. Finally, comparisons are made using a non-multiport converter instance as a benchmark.

II. DRIVELINE TECHNOLOGIES FOR HYBRID BUSES

A. DRIVELINE ARCHITECTURES

There are multiple methods of driveline electrification with each manufacturer applying the technology in varying degrees; resulting in a wide range of vehicles termed as 'hybrids' where the conventional fossil fuel powerplant-internal combustion engine (ICE) is still utilised but aided by electrical machines. Three popular implementations of these are the series, parallel and series-parallel hybrid (see Figure 1).

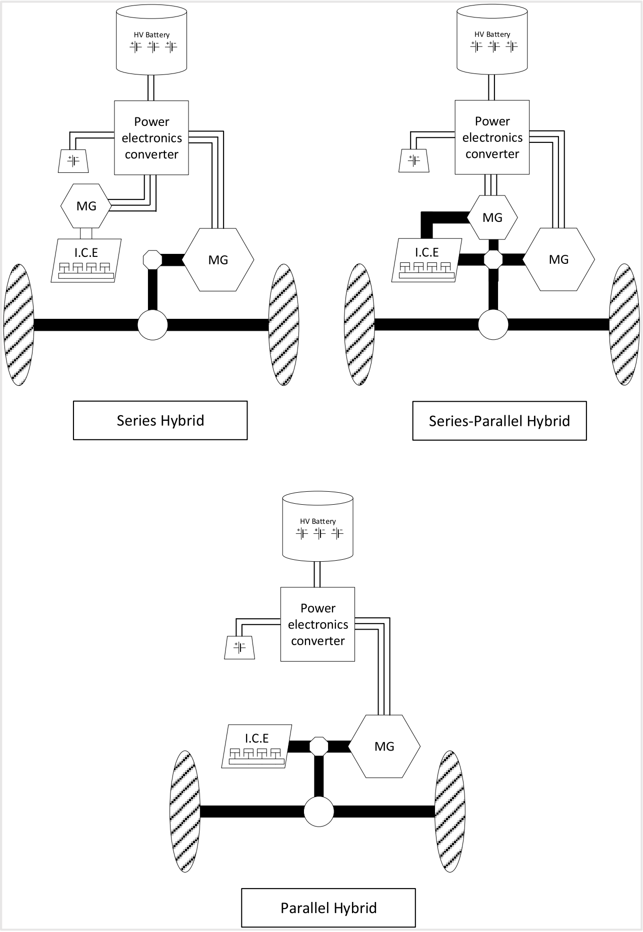


FIGURE 1. Illustrations of the basic topology of common hybrid topologies- Series hybrid, Series-parallel hybrid and Parallel hybrid.

Manufacturers adjust the ratings of each of the components in these topologies with different degrees to achieve different degrees of 'hybridisation'. In [9], an example of a mild hybrid system designed as a parallel hybrid with one EM assisting a diesel ICE is presented. The electric power distribution net is limited to 48 V and supported by a high-performance lithium-ion battery. In this example, it is important to note that the practical upper limit of ±310 A peak is considered due to device ratings; giving a peak power of ±15 kW, establishing the definition of a mild hybrid powertrain in this context. It is not uncommon to find full hybrids with a power rating of an order of magnitude higher. It is clear here that power requirements drive component selection which in turn influences the selection of driveline topology. Therefore, some of the key considerations here are technologies in the active switching devices and energy storage devices.

B. ENERGY STORAGE

Each of the hybrid topologies described relies on an energy storage medium that would supply the electric motor via the converter. When the idea of electric propulsion was first conceived, "wet cell" batteries were used as an energy supply. However, these batteries could not be recharged so development lead to the invention of the lead acid battery which allowed for thousands of recharge cycles and therefore prolonging the useful lifetime of the battery unit. Energy density requirements then furthered the search for an ideal energy storage medium leading to the utilization of lithium ion cells which removed the need for heavy lead plates and corrosive acid-based electrolytes. In [10], a comparison of the various types of lithium ion batteries is made in aspects such as charge and discharge cycles, energy density, specific energy, specific power, safety and operational temperature ranges; concluding that the predominance of lithium-ion batteries in the EV market is due to its high energy density and continual reduction in cost. However, an emerging technology is gaining attention in the form of ultracapacitors. Multiple manufacturers of electrolytic capacitors- a technology that has been utilised since the 1950s-such as Maxwell and Ioxus are investing greatly in this area. Ultracapacitors grant the added benefit of low equivalent series resistance and therefore have the highest charge-discharge cycle limits of all of the energy storage mediums currently on the market, as according to [11]. One of the drawbacks of ultracapacitors is the low voltage rating per cell, requiring cells to be stacked in series to build up voltage and then in parallel to increase storage capacity. This dramatically increases the number of cells within the ultra capacitor pack driving the need for efficient methods of controlling the charging and discharging process of the pack. Cell balancing and management are a key area of research to ensure uniformity in the charging process to avoid damage to the cells. An example of progress in this area is described in [12], wherein an approach utilizing a half bridge converter and full bridge diode rectifier is proposed in place of conventional methods of voltage balancing utilizing shunt resistor circuits and flyback converter-based balancing circuits for benefits such as faster equalization speed, higher efficiency, ease of control, higher reliability and lower cost.

Hannan et al ran a review and classified each energy storage medium as seen in Figure 2, highlighting automotive-based solutions in grey. Whichever the energy storage medium, each solution typically has an electronics interface which provides communications and isolation measurements. This forms the interface to the rest of the system. In summary, each implementation of hybrid technology utilises energy storage technology considering the specific use case and its tradeoff with cost- for example mild hybrids would only require a lead acid battery or ultracapacitor while propulsion hybrids (as seen in Figure 1) which implement higher levels of hybridization require the use of more energy dense, high voltage lithium-ion batteries.

