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Gearing up for lower cost electric drives: accelerating the development of optimal electrified powertrain architectures

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Summary

This paper will draw upon case studies derived from learning on projects, internal research and in testing to explore DSD's latest approaches to electric power train analysis and design which can help manufacturers develop lower cost and highly efficient system solutions by enabling them to fully understand and leverage complex sub-system trade-offs and interactions at a vehicle level within short development cycles.

Keywords: battery, cost, energy consumption, powertrain, vehicle performance

1 Introduction

As vehicle manufacturers adopt and integrate electric propulsion throughout their fleets, the costs associated with misguided decisions are increasingly large in such a competitive marketplace. The traditional tools and processes utilised to design and optimise powertrains have not necessarily kept up with current technology, and the changing needs of the industry. In their rawest forms, the traditional processes remain time consuming and fragmented, and overly dependent on subjective views, or unconscious bias towards ‘known solutions’. As a result, these processes make it challenging to objectively answer “what is the best electric powertrain for a given vehicle?”.

A fully considered system approach is required to begin to answer this question, and it is this philosophy that has driven the development of tools at Drive System Design (DSD). The Electrified Powertrain Optimisation Process (ePOP) allows thorough mapping of the potential design space of electric powertrain options. The key enabler to this process is the characterisation of subsystem and component design, allowing the process to build complete powertrain variants for simulation. ePOP rapidly generates the necessary input data (masses, efficiency maps, etc.) for each electric powertrain subsystem for a range of topologies and layouts. The rapid generation of input data permits the simulation of a large number of powertrain combinations, compared through intelligent cost functions and trade-off algorithms. This allows trade-off evaluations of cost and efficiency (or vehicle range), both of which are key to the future of highly efficient electric vehicles.

In this paper, the benefits of a system approach such as ePOP are demonstrated through exploration of the potential design space for an electric vehicle. This study will show some of the potential trade-offs that must be considered at a vehicle level in order to truly understand potential benefits or impacts of adopting one subsystem upon another. These trade-offs are specific to the vehicle application and its usage. In this example, the design space for a sports utility vehicle, with requirements of both city and highway driving, will be examined.

2 Optimisation Process

ePOP is a holistic powertrain optimisation tool which encompasses the modelling of each powertrain subsystem and vehicle modelling within a single simulation process. By enabling the tool to do so, it can quickly generate vast numbers of powertrain variants, unaffected by experience, opinion or bias. Each variant can be used in vehicle simulations, allowing quantifiable comparisons, and identification of trends. The user need only define the vehicles parameters, such as mass, aerodynamic and rolling resistance coefficients, and the performance targets to allow the process to define the optimal powertrain for either cost or range.

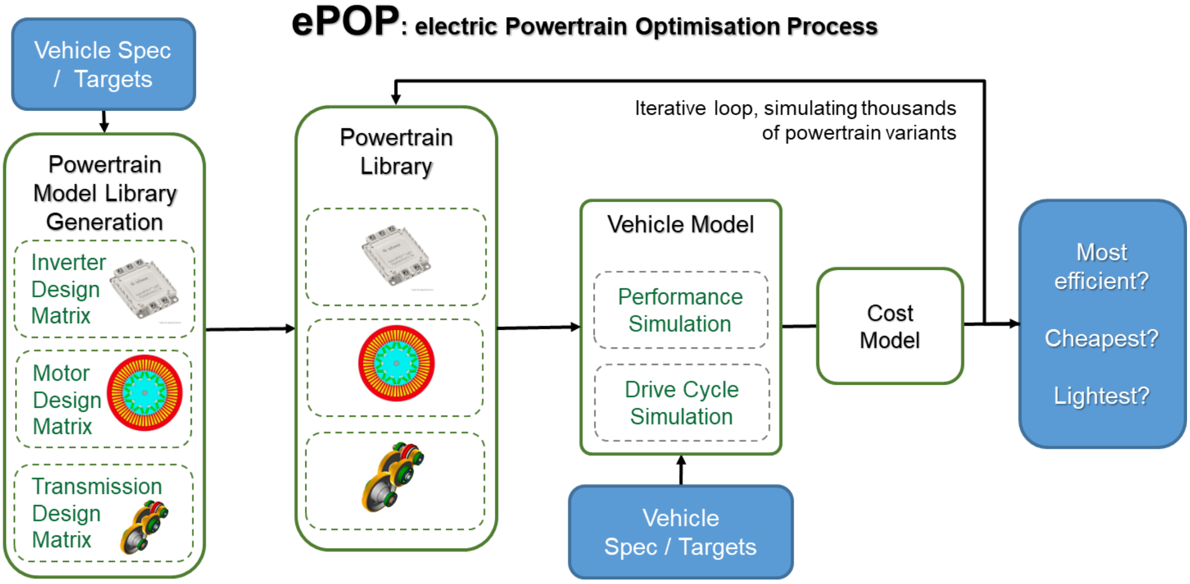

Figure 1 - Electrified Powertrain Optimisation Process (ePOP)

Figure 1 illustrates the overall process where the vehicle specification and targets are not only inputs to the vehicle model, but also used to intelligently define and limit the range of powertrain subsystems to be analysed. The selected powertrain combinations are simulated to analyse the performance of the electric vehicle and the range over drive cycles of interest. Subsystem data and results from the vehicle simulation can then be used in a number of cost functions. As ePOP has generated each subsystem specification itself, sufficient data is known about the subsystem and its constituent components to determine accurate relative costs. The information provided by adopting an analytical system approach gives the user the ability to understand complex trade-offs. An accurate assessment of cost versus range allows the user to explore the design space and determine the best powertrain for the given application.

