https://doi.org/10.21122/2227-1031-2019-18-6-461-470

UDC 629

Electric Propulsion Systems Design Supported by Multi-Objective Optimization Strategies

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Abstract. Electric drive systems consisting of battery, inverter, electric motor and gearbox are applied in hybrid- or purely electric vehicles. The layout process of such propulsion systems is performed on system level under consideration of various component properties and their interfering characteristics. In addition, different boundary conditions are taken under account, e. g. performance, efficiency, packaging, costs. In this way, the development process of the power train involves a broad range of influencing parameters and periphery conditions and thus represents a multi-dimensional optimization problem. State-of-the-art development processes of mechatronic systems are usually executed according to the V-model, which represents a fundamental basis for handling the complex interactions of the different disciplines involved. In addition, stage-gate processes and spiral models are applied to deal with the high level of complexity during conception, design and testing. Involving a large number of technical and economic factors, these sequential, recursive processes may lead to suboptimal solutions since the system design processes do not sufficiently consider the complex relations between the different, partially conflicting domains. In this context, the present publication introduces an integrated multi-objective optimization strategy for the effective conception of electric propulsion systems, which involves a holistic consideration of all components and requirements in a multi-objective manner. The system design synthesis is based on component-specific Pareto-optimal designs to handle performance, efficiency, package and costs for given system requirements. The results are displayed as Pareto-fronts of electric power train system designs variants, from which decision makers are able to choose the best suitable solution. In this way, the presented system design approach for the development of electrically driven axles enables a multi-objective optimization considering efficiency, performance, costs and package. It is capable to reduce development time and to improve overall system quality at the same time.

Keywords: automotive engineering, electric powertrain, mechatronics system, development process, system design, multi-objective optimization

For citation: Hirz M., Hofstetter M., Lechleitner D. (2019) Electric Propulsion Systems Design Supported by Multi-Objective Optimization Strategies. *Science and Technique*, 18 (6), 461–470. https://doi.org/10.21122/2227-1031-2019-18-6-461-470

Проектирование электрических силовых установок при поддержке многоцелевыми стратегиями оптимизации

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Реферат. Системы электропривода, состоящие из аккумулятора, инвертора, электродвигателя и коробки передач, применяются в гибридных или чисто электрических транспортных средствах. Процесс компоновки таких движительных систем осуществляется на системном уровне с учетом различных свойств компонентов и их интерферирующих характеристик. Кроме того, учитываются разные граничные условия, например технические характеристики, эффективность, комплектование, стоимость. Таким образом, процесс разработки силовой передачи включает в себя широкий диапазон влияющих параметров и периферических условий и тем самым представляет собой проблему многомерной

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оптимизации. Современные процессы разработки мехатронных систем обычно выполняются в соответствии с V-моделью, которая представляет собой фундаментальную основу для управления сложными взаимодействиями различных дисциплин. Кроме того, применяются этапные процессы и спиральные модели, чтобы справиться с высоким уровнем сложности при разработке, проектировании и тестировании. Вовлекая большое количество технических и экономических факторов, эти последовательные рекурсивные процессы могут привести к неоптимальным решениям, поскольку процессы проектирования системы недостаточно учитывают сложные отношения между различными, частично конфликтующими областями. В этом контексте настоящая публикация представляет интегрированную многоцелевую стратегию оптимизации для эффективной концепции электрических силовых установок, включающую комплексное рассмотрение всех компонентов и требований на многоцелевой основе. Синтез системного дизайна основан на Парето-оптимальных конструкциях со специфическими компонентами с целью обеспечения работы, эффективности, комплектации и затрат, предусмотренных для данной системы. Результаты отображаются в виде Парето-фронтов вариантов систем электрических трансмиссий, из которых лица, принимающие решения, могут выбрать наиболее подходящее из них. Таким образом, представленный подход к проектированию системы для разработки осей с электрическим приводом обеспечивает многоцелевую оптимизацию с учетом эффективности, функционирования, стоимости и комплектации. Данный подход позволяет сократить время разработки и одновременно обеспечить улучшение качества системы.