C. START STOP

A hybrid typically still employs the use of a conventional prime mover- typically and internal combustion engine. It is within the best interest of the manufacturer to operate these engines in the most fuel-efficient way possible as to offset the additional weight of the hybrid components. Therefore, extensive studies are done on the integrated driveline to obtain the maximum efficiency band of operation for the engine, and to limit engine idle; or to switch off the engine when it isn't required- a feature the industry commonly refers to as start-stop. [13] details the testing done on a fast start-stop system on a GMC Envoy from which a fuel saving improvement of 5.3% in city cycle and 4.0% improvement was demonstrated in on-highway driving purely from implementing this feature.

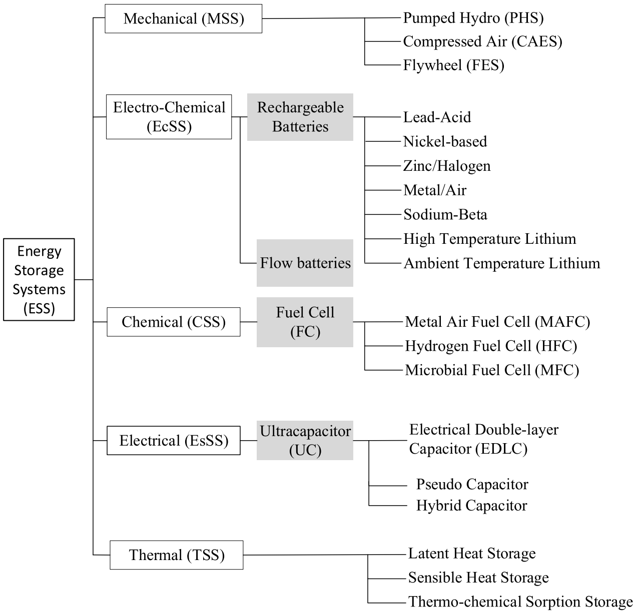


FIGURE 2. Classifications of energy storage technologies currently employed by automotive manufacturers. Referenced from Hannan et. al [10].

In order to implement a start-stop system, start duration, energy consumption, comfort and emissions have to be considered. In [14], the efficiency of a fast start system utilising a conventional starter motor is compared against an engine start using a hybrid motor generator for starting an Internal Combustion Engine. The results obtained in a lab setting were 60% and 89% respectively showing that replacing the conventional starter is highly beneficial- especially if a high torque motor generator is already available on the drivetrain. It was found that start-stop does affect the economic model for all engine capacities (2.0L to 5.0L) and lifetime of the starter, however it is limited by the use of modern fuel injection techniques and control systems [8]. It is therefore desirable to utilise the power electronics and motor generator in any of the 3 topologies in Figure 1 to implement start-stop in order to gain from the benefits without any of the drawbacks to reliability.

D. APPLICATION: CASE STUDY OF START-STOP APPLIED WITHIN A LONDON BUS DRIVE CYCLE

A method of start-stop implementation is proposed where the multiport converter (MPC) presented in Figure 4 is used

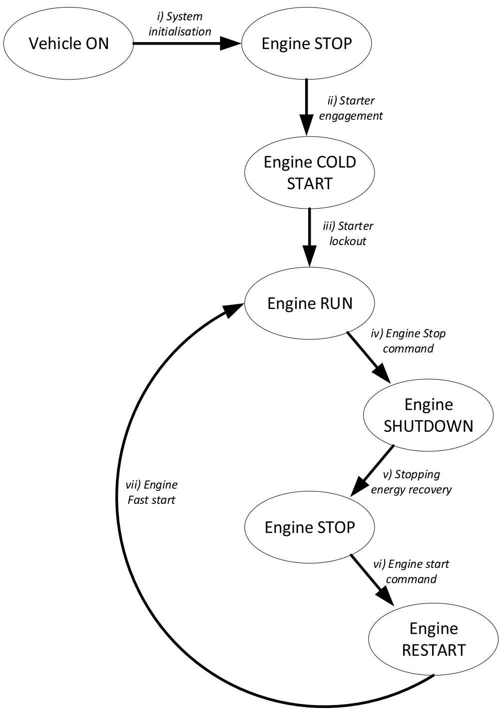


FIGURE 3. State diagram illustrating start-stop-restart routine performed by hybrid drivetrain.

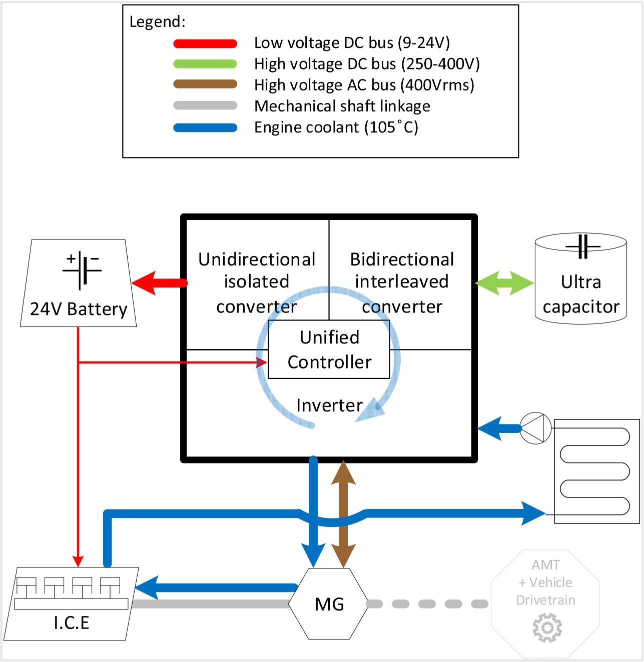


FIGURE 4. Block diagram illustration of power conditioning within MPC.

to manage power flow between an ultracapacitor bank, low voltage battery and an ICE (via a crank mounted PMSM).

The MPC has two main functions:

1) it performs the role of power electronics controls by running closed loop control algorithms for control of torque, current and voltage.