3 Subsystem Modelling

A key feature of the process is the ability to rapidly and accurately model subsystems and components, to create input data for a range of inverter, electric motor and transmission variants, tailored to the requirements of the application. The process generates each subsystem's characteristics, required for the vehicle simulation and cost functions. Each subsystem model generation process is explained in detail in the following section.

3.1 Transmission Modelling

The transmission subsystem modelling procedure enables the generation of input data for any characterised transmission architecture. A modular approach is adopted where the transmission is broken up into systems of parallel shaft and planetary sets which can be connected in any way to generate a plethora of transmission architectures. Components such as gears, shafts and bearings are primarily sized based on torque and gear ratios that act as multipliers. For example, gears are sized by determining input torque and requested ratio. Whilst the detailed design of a gear pair is a complex process, factors impacting size and power loss are more limited. By controlling key design parameters, the gears' size can scale for torque and ratio, maintaining stress targets based on ISO standards. Multi speed transmissions can be included by adding in systems such as clutches, sized using similar methodologies.

Figure 2 - A range of transmission systems can be considered

Once sized, the masses of transmission internals, gears, shafts, bearings and clutch packs, where relevant, can be determined relatively simply. A comprehensive algorithm is used to calculate an accurate casing size, and therefore mass, for each transmission. The moment of inertia of the system is calculated through the mass and geometry of the system components. A cost is given to the raw material mass of aluminium, steel, and actuation systems, with cost functions for machining and manufacturing.

The subsystem model for each transmission outputs an efficiency map, cost, mass, and moment of inertia. The efficiency of each transmission is based on the mesh losses, loaded and unloaded bearing losses, churning losses and seal losses. Clutch drag losses are also considered along with pump power losses if a mechanical shift system is utilised for a multi speed transmission. Losses are typically based on ISO standard methods, supplemented by further techniques developed and validated in-house at Drive System Design.

An example of the calculated loss breakdown for a single operating point for two transmission architectures is shown in Figure 3. By extending these calculations to a range of speed and torques, operating efficiency maps can be created. A three-stage parallel axis transmission is likely to be both more costly and have more power loss than a two-stage alternative as a result of the additional components and additional interactions. However, for a given total transmission ratio, a three-stage transmission would require smaller individual mesh ratios, which is of benefit to power loss. Furthermore, higher total transmission ratios are possible in a three-stage design, which in turn enables faster, lower torque and thus potentially smaller motor options for the application. Can the additional mass, cost and power loss in the transmission be offset and surpassed by savings elsewhere? Only a system approach as described will give indications as to where this is possible.

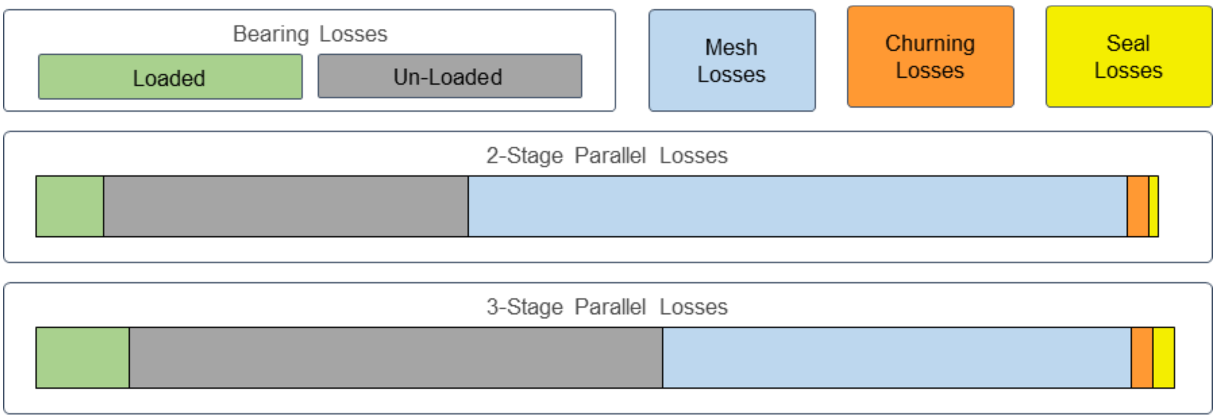

Figure 3 - Example loss breakdown for two transmission architectures for a given operating point

3.2 Electric Motor Modelling

The electric motor models are generated through a subprogram developed in-house in Python, which calls Motor-CAD and automatically parameterises models to generate efficiency maps, material masses and inertias. The motor generation program is capable of generating a number of electric motor design types, utilising the appropriate Motor-CAD modules, including Permanent Magnet Synchronous Machines

(PMSM) with multiple rotor topologies (surface permanent magnet (SPM) and interior permanent magnet (IPM) with multiple layers), induction machines and switched reluctance machines (SRM) as shown in Figure 4.