Ключевые слова: автомобилестроение, электрическая трансмиссия, мехатронная система, процесс разработки, системное проектирование, многоцелевая оптимизация

Для цитирования: Хирц, М. Проектирование электрических силовых установок при поддержке многоцелевыми стратегиями оптимизации / М. Хирц, М. Хофштеттер, Д. Лехляйтнер // *Наука и техника*. 2019. Т. 18, № 6. С. 461–470. https://doi.org/10.21122/2227-1031-2019-18-6-461-470

Automotive development processes and integration of propulsion systems design

Car development processes are composed of a number of steps and require complex interaction of car manufacturer, system- and components supplier as well as engineering provider. During past decades, an increasing application of virtual engineering provided great potential for reduction of development time and increasingly supported collaboration of the different involved parties. Nowadays, a typical full-vehicle development project has a duration of about 4 years (in case of derivate development less than 3 years) and the trend is moving towards further decrease [1]. As one main module, the drivetrain system plays an important role in the development of new cars – especially in case that new, electrified propulsion systems are going to be designed and integrated into the full-vehicle architecture. Fig. 1 shows the sequence of sections of a typical automotive development process. In addition to the main process phases, selected development disciplines are added, which are relevant for the development of propulsion systems.

In the beginning, the *Definition Phase* includes a compilation of characteristics of the new car to be developed, which comprises market research of future trends under consideration of customer demands and legislative boundary conditions. In addition, manufacturer-related strategic aspects are considered, e. g. integration of the planned model into existing model ranges or the development of new vehicle architectures, e. g. electric car platforms. At the end of the *Definition Phase*, product specifications are defined, which involves a definition of requirements for the subsequently performed vehicle development, containing a long list of prescribed product characteristics. In view of the propulsion system, this includes performance parameters, energy/fuel consumption, different types of boundary conditions, e. g. packaging- and space requirements, costs and others. In addition, technological specifications are pre-defined in this phase, e. g. type, layout and configuration of the powertrain to be developed.

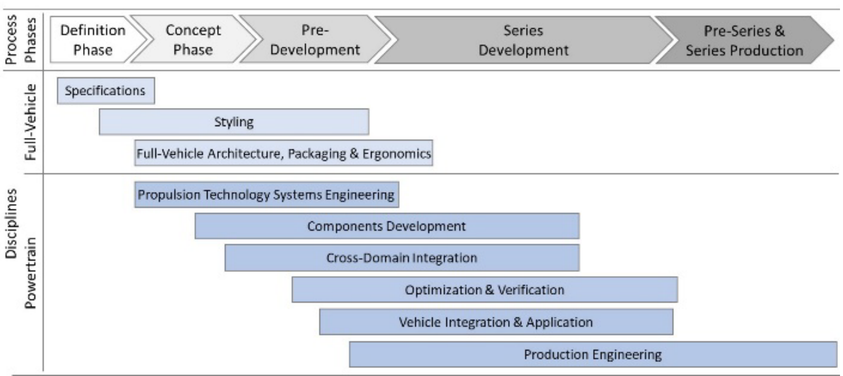

Fig. 1. Process phases and development disciplines in typical state-of-the-art car development

The development process itself starts with the *Concept Phase*, which includes conceptual design of the complete vehicle layout including styling, vehicle packaging and ergonomics, body and component development, and of course the propulsion system. Beginning with initial styling works, the vehicle architecture is built up and all components are integrated [2]. Drivetrain modules are taken over from existing platforms or newly developed, including new technologies, e.g. electric or hybrid propulsion systems. Here, it has to be distinguished between so-called conversion design and specifically developed electric vehicle platforms. In conversion design, hybrid- or electric drivetrain technology is implemented into traditional vehicle architecture. In many cases, the car to be developed is built on an existing vehicle platform that enables the integration of different types of drive train systems, e. g. combustion engine, hybrid-concepts and purely electric drive.