2) it performs hybrid system controls- reading vehicle inputs for crank vs run vs stop decisions and managing the Battery Management System (BMS). Therefore, from Vehicle ON, the MPC is regulating all of the internal parameters such as dc link voltage, and power demands from each of the components, charging ultracapacitors and motoring the PMSM for example. Each of the modes is listed with more detail in Table 1.

TABLE 1. Engine mode description.

Mode	Description
Vehicle ON	All system controller modules boot and in ready state. MPC controller requests contactors close and precharge dc link (i). PMSM in standby.
Engine Stop	System ready to start engine using 1) starter motor for cold start or 2) hybrid system for fast restart-PMSM MOTORING (see Figure 7, Figure 11). Ultracapacitor energy is used to support LV battery and vehicle hotel loads.
Engine COLD Start	Conventional engine start applied using low voltage starter (ii). On completion of engine crank, low voltage starter is locked out (iii) for remainder of vehicle operation.
Engine Run	Vehicle-in-motion. Engine speed> idle (700rpm). Engine in drive mode. MPC calculates available electrical power according to engine power vs speed curve. PMSM REGENERATION (see Figure 8, Figure 12) to charge ultracapacitor and LV battery from braking events (see Figure 14). Transition from this mode is governed by an internal state machine which demands engine turn-off for fuel conservation (iv).
Engine Shutdown	Vehicle stopped. Engine begins shutdown routine. Hybrid system recovers energy and prepares for subsequent fast restart (v).
Engine Restart	Hybrid system provides torque to crank to restart engine in less than 1s (engine fast start (vii)).

It is assumed that the engine controller (ECU) manages components related to exhaust treatment and air induction in all modes. For clarity, the connected MPC, ultracapacitor bank, low voltage battery and PMSM are heron referred to as ‘Hybrid System’.

III. POWER CONDITIONING IN MULTIPORT CONVERTER DESIGN

It is apparent from Figure 1 that the power electronic converter is the key enabler of fuel saving techniques. The converter conditions and transfers energy between all energy storage mediums-typically DC and motor generators-typically AC at various ratings. This gives rise to the requirement for a multiport converter with a common bus. According to [15], multiport converters have been gaining increasing popularity lately due to the advantages of being able to diversify energy sources with various V-I profiles, utilise shared component and parallel port topologies which, in result, provides a low cost, high density and reliability solution.

As a result of the case study, a multiport converter design is proposed as shown in Figure 4 which seamlessly couples electrical and mechanical design with the following key features: produce AC power to control a motor, DC bidirectional power to condition power from an energy storage device and low voltage DC power as an alternator replacement. As power electronics designs for traction applications must feature high power density and reliability at a cost-effective price point, high frequency pulse width modulation switching is utilised with high rated, low losses devices- Silicon Carbide MOSFET. A bespoke SiC MOSFET was designed for this application considering the expected losses for the switching frequency and operational load point as described in [16]. This results in physically smaller magnetic components and fewer overall active devices in the converter package. For clarity in presentation, the multiport converter high level schematic is illustrated in Figure 5 where the converter topology may be divided into 3 distinct components: inverter, bidirectional power converter and unidirectional power converter. A description of the design of each stage follows.

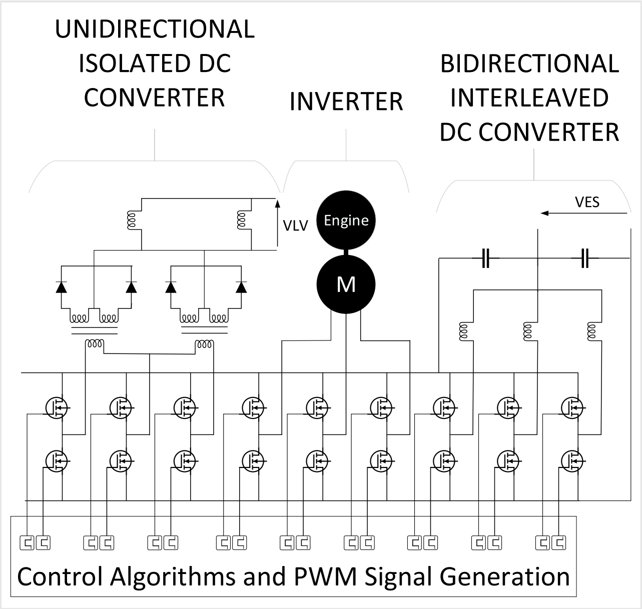


FIGURE 5. Multiport converter circuit layout.

A. INVERTER

A 3-phase, 2 level inverter was proposed as the optimal solution to control a 3-phase interior permanent magnet synchronous machine due to the high degree of control achievable via vector control, whereby field oriented control techniques are used to set up flux, current and voltage within the motor to produce torque. The topology is illustrated in Figure 5, whereby each leg is connected respectively to one of the phases of the electrical machine. Table 2 lists the parameters of the machine used for experimental validation.

The inverter is controlled by means of classic cascaded torque-current controller whereby the motor torque demand is determined via the Maximum Torque Per Ampere (MTPA) tracking strategy to precisely calculate control parameters taking into account variation of machine inductances in the d and q axes as described in [17]. As motor speed increases, control modes shift to provide field weakening current. The cascaded controller is implemented with classical Proportional Integral controllers as illustrated in Figure 6.

TABLE 2. Inverter & machine parameters.

Parameter	Value
Machine type	IPMSM
Polepairs	8
Base speed	1200rpm
Torque	200Nm (cont), 350Nm (peak)
Inverter	3ph 2-level inverter
Coolant inlet temperature	105 degrees C
Heatsink	Aluminium, Liquid cooled

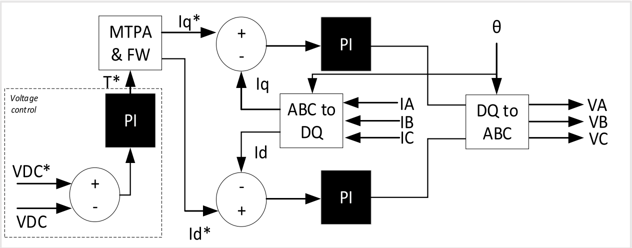


FIGURE 6. Inverter control architecture.