Figure 4 - A range of different motor types and topologies can be considered

The program receives a topology demand along with a target peak and continuous power/torque, as well as further requirements such as Constant Power Speed Ratio (CPSR), maximum speed or a range of required torque or speed operating points. The program then selects the most suitable base geometry which meets the target power within thermal and structural limits, and iterates through a number of variables, including number of poles, magnet material, diameters and length, among others, to generate multiple designs that meet the required specification. A number of mechanical, manufacturing and electromagnetic constraints have been set to ensure each design is practical, such as rotor tip speed, length and diameter ratios, magnet and bridge thickness, current density, magnetic flux density, DC link voltage and back EMF at maximum speed. The material masses are exported from Motor-CAD and used to generate the total system mass, with motor geometry also contributing to the casing calculation. The cost of the motor is estimated from the raw material weights, and from considering manufacturing processes, in a similar manner as with the transmission.

An example of the losses for a PMSM and induction machine for a single operating point are shown in Figure 5, which in turn allow the generation of efficiency maps. It can be seen that on first impressions, a PMSM machine may be considered the best option, as it is likely to be more efficient. Both copper and iron losses are smaller, and despite the addition of magnet losses, these are sufficiently small such total losses are still less than the induction machine. What ePOP allows is the trade-offs to be investigated. An induction machine would typically be expected to be lower cost than a PMSM due to the lack of magnet content, but without a complete system approach, it would be unclear as to whether this cheaper motor option would be offset by impacts on the system as a result, i.e. increased battery pack size. How efficient could an optimised induction machine based system be in comparison with an optimised PMSM based system, and does the difference in motor cost significantly impact total system cost?

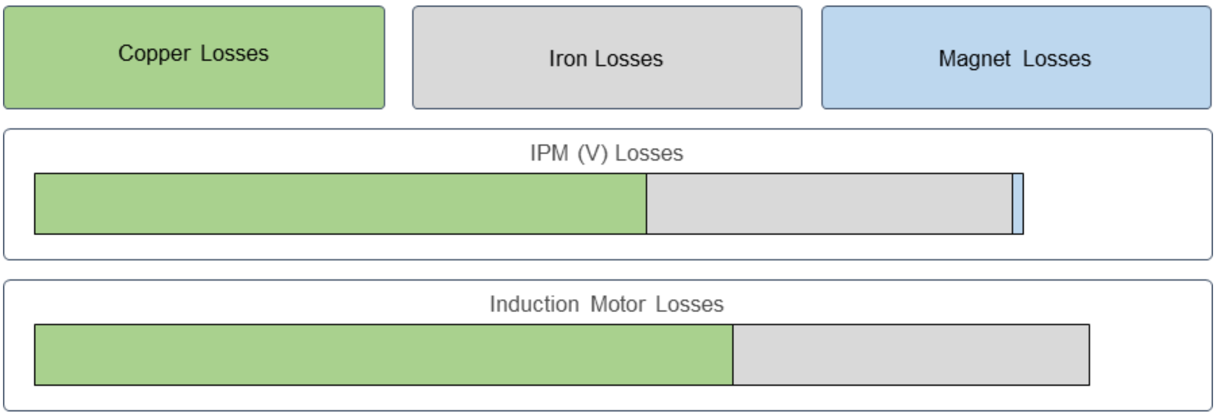

Figure 5 - Example loss breakdown for two electric motor designs for a given operating point

3.3 Inverter Modelling

The two main inverter technologies currently in consideration are the conventional insulated-gate bipolar transistors (IGBT) and more recently available silicon carbide (SiC) metal-oxide-semiconductor field-effect transistors (MOSFETs). ePOP utilises a bespoke, DSD developed and validated inverter model that calculates the inverter efficiency map, mass and cost, all of which are required as inputs for the optimisation process. The inverter efficiency map is based on the inverter losses which comprise four main components; switching and conduction losses of the IGBT/MOSFET, turn-off losses, and conduction losses of the body diodes. These four losses are affected by the device temperature, gate driver resistance, motor power factor, current and DC linkage level, switching frequency and pulse width modulation (PWM) strategy. The inverter loss model incorporates all of these factors, characterising the inverter based on a known switch data sheet or future trends. The inverter cost and mass are based on the module technology and maximum voltage and current ratings.

An example of the losses for an IGBT and SiC inverter are shown in Figure 6. The SiC inverter can be seen to be more efficient than the more standard IGBT, by reducing gate losses, and eliminating diode switching losses. However, this benefit comes at an additional cost. This is an interesting trade-off that ePOP allows the user to investigate: for a given application, when does a SiC inverter become a viable solution, and what can be done in the remainder of the powertrain to enable this decision?