Fig. 2 shows such a vehicle architecture by an example of the Volkswagen Golf. As a difference, special-purpose design enables the optimized development of vehicle architecture according to the requirements of a specific propulsion technology. In this way, the result is optimized regarding the demands of electric drive architecture, but the flexibility concerning an implementation of different propulsion technologies is reduced. Fig. 3 exemplary shows a modern electric platform design, which is modular in view of variable wheelbase and configuration of the driven axles.

The *Pre-Development Phase* includes a continuation of concept development under consideration of detailed technological and economical aspects. This covers finalization of styling works, engineering of all components and modules, as well as far reaching verification and validation. In addition to virtual development, prototypes of modules and even vehicles are tested and investigated on test beds and on road. In this phase, engineering-, component- and module suppliers are increasingly involved in the development process.

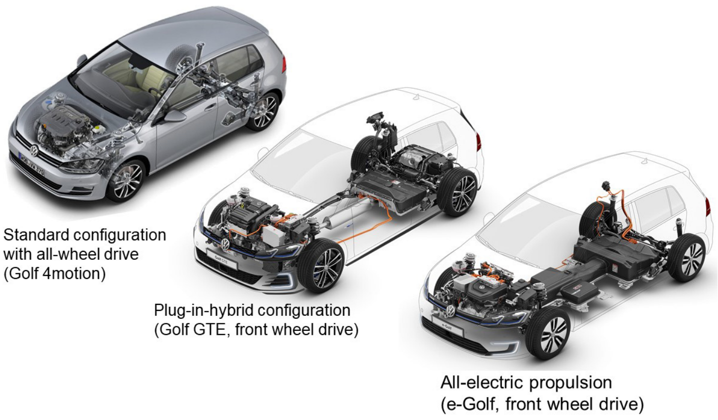

Fig. 2. Different drive train configurations of the Volkswagen Golf [3]

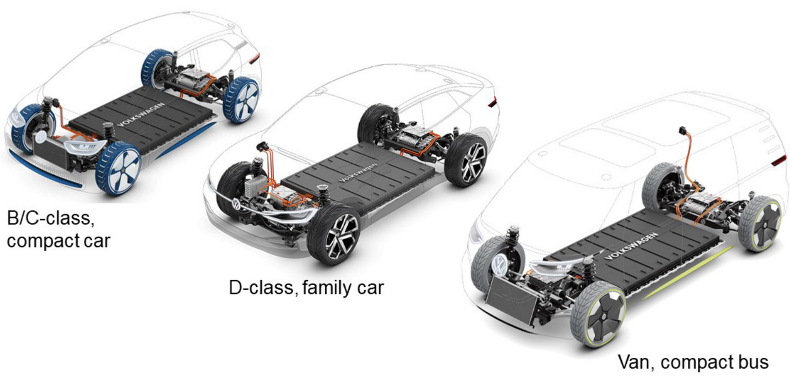

Fig. 3. Modular electric car platform from Volkswagen [4]

The *Series Development Phase* has a strong relation to production development and supplier integration including logistics, assembling processes and quality engineering. In this phase, a comprehensive virtual vehicle model serves as a basis for far reaching investigations of manufacturing-related procedures. At the end of this phase, both the new car model and its production are completely developed and all interactions with manufacturing facilities and suppliers are defined.

The final phase of car development includes *Pre-Series & Series Production*. Final settings of the assembly line and in the logistics management are done during the production of initial pre-series models. This includes final adjustments of machines and robots as well as quality related investigations, e. g. in the paint shop or optimizations in view of tolerances. After homologation of the new car in target markets, series production phase starts.

Electric propulsion systems are increasingly applied in both hybrid- and purely electric driven cars today.

In case of hybrid drivetrain technologies, there are different topologies available, e. g. parallel, serial and combined hybrids. Some of these topologies directly connect the electric motor(s) to the combustion engine or integrate them into the gearbox; others use electric driven axles. In case of purely electric propulsion, electric axles come to use. In this way, electric axle drives represent central components in a wide range of applications of hybrid- and electric driven cars. Fig. 4 shows an exemplary design of an integrated electric axle drive, consisting of power electronics (inverter), electric motor and a gearbox unit, which also contains the differential gear and drive shaft joints. Not shown in the figure, but essential is the drivetrain control system that is typically part of the inverter, consisting of a powerful microcontroller and embedded software.