During engine start, the maximum motoring torque is applied via the motor generator, and therefore the maximum current is applied via the switches momentarily. During regeneration, the polarity of current is reversed. In this operational mode, voltage across the dc link is controlled with power limits governing the maximum current drawn from the machine.

The inverter has two specific modes of operation: motoring (torque production in the same direction as machine rotation- see Figure 7) and generating (torque opposing direction of machine rotation- see Figure 8) where peak torque required phase current of 350 Nm.

As described in [16], the losses in the SiC MOSFET were considered for estimated power factor, switching frequency and collector current during acceleration of the motor from standstill. Next, the propagation of losses was studied using RC thermal networks to understand their impact on mechanical integrity and therefore, reliability. The results drove the design and requirements of the liquid cooled heatsink. Figure 9B illustrates the estimated (in black) vs experimental (in blue) temperature profile of the SiC MOSFET junctions during an emulated engine start event with a speed profile in Figure 9A, verifying the junction temperature, T_{jM1} achieved for a coolant temperature of 105 degrees C and its correlation to the temperature readout by the NTC temperature sensor, T_{NTC}- shown in Figure 9C. The discrepancy

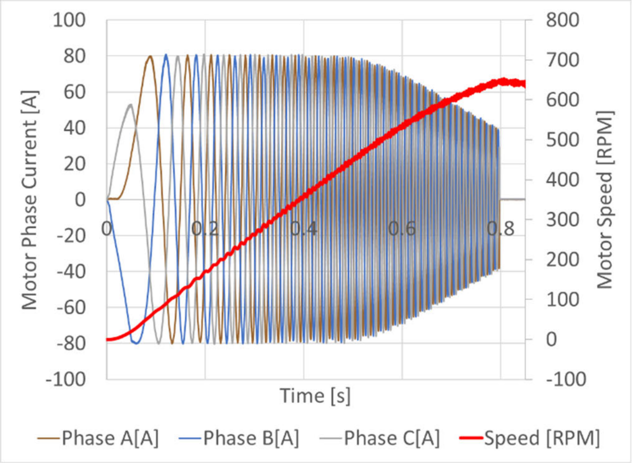


FIGURE 7. Experimental phase currents during engine start event (motoring).

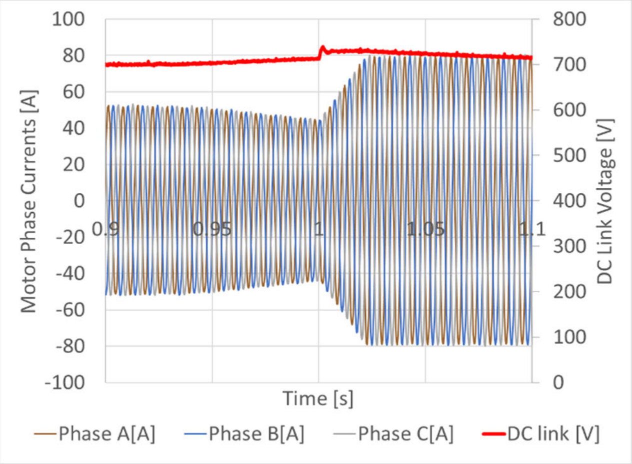


FIGURE 8. Phase currents during engine running event (generating).

between the two temperatures was attributed to the physical displacement of temperature sensor to the junction.

B. BIDIRECTIONAL INTERLEAVED DC CONVERTER

The concept proposed here is a PWM buck boost converter using a half bridge. However, it is found that by interleaving multiple of these, in our example 3, it is possible to distribute the voltage and current ripple over the switching period. This grants multiple benefits such as the ability to reduce the size and weight of passive components such as filter inductors and capacitors as well as EMI emissions as described in [18]. The most important feature of this inverter is the ability to control bidirectional current flow. This fulfils the multiport converter requirement of charging and discharging an energy storage device. Current flow is controlled by means of cascaded voltage- current PI controllers in both directions as illustrated in Figure 10.

In charge mode, the voltage across the ultracapacitor bank, VES, is controlled while the voltage of DC link, VDC is controlled in discharge mode as illustrated in Figure 10. Therefore, control of power flow is achieved by changing the references and feedback of the outer loop. Figure 11 illustrates an engine start event where the converter is in discharge mode.