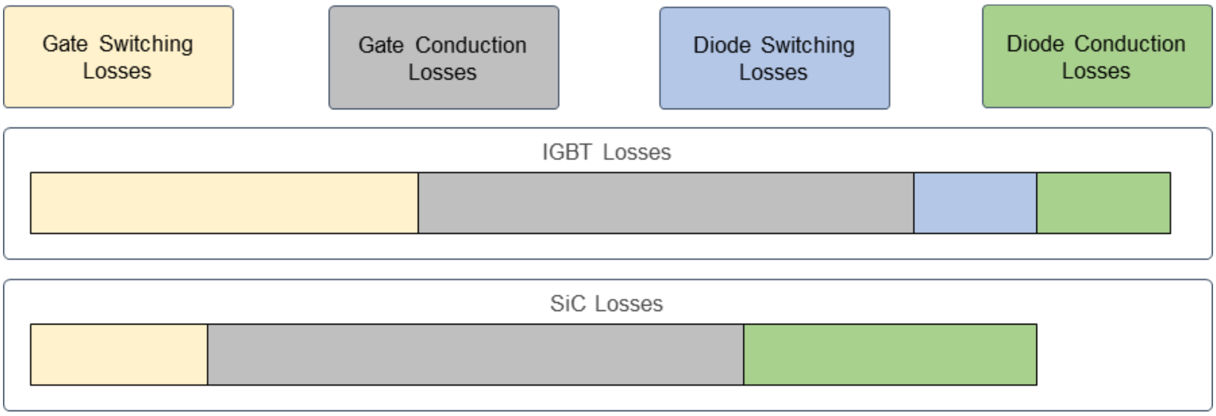

Figure 6 - Example loss breakdown for IGBT and SiC inverters at a given operating point

4 Vehicle Model

The vehicle models are based in MATLAB/Simulink with a backwards-facing model being utilised for drive cycle simulation due to the computation efficiency, and a forward-facing model used for performance simulations (full-throttle acceleration tests). The backwards-facing vehicle model accounts for the vehicle inertia, rolling resistance, aerodynamic drag and gradient to calculate the torque required at the wheel and, through considering each components inertia and efficiency map, the energy required to carry out each drive cycle is calculated. The performance model can consider the first-order drivetrain dynamics and a tyre model.

The benefit of the vehicle model is that it allows subsystem performance to be directly related to vehicle targets, whether that's acceleration, top speed, or drive cycle efficiency. This extends the system approach further, allowing assessment and comparison of different systems across their operating conditions, rather than contrived load cases where one system may outperform another, in an unfair comparison. This allows the user to identify trends that result in quantifiable performance benefits, such as effects on 0-100 kph time, drive cycle energy usage, or vehicle range for a given battery size.

When simulating multi-speed transmissions, an idealised approach is taken to allow the fairest comparison of powertrain architectures, avoiding the influence of pre-defined control strategies. As a result, the vehicle is allowed to operate in the optimal gear at each time during the cycle. The shift energy is calculated during post processing to account for all energy losses/regeneration, with shift efficiency taken into account.

5 System Cost

The cost function is primarily based on the bill of materials (BOM) cost of each powertrain subsystem which is accurately estimated for each subsystem architecture considered. Additional costs and weightings can be added based on exceeding or not meeting targets for weight and/or performance, or penalised as a result of associated NVH risk, or exceeding a given package volume or shape.

A key contributor to electric vehicle cost is the battery. Within the cost function, the process can adjust the battery capacity required to attain a defined target range through consideration of the change in system energy consumption over the drive cycle. This affects the total vehicle cost and enables the powertrain cost to be offset against the battery cost, allowing the user to accurately quantify the benefit of investing in the powertrain. An alternative to this approach would be to consider a fixed battery capacity and cost and evaluate the effect on vehicle range as an effect of powertrain decisions. Vehicle range is a key marketable attribute, as a perceived shortfall of electric vehicles, and a barrier to entry to many consumers.

6 Case Study

To explore the benefits of a system approach such as ePOP, this section will explore the design space of an electric vehicle powertrain for a case study vehicle. The aim of this study is to understand the potential trade-offs involved in the specification of the powertrain subsystems, and ultimately identify optimal solutions in terms of energy consumption and cost.

In order to do so, first the vehicle and application must be understood. In this case study we will examine a purely electric, premium sports utility vehicle (SUV) with a fixed battery capacity. The requirements of the vehicle were to attain a top speed of 180kph and have at least 3750 Nm maximum torque to be available at the wheels, to meet both acceleration times and gradeability requirements. These specifications alongside other vehicle data provide the starting point for the examination of the design space. The vehicle parameters can be found in Table 1 in the Appendix.

The design space exploration was run using a range of powertrain options, with variations in inverter, motor and transmission. In this example, all powertrains were simulated using the Worldwide Harmonised Light Vehicle Test Cycle (WLTC) to assess energy consumption. The number of powertrain options used in the simulation were limited for presentation in this paper. However, further variations can be considered, depending on the application and requirements, with areas of interest studied further.

The motors studied here are designed to a maximum speed of 18,000 rpm only and has one of two different magnet topologies; V-shaped, or U-shaped magnet topologies. Each variant was designed with 6, 8 or 10 poles, and operated with a maximum motor current of 350 A_{rms}, 400 A_{rms} or 450 A_{rms}. Each motor was paired with either an IGBT or SiC MOSFET inverter. Finally, each motor-inverter combination was combined with each transmission type. For this case study, the options were limited to parallel axis transmissions, considering either two or three gear stages. The two-stage transmissions were also simulated with a two-speed option. Within each of these transmission options, a wide number of ratios were simulated in order to be able to select an optimal ratio for energy consumption and cost.