The design process of electric axle drive systems is of high complexity because of the required integration of inverter, electric motor and mechanical gear, which covers three technological domains: mechanical, electrical and software engineering. In this way, a development process for mechatronics systems is presented, which supports an effective integration of cross-domain development. Initially, the so-called V-model stems from software development, and was taken over into other industries during the past decades. Today, it represents a standardized development process for mechatronics systems [6].

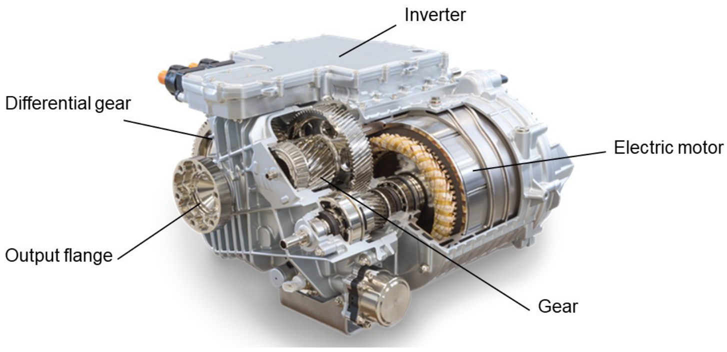

Fig. 4. Exemplary electric axle drive configuration [5]

Fig. 5 shows a typical development process of automotive mechatronics systems according to the V-model [6, 7], which represents a special case of a waterfall model that describes sequential steps of product development [8, 9].

The process starts at the top end of the left branch with product specifications that result from a list of requirements. The entire left branch focusses on product design and is divided into a sequential chronology with increasing levels of detail. The *System level* includes product main level-related development, e. g. vehicle architecture, packaging, technology integration. After having defined main characteristics on *System level*, the *Module level* includes a breakdown of complex systems into several modules, e. g. vehicle body, drivetrain, chassis, comfort and driving assistance modules.

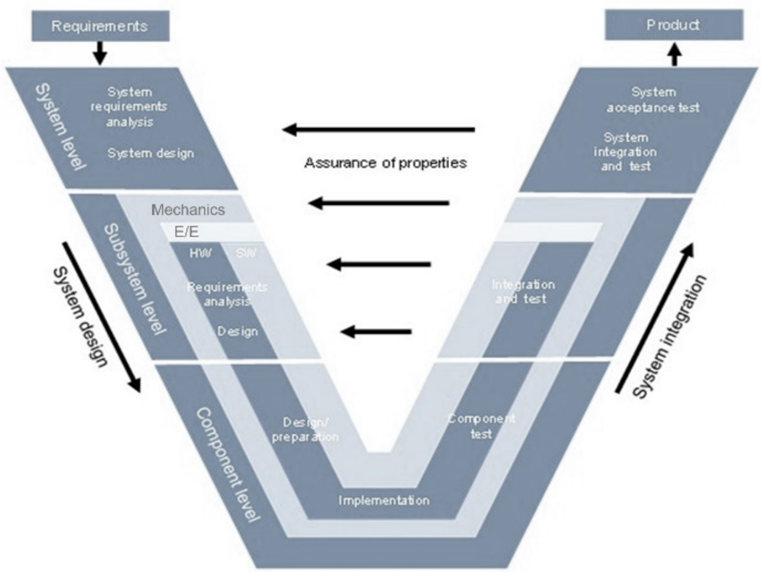

Fig. 5. Development process according to the V-model, according to [6, 7]

The different modules are designed under consideration of their interaction with other modules and in accordance with full-vehicle related specifications. Finally, modules are divided into their components, which are developed in the *Component level*. Cross-domain implementation is performed at the bottom level of the V-model in the course of component integration. Today, this is mainly done by product-oriented processes, which focus on product characteristics and functionalities.