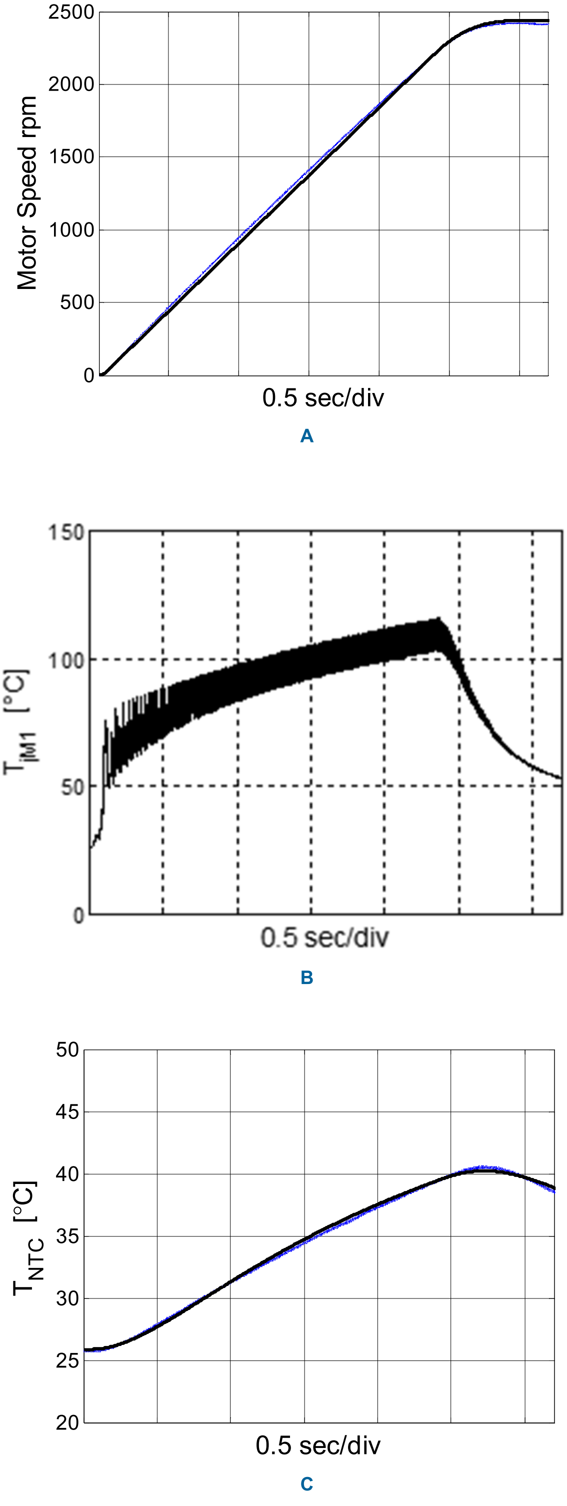


FIGURE 9. Experimental vs Simulated SiC MOSFET junction (B) and temperature sensor (C) results during engine start event (A).

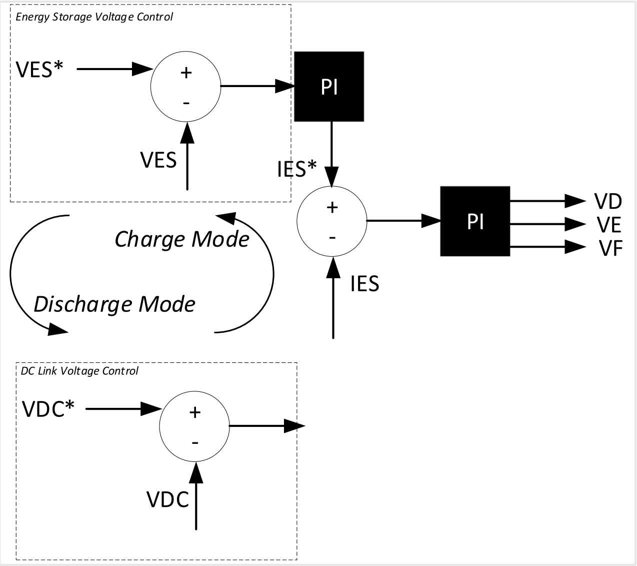


FIGURE 10. **Bidirectional converter control architecture.**

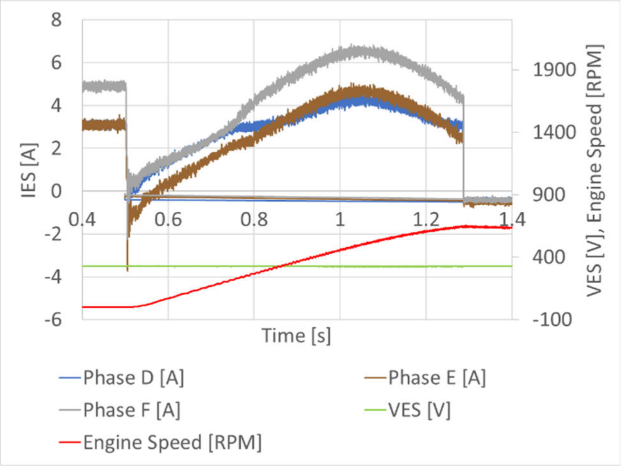


FIGURE 11. **Bidirectional Interleaved DC converter phase currents, IES during transition from hotel load supply (0.75s to 1.00s) to engine start event (1s to 1.8s).**

The realisation of the interleaved converter achieved by interpolating the currents of three identical SiC MOSFET half bridges and offsetting the phase of each equally, in order to increase power density by adding parallel channels of current: in this application 3 × 71A peak at a junction temperature of 150°C; while reducing the overall ripple in the resultant current and output voltage as demonstrated in [19]. Doing so also offers the added benefit of additional reliability through redundancy as the vehicle will still be able to operate at a reduced rating in order to return to be repaired; otherwise known as "limp home". As in the inverter, switching and conduction loss studies drove the design. Here, a trade-off study was carried out to compare the benefits of switching frequency against the losses and size of the magnetics components. Figure 12 illustrates data from Finite Element Analysis that shows the variation of total losses (combination of iron losses and copper losses) in the inductor as the dc components and ac components of the current were varied for three different switching frequencies (25kHz, 50kHz and 100kHz) as multiples of inverter switching frequency, 12.5kHz to synchronise the 3 converters within a single controller.

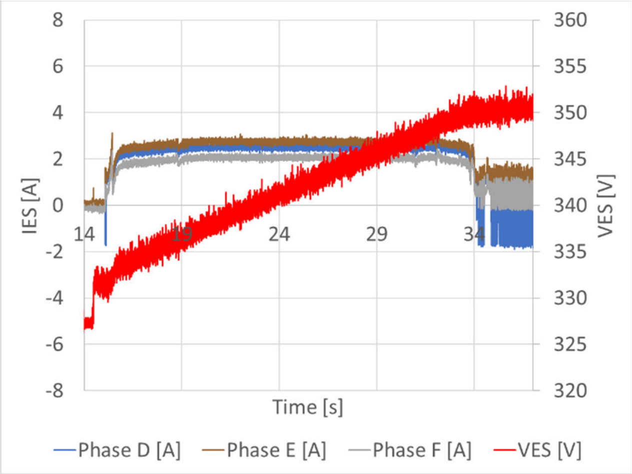


FIGURE 12. **Bidirectional Interleaved ED converter phase currents, IES and energy storage voltage, VES during energy storage charge event.**

It was concluded that a switching frequency of 50kHz was the optimum balance between switching losses and component size reduction benefits as switching frequency was increased. Any further increase of switching frequency would increase magnetic losses in addition to switching losses. While the magnetics would get smaller with the increase of switching frequency, reduced geometrical dimensions of the thermal interfaces could limit thermal flow.