7 Results

Every combination of powertrain that met the constraints set by the performance criteria for the case study vehicle was analysed over the WLTC. The resulting energy consumption and system cost for each powertrain iteration are shown in Figure 7, where the large number of unique powertrains that have been analysed can be seen.

The two clear clusters in Figure 7 indicate the two inverter types analysed in the study. The powertrains utilising a silicon carbide inverter form the top cluster of results, shown in green, whilst the powertrains with IGBT inverters are in the lower cluster, shown in blue. This shows the clear benefit in energy consumption through the improved efficiency associated with the use of the newer technology (SiC), owing to reduced switching/diode losses. Whilst this technology is in its relative infancy in the automotive sector, the technology is beginning to become more common place, especially in higher specification vehicles. As a result, it is likely to become the industry standard, leading to lower costs, but also risk associated with not adopting the technology and the effect on position in the marketplace once it becomes more viable.

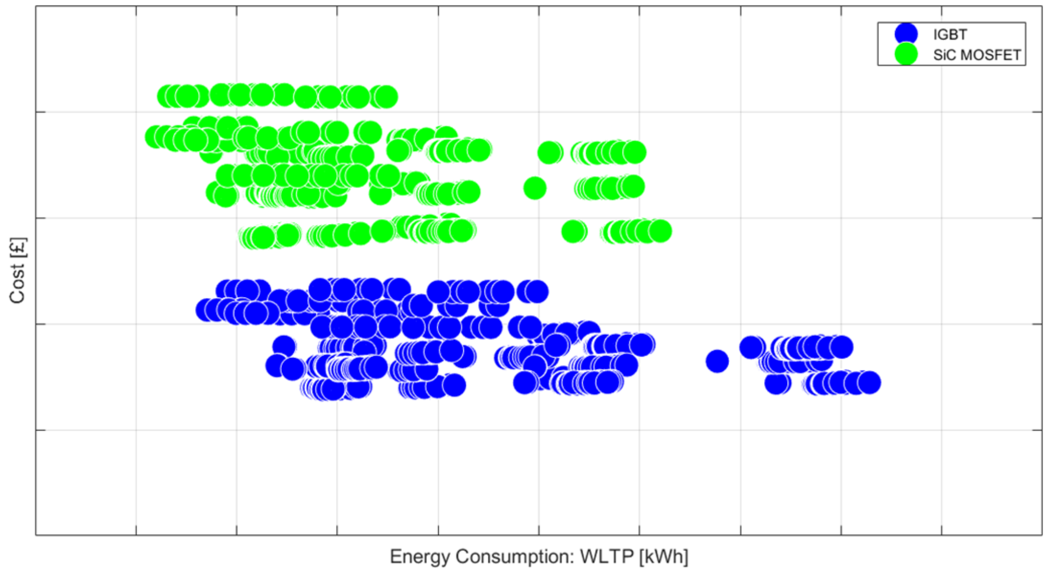

Figure 7 - WLTC energy consumption vs. system cost for alternative inverter designs

For clarity, Figure 8 shows the IGBT based powertrains only and shows the effects of motor magnet topology on drive cycle energy consumption and system cost. The two motor topologies considered, V-shaped and U-shaped, are indicated in blue and green respectively. The trends show a distinction between powertrains utilising a V-shape motor topology in comparison with a U-shape, with U-shape topologies typically using less energy over the drive cycle. The U-shape motors have greater reluctance torque contribution, and so require less field weakening current at high speeds, in turn reducing copper losses. This results in slightly different shapes of efficiency map for the two motor topologies. The U-shape topologies typically have a wider peak efficiency region that extends to higher speeds, whilst the V-shape are typically more localised at lower speeds. For a single ratio transmission, this favours the U-shape motor topology. However, for a two-speed transmission, the impact is reduced.