The right branch of the V-model includes integration, testing and optimization at *Component-Module*- and *System level*. After being tested, components are built together into modules, which are integrated and tested according to their specific functionalities. In the final *System level* at the top end of the right branch, all elements are assembled to a full-vehicle prototype and tested for product compliance with the initially defined specifications. Typically for development according to the V-model is a close interaction of design and testing. In this way, data and information exchange between product design (left branch) and integration & testing (right branch) supports efficient improvements and optimization.

Fig. 5 also points to the different domains that occur in the development of mechatronics systems: mechanics, and electrics/electronics (*E*/*E*). *E*/*E* is divided into hardware and software development. One key of success lies in the introduction of flexible, interdisciplinary processes, which are able to consider different domain-specific methodologycal, functional and development-cycle-time related characteristics with the target of providing all product- and process-related information for effective cross-domain development of the mechatronics systems. Besides geometrical, structural, functional and production-related information of mechanics and hardware, this also includes software-related requirements, structural and functional information.

In case of highly complex products, e. g. electric axle drives, the development process is run through several times, especially on module and component level. Both duration and complexity of these development cycles differ significantly in the three domains, which leads to varying levels of maturity levels throughout mechanic, hardware and software development. The different domain-specific development procedures in combination with varying cycle frequency lead to a considerable increase of complexity in the development processes. This complexity can be handled by use of so-called spiral models. The spiral model stems initially from software industry, where it was developed to support handling of the complex (purely virtual) development processes during design and testing of control algorithms, programs and IT-applications, [10]. Fig. 6 displays an exemplary spiral model of mechatronics systems development processes following the V-model that highlights the separation of the development processes into *System* design as well as *Mechanics-Electrics* and *Software* development. In the example, the subsequently performed process phases are shown in more detail for the *System* level. The processes of the three development domains are not shown in detail but follow the same principle, considering the specific procedures of mechanics, electrics and software development. In practical applications, the V-model is run through repeatedly at the different levels and domains.

The phase of systems engineering plays an essential role in the development of complex mechatronics products, because it includes the general functional and structural layout. Out of knowledge gathered in the systems engineering phase, the subsequently performed domain-specific processes are supplied with required data and information for successful product development. In this way, the systems engineering phase has to fulfill the task of cross-domain conceptual design of mechanical, electrics and software components as well as their integration into the product to be developed.

In the development of electric propulsion systems, e. g. electric axle drives, the systems engineering phase includes the conceptual layout, optimization and integration of all involved components. Besides functional development, which focuses on performance characteristics, energy efficiency, controller design and embedded software, the proper selection and layout of electrical and mechanical components plays a crucial role. According to the introduced development process of mechatronics systems (Fig. 5, 6), system design is placed at the beginning of the V-model, respectively in the center of the spiral model. Considering the general automotive development process as stated in Figure 1, the focus of the presented approach is put on the initial phases, e. g. *Definition Phase* and *Concept Phase*. During these early layout and design procedures of electric axle drives, a number of boundary conditions, parameters and influencing factors have to be considered. These factors are partially uncertain because of early development stages and in addition often conflicting in terms of system optimization. In this context, the layout of electric axle drives represents a multi-objective, multi-criterial task that requires enhanced optimization methods.