C. UNIDIRECTIONAL ISOLATED DC CONVERTER

The sole purpose of this converter is as an alternator replacement. As seen in Figure 5 PWM switching of all 6 switches is applied to control the voltage across the primary winding of a step-down transformer. The transformer was designed to meet three main requirements: 1) to aid in reducing commutation stress in the rectification diodes on the output to the 24V vehicle battery, 2) to complement switching ratios to step 800V on the primary side to 28V on the secondary side and 3) to meet thermal requirements of the heatplate.

Power flow is controlled by means of a cascaded voltage-current PI controller (illustrated in Figure 13). Power saturation limits are applied according to the engine power-speed profile to avoid engine overload. Figure 14 presents experimental test results of the low voltage battery charging event.

Identical SiC MOSFETs were utilised primary side of the transformer which enabled high frequency (50kHz), low loss switching. On the secondary side, rectification diodes with the lowest possible on-state resistance had to be selected to reduce forward voltage drop and conduction losses in order

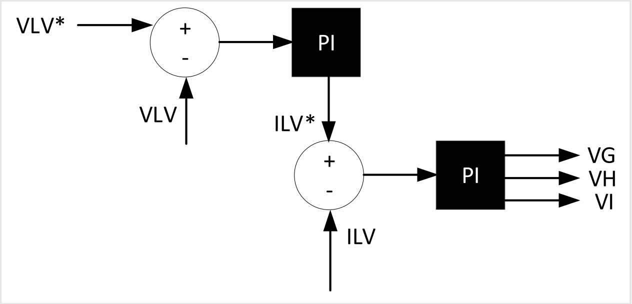


FIGURE 13. Unidirectional isolated converter control algorithm.

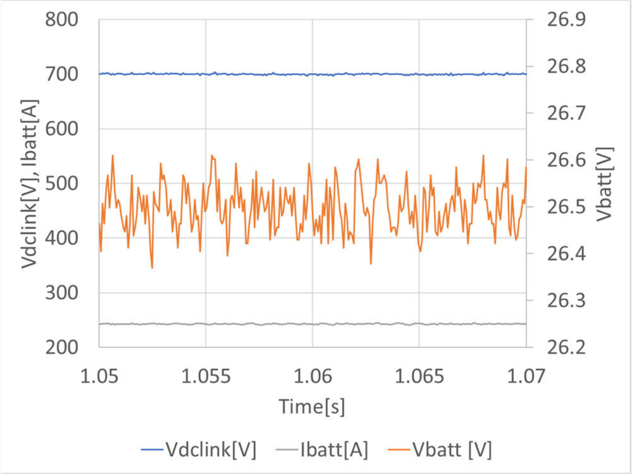
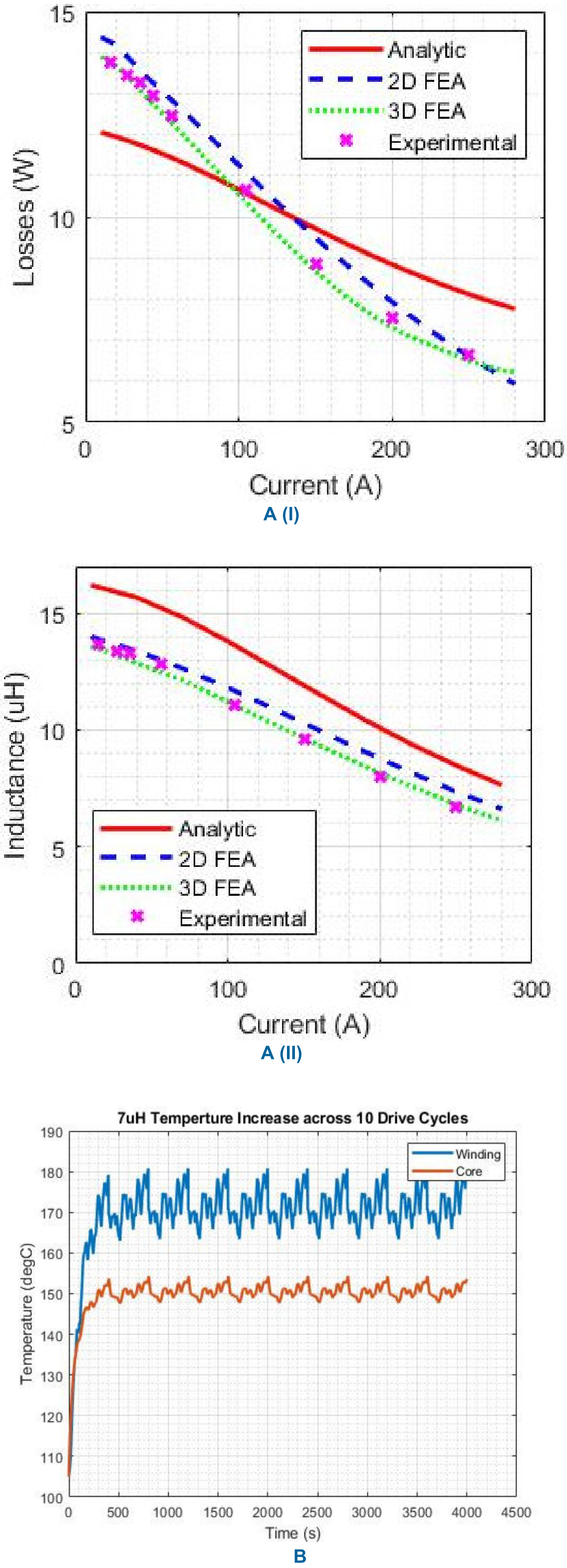


FIGURE 14. Experimental battery current and voltage during battery charge event.

to achieve optimum performance and reduce thermal stress on the device while operating with much higher current amplitudes than the SiC MOSFETs on the primary side. Paralleling both primary and secondary currents distributed the heat across the heatplate more evenly and therefore increased the heat exchanged with the coolant.