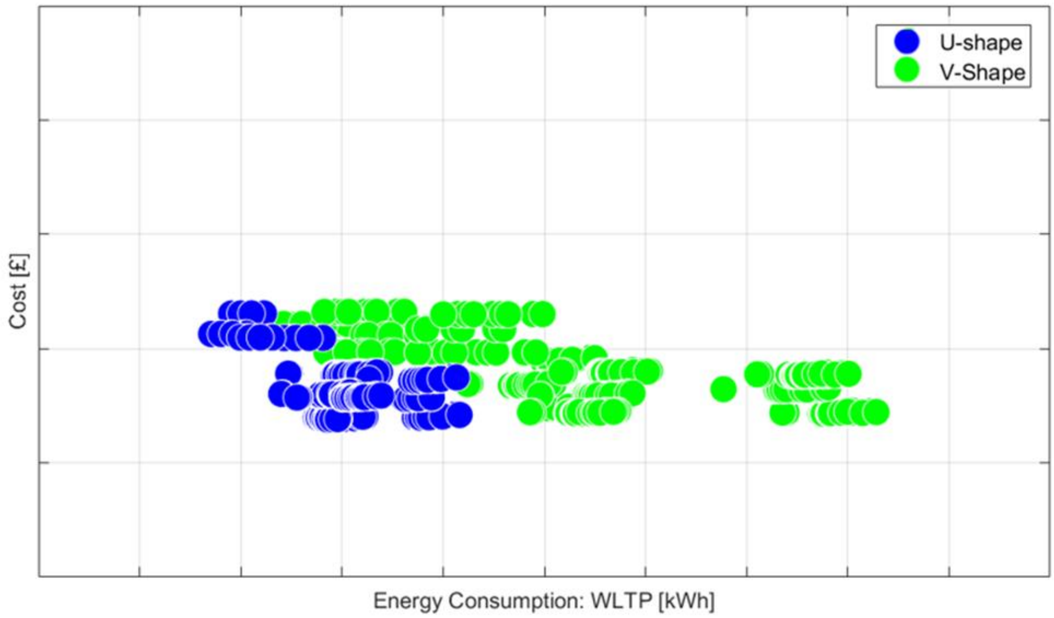

Figure 8 - WLTC energy consumption vs. system cost for alternative motor designs (IGBT inverter based powertrains only)

Figure 9 shows the effect of transmission selection on the same group of powertrains. A two-speed transmission enables the peak efficiency region the motor to be more effectively utilised, and this is reflected in the reduced energy consumption. Not only is the minimum energy consumption reduced, but so is the difference between the most and least efficient powertrains. Through further study of the design space, this opportunity could be further explored to optimise the motors and the peak efficiency region specifically for a two-speed transmission and optimise gear ratios to further reduce energy consumption. This further work is of importance to attempt to offset the additional cost associated with a two-speed design in shift mechanism and additional components.

For a simpler, single speed transmission, it can be seen there where possible, reducing the number of gear meshes and bearings results in reduced energy consumption, as seen by the comparison of two-stage to three-stage architectures. As the costs are typically dominated by the inverter and motor, the additional components in the three-stage transmission add relatively little to the cost of the system as a whole.

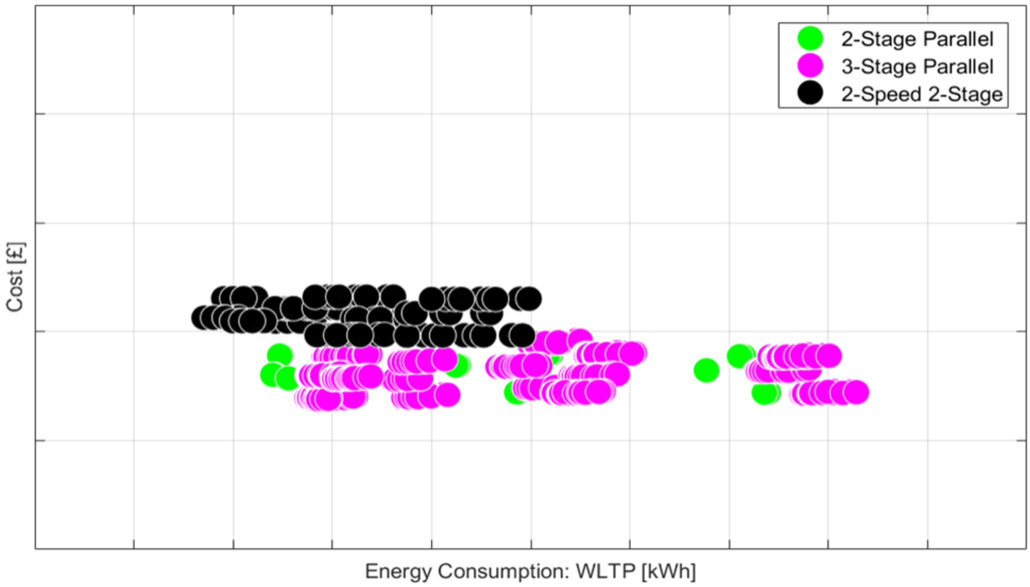

Figure 9 - WLTC energy consumption vs. system cost for alternative transmission designs (IGBT inverter based powertrains only)

Within each of the groups studied thus far, more parameters can be explored to further assist in the decision making process. Figure 10 and Figure 11 show the effect of two further motor parameters on system cost and energy consumption; the number of poles, and the motor current. Figure 10 shows that increasing the number of poles and the subsequent electrical frequency of the motors tends to increase energy consumption. This is due to both increased switching losses in the inverter, and increased iron losses in the motor. One potential benefit of the increase in pole number, is the effect on NVH. Increasing the number of poles could result in reduced amplitude of motor excitation sources such as torque ripple. In future detailed studies, NVH risk associated with different design decisions can be penalised as part of the cost model, and trade-offs considered against energy consumption.