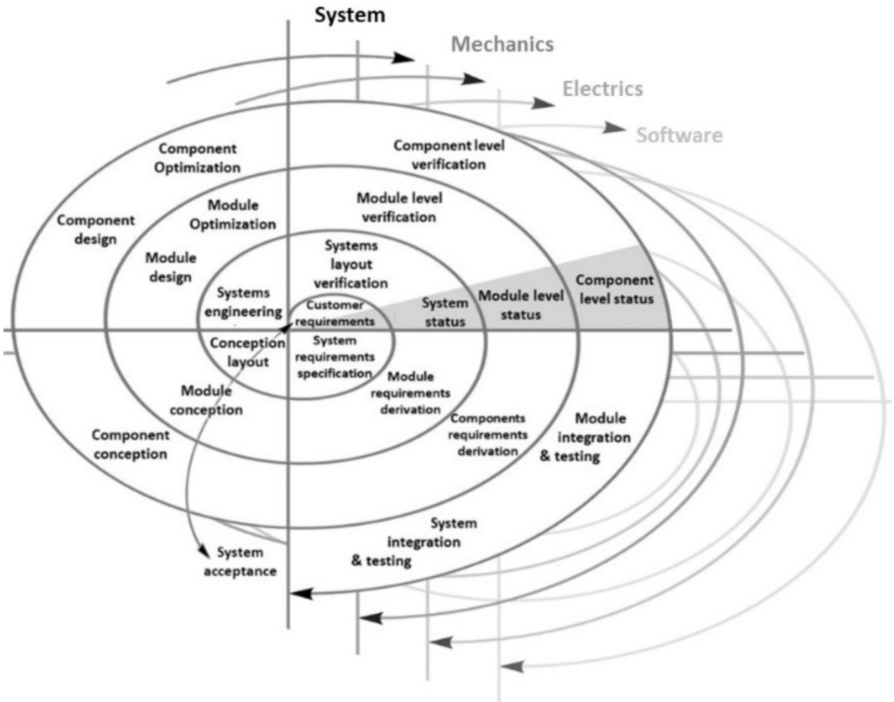

Fig. 6. Spiral model of mechatronics systems development processes following the V-model

Multi-objective design optimization of electric axle drives

Multi-objective design optimization of electric axle drives comprises the components electric motor, gearbox including differential gear, and the power electronics (inverter). The power supply system (battery, a combination of combustion engine and battery, or a combination of battery and fuel cell) is an additional important area of development, but this topic is not considered in the present work in more detail.

Today, there are two major topologies for electric axles available, which are basically set by the gearbox design: offset configuration and concentric configuration (Fig. 7). The offset design is the most common topology in the market, which is characterized by an axial offset between helical gearbox input and output shaft [12]. The concentric design often uses planetary gears and is more compact in general – but axial length restrictions and ground clearance are more critical, e. g. [13].

Typically applied electric machines are induction motors (IM, also called asynchronous machines, ASM) or permanent magnet synchronous machines (PSM). Both technologies are used as traction motors and should be considered in the systems engineering phase. Due to the introduced drivetrain configurations (Fig. 7), most of the gearbox solutions have an offset helical gear design (single-gear, two stage) or concentric designs with planetary gears.

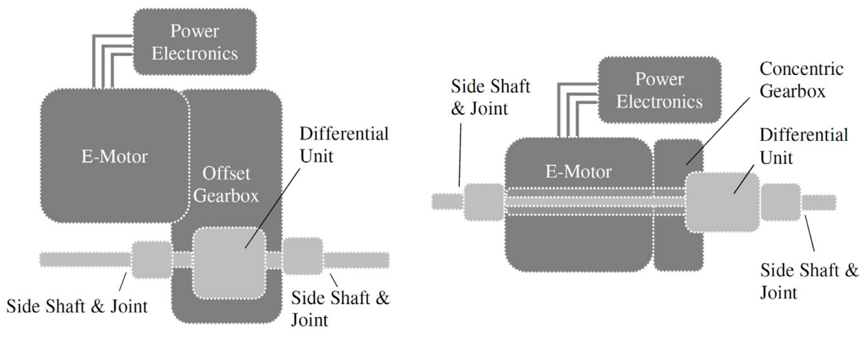

Fig. 7. Exemplary axle drive designs in offset (left) and concentric (right) configuration [11]

The gearbox design is adjusted to the mechanical loads induced by the electric motor under consideration of different load conditions. The integrated differential unit is usually a common part for all variants. Non-shiftable gearbox design is well established, since the speed range and torque characteristic provided by the electric motors is sufficient to cover the vehicle speed and torque requirements with one fixed transmission ratio. However, there are also some electric cars with two-speed gearboxes to enlarge the vehicle speed range and to improve the longitudinal vehicle dynamics behavior.