Finite Element Analysis (FEA) was carried out to determine the temperature rise in the output filter inductor where the losses were split into three components: DC winding loss, AC winding and total core loss (iron loss). To validate these models, the results were compared against those from analytical models and experimental setups. Figure 16A (i and ii) show high accuracy of the simulation and analytical models both in predicting inductance degradation with increasing saturation levels and then the subsequent reduction of losses. This data was then used to drive simulation of 10 drive cycles to allow the thermal paths to arrive at steady state, then ensure that maximum temperature limits were never exceeded. Figure 16B shows the predicted temperature in the winding and the core across 10 cycles.

As shown, the temperature never exceeds 200°C-the rated maximum temperature of the core and potting compound. Design parameters for the inductor are listed in Table 3.



A (I)

A (II)

B

FIGURE 15. Side cross-section of MPC illustrating ambient air and heatplate temperature distribution.

IV. DISCUSSION

Power converter design remains as the main barrier to achieving power densities to rival conventional

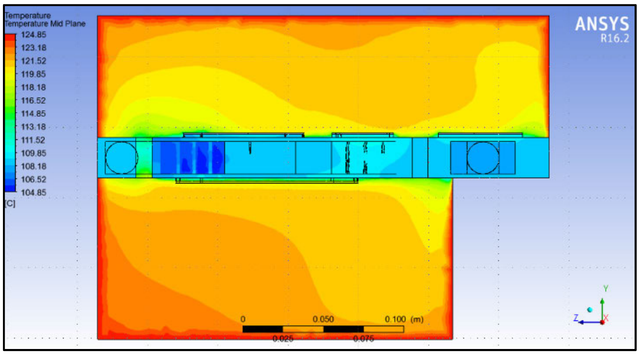


FIGURE 16. Analytical, FEA and experimental results (A (i) and (ii)) comparison and drive cycle validation (B).

TABLE 3. Bidirectional interleaved converter inductor design parameters.

Inductor design parameter	Value
Material	Kool Mu
Core Shape	E Core
Core	6527 26µ
Thickness (mm)	27
Core width (mm)	65.15
Core length (mm)	65.02
Volume (L)	0.114
Mass (kg)	0.42

drivetrain powerplants. A volumetric breakdown on commercial inverters is performed in [20] which showed that 60% of the converter volume was occupied by air and the heatsink, 25% was taken up by packaging and only 15% is taken by electrically functional parts. This was because air played an active role in heat removal, the converters were built from components from different manufacturers resulting in geometry mismatch and that the converters were designed with electrical performance as the focus while thermal and power density was considered only as an afterthought.

The MPC offers two distinct advantages that make critical contributions to the focus on improving power density – firstly, in integration. From a physical aspect, an integrated design where all the converter components are co-located together reduces the number of components required and simplifies the electrical and thermal design. Secondly, is in maximising the utilisation of devices. In this application, having a common dc link between all three converters reduces the number of copper busbars while clustering the active switching devices in close proximity on a common heatsink. By maximising the ratio of heat exchange surface area to component volume, it becomes more feasible to route coolant channels around to electrically functional parts. This enables the devices to run at higher power resulting in greater utilisation of the heatsink as well as a lower number of connections between components. Figure 15 shows the temperature distribution across the heatsink and the internal components of the converter while Figure 18 illustrates the prototype converter used to validate design elements both in lab testing and in the field.

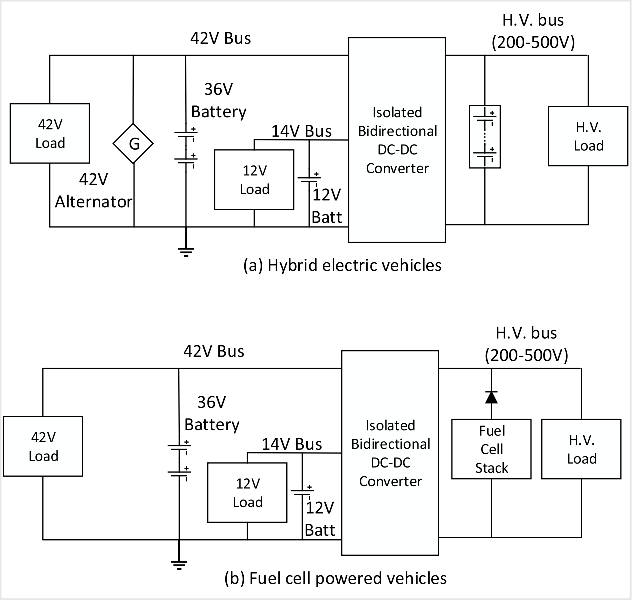


FIGURE 17. Proposed dc converter interconnecting 14V/42V/High voltage ports proposed in [20].