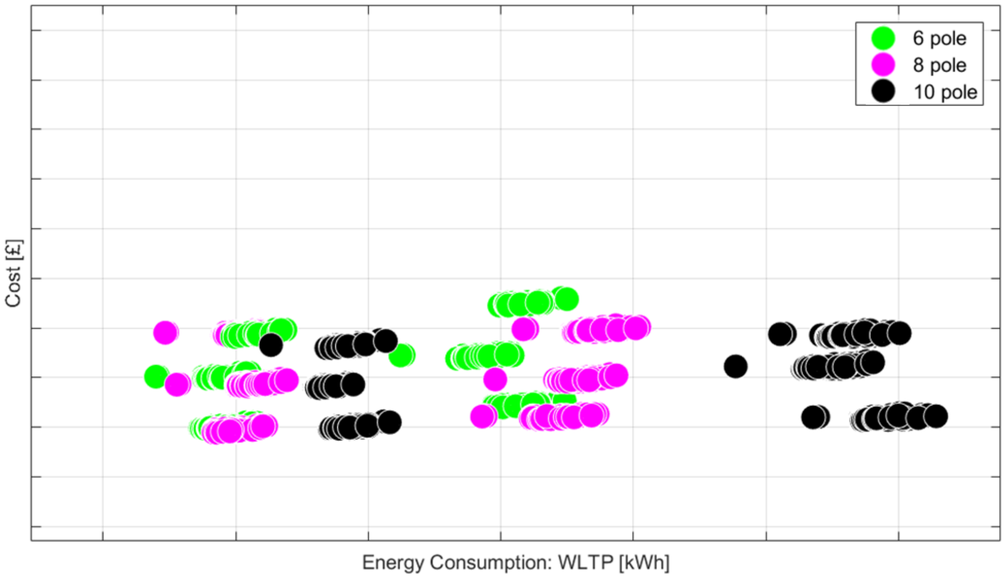

Figure 10 - WLTC energy consumption vs. system cost for alternative motor pole numbers (IGBT inverter based powertrains only)

Figure 11 shows the effect of changing the operating current of the motors. The effect on the energy consumption is relatively minor, with the range fully covered by all current alternatives. However, as a result of changing current there is a clear change in the system cost. By utilising more current, the amount of magnet within a motor can typically be reduced. This would appear to be an appealing prospect due to the cost, and cost instability, typically associated with magnets. However, this is contradictory to the trends observed in this example. By increasing the current, the kVA demand on the inverter has increased, and the cost benefit of the reduced magnet content has been offset. As a result, the powertrains utilising higher current motors cost more as a system, than those at lower current. This reinforces why a system approach is necessary, and that focussing upon the optimising of subsystem may not yield the best overall outcome.

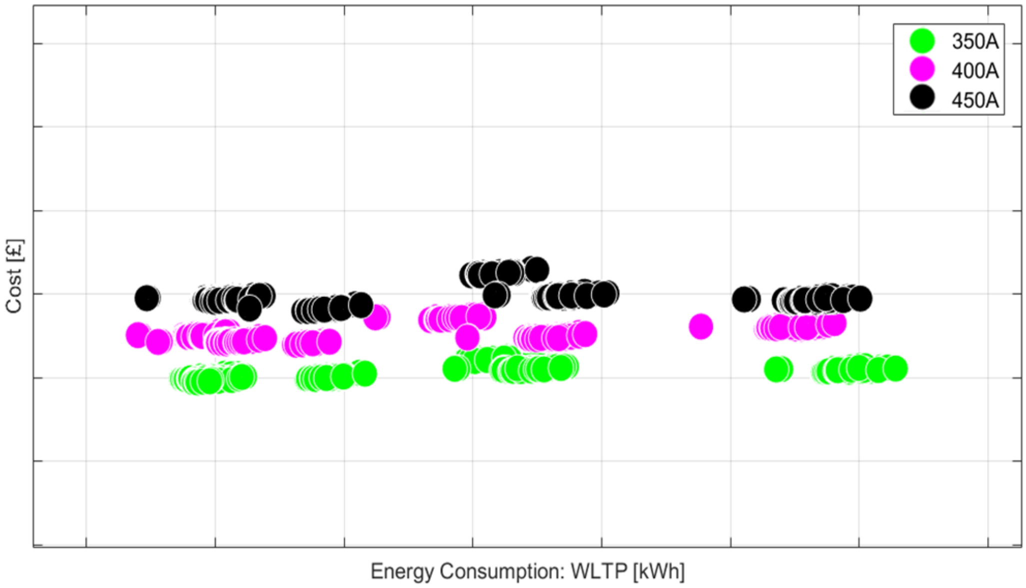

Figure 11 - WLTC energy consumption vs. system cost for alternative motor currents (IGBT inverter based powertrains only)

However, whilst the results presented so far show the effects of a system approach for the powertrain, a key subsystem in electric vehicles has not yet been considered; the battery. Battery size, capacity and cost are all key drivers in what electrified powertrains will look like today, tomorrow and further into the future.

Figure 12 shows the same results as previously shown in Figure 7, where the energy consumption and system cost for the two inverter variants, IGBTs and SiC MOSFETs, are shown in blue and green. In Figure 12 however, the battery has been considered in the cost model, as described in Section 5. In this example, a fixed battery capacity has been assumed, and the subsequent average vehicle range has been considered as a baseline. For every kWh extra required to achieve this baseline range, the specific powertrain variant is penalised with an additional battery cost. Similarly, those powertrains that achieve the target range with energy to spare, are rewarded with a battery price reduction.