A power electronics (inverter) unit supplies the electric machine with corresponding voltage and current and consists of semiconductor technology and controller area. There are two variants of inverter placement, remote and attached. Remote inverters are placed remotely from the electric machine and connected by phase cables, whereas attached inverters are directly mounted on the electric machine. For the latter, there are variants with a single flat circuit board as well as with a segmented circuit board, e. g. [14], to achieve a better package integration into the electric machine.

Due to the fact, that in electric drivetrain development the phase of systems engineering plays a major role, several works have dealt with multi-objective optimization of electric propulsion systems. Eghtessad [15] investigates different powertrain topologies, component technologies and component parameters of battery-electric vehicles. Schulte-Cörne [16] describes the dimensioning of a hybrid architecture including electric axle drives with an integrated consideration of the hybrid operation strategy. Meier [17] uses a statistical design of experiments (DOE) as a means of establishing optimal hybrid powertrains. A major contribution has been developed by Hofstetter, who integrates packaging-related aspects of the vehicle, building-block system-related considerations of the drivetrain components as well as cost-related factors into the optimization approach [18, 19]. This approach is elaborated more detailed in the following section.

In general, systems design optimization targets the best fulfillment of requirements, which are defined in accordance to related evaluation criteria. For an axle drive layout, this includes *performance*, *package* and *costs* aspects. In this context, a multi-objective optimization process has to handle the trade-offs between different objectives, respectively evaluation criteria. The evaluation criteria themselves are derived from vehicle-related system requirements (Fig. 5).

Performance-related criteria include the required axle torque, power and efficiency at different operating points under specified power supply conditions. These requirements can be derived by analyses of vehicle dynamics and operation conditions, e. g. by use of longitudinal vehicle simulation, while also considering influences of the electric energy supply. In this way, torque, power and efficiency characteristics are derived by expert software tools for a specific motor type, based on analytical motor theory [20]. These information servers as a basis for conceptual layout of the electric machine. More demanding requirements, such as continuous power ratings and thermal management, are derived by use of 1*D*- or 3*D*-thermal simulation tools, e. g. [21]. The generated parameter sets can be used for more detailed electric machine design, e. g. by use of specified electric simulation software, e. g. [22].

Package criteria include the installation space provided by the vehicle architecture. They are developed in correlation with geometrical full-vehicle design and include geometrical restrictions caused by different aspects, e. g. wheelbase, track width, ground clearance, rear seats, trunk size or exhaust system. In conceptual development, the installation space available for electric axle drives is described as geometrical model. Evaluation of the axle model packaging is enabled by use of volume models created within computer-aided design (CAD) environment considering the main geometrical extensions, e. g. [23]. Besides the extensions of the main volume elements, also specific shapes, such as the corridors for the two side shafts, can be included. Fig. 8 shows the conceptual volume model of an exemplary electric axle drive, including inverter model (orange), electric motor model (yellow) and gearbox model (grey). The provided installation space, which is derived from the vehicle packaging model, is displayed in turquoise color. During geometrical optimization, the perfect positioning of all involved components within the pre-defined available volume is determined. This process also includes variable geometrical extensions of the components, e. g. variable length and diameter of the electric motor, variable gearbox configurations and dimensions.

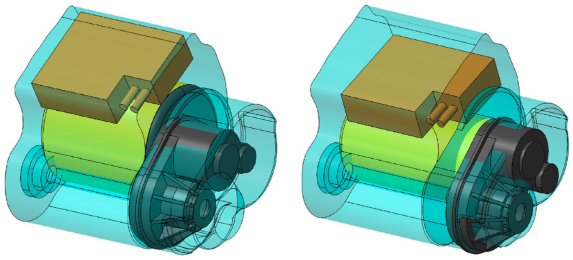

Fig. 8. Conceptual volume model variations of an axle drive system in offset-configuration [19]

Costs-related criteria consider material, supplied components, production effort and expenses of development. The material costs are calculated based on object lists in combination with CAD data. The production effort is assigned to specific component technologies and their manufacturing processes. Development costs are considered by favoring carry-over-parts over new product development if beneficial. In a more general approach, common parts of different electric axle configurations may also be taken into account, as proposed by [24]. All these influences are considered in cost estimation models covering the most important cost drivers. A maximum cost requirement may be set for the axle drive to allow only solutions below a certain cost level. Another example is to assess the best solutions achievable with limited development costs, which implies the existence of a higher carry-over-parts level, but might also come along with compromises in performance or package.