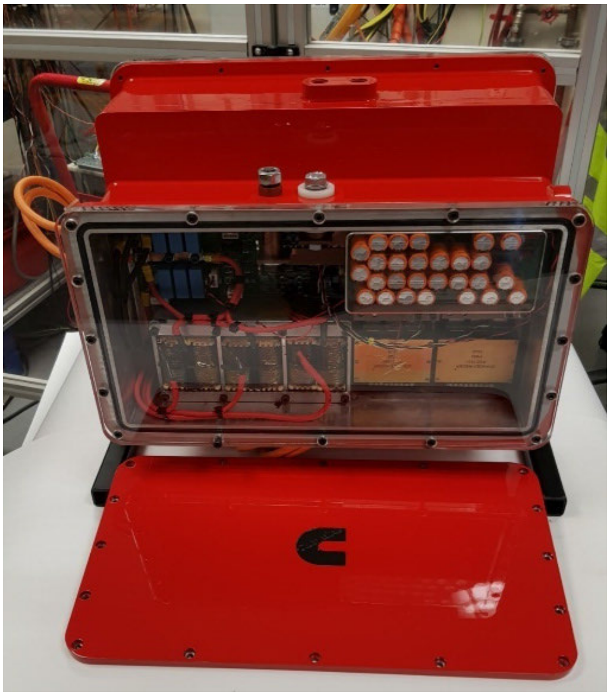


FIGURE 18. Prototype MPC used in field-testing.

The benefits in integrated design and greater utilisation of components make the MPC a strong contender particularly when compared against the approach with discrete converters. In this case study, the discrete converters used were purchased off-the-shelf components. Comparisons between a

TABLE 4. Comparison: multiport vs discrete converters.

	MULTIPORT	Discrete
Number of CPUs	1	4
Power density (kW/kg, kw/L)	1.143kW/kg, 2kW/L	0.766kW/kg, 0.873kW/L
Integration of machine, cooling loops, converter	Yes	No
Manufacturing complexity	Single flowline	3 unique flowlines
Thermal design (low level)	Simple, high utilisation of thermal paths	Complex, low utilisation of thermal paths
Electrical design (low level)	Simple	Complex, higher number of interconnects and interfaces
Ease of vehicle integration and assembly	High	Low
Reliability	High	Low due to increased number of interfaces

multiport converter versus the 3 discrete converters are listed in Table 4.

Further comparisons are also made between the proposed multiport converter against contemporary implementations. Although it must be stated that there are few integrated multiport implementations in literature or commercial product documentation.

A similar application of multiport converter made up of two low voltage ports (14V and 42V) and a single high voltage port (>200V) for hybrid vehicles is presented in [21] where part reduction and commonisation through use of dual half bridges in the isolated dcdc converter is investigated. Bidirectional power flow with soft-switching was demonstrated with the phase shifted dc converter. However, it is observed that voltage and current ripple on the low voltage ports is more significant when transferring energy from the 42V port to the 14V and 200V ports than in other modes. While this may be acceptable for a 2kW technology demonstrator, the magnitude of ripple may present a challenge for on-vehicle application, particularly at power nodes of more than one order of magnitude larger as in the MPC proposed. The topology presented in [21] is illustrated in Figure 17. A major difference between the topologies presented here is the requirements for galvanic isolation between the high and low voltage busses. All power flow between ports pass through the transformer which will impact overall system efficiency and therefore is traded off against the ability to achieve soft switching. The approach with the MPC differs from this by way of using high voltage energy storage, so that only one conversion stage uses the transformer. Phase interleaving provides lower voltage and current ripple and switching stress is reduced by the turns ratio of the transformer.

There are further examples of multiport converter implementations outside of the automotive application demonstrating other benefits of the approach, for instance where a topology implementing a Solid State Transformer (SST) based on a Quadruple-active-bridge (QAB) converter for power conditioning of photovoltaic energy from source port: photovoltaics (48V) to the battery (48V) connected to the load port as presented in [22]. Despite a clear difference in operational parameters, the benefit of the multiport approach is that commonising components simplify the plant modelling and therefore control, allowing control loops to be designed to minimise effects of cross coupling in the QAB, improving its overall transient performance. Analysis presented in [23] goes further into detail comparing the benefits of current feedforward and static and real-time decoupling on the tracking performance to reduce dependency on controller bandwidth. In addition to this, the three-port bidirectional DC-DC converter presented in [24] was designed to reduce system losses by implementation of zero average power controls: direct supply of a load without charging or discharging an energy storage device on the third port. Similar approaches could be considered for the proposed MPC in further iterations of its design.

In summary, the integration of multiple discrete devices into a multiport design clearly presents many benefits but depending on application, a partially isolated MPC will have the advantage over its fully isolated counterpart.

V. CONCLUSION

This paper has shown the potential of multiport converters as a unique solution as a means to increase power density of electrical drivelines. The three main concepts presented in this approach is firstly to identify the specific power needs by the vehicle, next optimised integrated controls is applied within an integrated multiport converter design to achieve reduction in thermal and electrical design complexity, improve reliability and ease of vehicle integration and finally through careful integrated design with a multiphysics approach taking into account thermal, packaging and electrical design aspects, it is possible to achieve higher degrees optimisation of driveline electrification.

The true value of this approach was demonstrated in a case study where, for a 40kW automotive drive, the MPC showed an improvement of approximately 2.3 times volumetric power density and 1.5 times specific power density over that that of discrete devices.

For completeness, some drawbacks of the MPC approach are discussed. One main downside is in serviceability of components. Where the discrete approach offers the ability to simply replace malfunctioning components, the MPC requires specialised tools and techniques in order to gain access. It should be highlighted however that in this particular case study, the converter was an early prototype. The process and workflows involved to take this converter to market will streamline the design to improve serviceability, resulting in lower overall cost and downtime. Next are challenges in scalability of the highly optimised MPC where increasing the power requirement will require a higher degree of redesign of components. The solution to this is to apply the tools derived in the design of the prototype to limit the scope of changes.

In summary, this paper has presented a comprehensive process and solution to improving overall drivetrain power density and reliability in line with ever increasing development requirements as the push towards higher degrees of driveline electrification continues.

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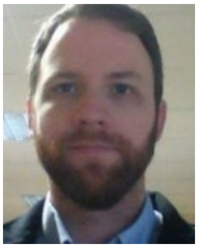

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