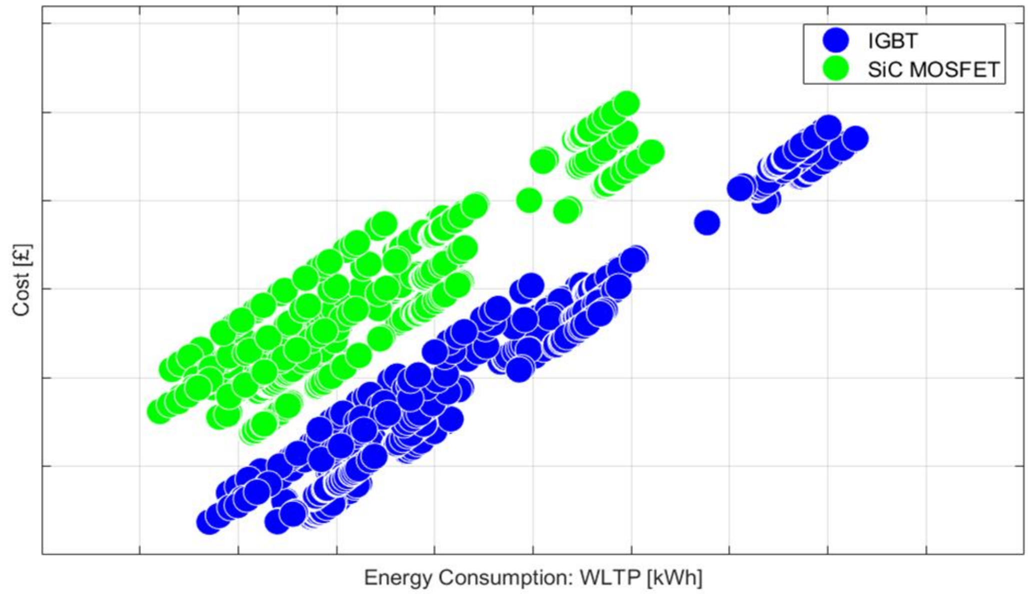

Figure 12 - WLTC energy consumption vs. system cost including battery for alternative inverter designs

Consideration of the battery cost further rewards an efficient system. Less efficient systems become increasingly expensive to ensure target range can be met. As battery costs dominate those of the powertrain, as well as causing packaging and weight management issues, any saving in energy consumption results in substantial benefits to the vehicle manufacturer. This can be utilised in several ways, for example, for a given vehicle range target, a reduced capacity, cheaper, smaller and lighter battery could be specified. Alternatively, the same capacity battery could be specified in order to gain extra vehicle range, resulting in a competitive advantage over another manufacturers.

From the results of this case study, the benefits of a system approach can be seen. This allows powertrains with low energy consumption to be selected for further concept design studies. For this case study, this results in a two-stage, two-speed transmission, with a U-shape, 6 pole motor. In this instance, using a current of 400 A_{rms} resulted in the most efficient system, although energy consumption results were shown to be relatively insensitive to current. It would be recommended to use the results of the study to investigate further. The final specification depends the target cost of the system. For the most efficient system, a SiC MOSFET inverter should be selected, although this comes with increased cost. To minimise the cost of the system, an IGBT inverter could be selected as an alternative.

8 Conclusions

The design and optimisation of electric powertrains remains, as a process, in its infancy, resulting in both challenges and opportunities. New technologies are being continually developed, but the cost of adoption in comparison with performance benefits are not always easy to quantify. The process and tools used by DSD aim to do so by considering a system approach, that allows subsystem model generation within itself, enabling concept generation to occur iteratively. Through characterisation of subsystem and component level behaviour, accurate system performance and costs can be predicted. This enables mapping of the potential design space, investigation of a wide range of complex interactions, and evaluation of new concepts at a system level.

In the example presented, several counter intuitive behaviours have been observed as a result of a comprehensive system analysis approach such as ePOP affords. It has been shown that drive cycle energy consumptions must be optimised, rather than an outright peak efficiency, as shown by comparing two typical motor magnet topologies. Two-speed transmission variants can be utilised in order to take advantage of peak efficiency but require further optimisation to outweigh associated costs. Finally, optimisation of subsystems in isolation is unlikely to result in the best overall system, as demonstrated by the increase motor current to reduce magnet mass merely shifting cost from the motor to the inverter.

The results presented in this paper are intended to be indicative of the potential that exists using this, or similar processes. All electric vehicle powertrains should be designed using a system approach, that allows each major subsystem to be designed to work harmoniously with one another. The process outlined in this paper allows optimisation of the powertrain for a given application by considering the operating conditions of a given powertrain option over a given drive cycle.

Acknowledgments

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Appendix

Table 1- Vehicle simulation parameters

Parameter	Unit	Value
Mass	kg	2500
Wheel radius	m	0.35
Drag Coefficient, Cd	-	0.32
Front Area	m^2	3.5
Rolling Resistance Coefficient	-	0.013

Authors

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