The electric axle layout is evaluated in the three criteria domains, whereby in each domain multiple objectives have to be defined, which are measured by metrics. The objectives define if a higher or lower metric is beneficial. In addition, pre-defined requirements are set, demanding a specific minimum or maximum value of an objective (which corresponds to a metric). The intersection of the requirements on the three domains (performance, package, costs) sets up the feasible design space, as illustrated in Fig. 9.

Numerous solutions may exist within the previously described design space. Every solution is evaluated with respect to the pre-defined objectives. It is thus not possible to determine a unique best solution in general terms, since these objectives may be conflicting. The outcome of the multi-objective optimization are the Pareto-fronts, which show the trade-offs between multiple and possibly conflicting objectives. For each criteria domain (performance, package, costs) numerous metrics are used to quantify the degree of compliance. For example, there are three different kinds of performance domain metrics (power, torque, efficiency) for several operating points. For each of these metrics, a compliance measure is applied to quantify the degree of compliance.

The proposed computer-aided optimization process is based on a library of available component technologies, which can contain parametric as well as non-parametric component models. The underlying models describe the component properties regarding performance, package and cost (Fig. 9). First, a preselection process is applied to cut down the number of possible component candidates. In this process, all those components are discarded, which obviously do not meet the axle drive requirements in any arrangement (component filter). For example, the peak power requirement eliminates all components that are not capable of providing or transmitting this peak power. The remaining components are combined to functional axle drive assemblies in a fully factorial way and those assemblies, which are obviously not capable of meeting the performance or cost requirements are discarded (performance/cost assembly filter).

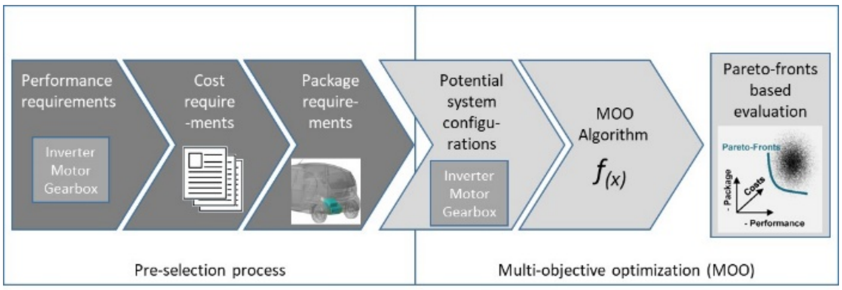

Fig. 9. Optimization process

The remaining configurations are tested against the package restrictions, also considering degrees of freedom in the package assembly (package assembly filter). Finally, the remaining assembly candidates contain the component candidates including all parameters that are used to determine the package-related parameter search ranges for the multi-objective optimization. The multi-objective optimization explores these parameter ranges as well as additional internal parameters, which are not essential for the package check, but do affect other properties (for example the number of turns per notch in an electric motor do not affect the outer dimensions, but change the torque-over-speed characteristics). The component parameters are applied to expert software tools, which generate the resulting component characteristics for the electric motor, the gearbox and the inverter. The assemblies of these components are then evaluated on system level to generate the performance and cost metrics, while the package metric can be obtained from the pre-processing evaluations by use of the pre-defined CAD models.

The system synthesis concept is based on a sequential optimization of the three main components *Power electronics*, *Electric machine* and *Gearbox* (Fig. 10). Finally, the computation results represent the trade-offs between the multiple objectives, which are depicted as Pareto-fronts and computed according to the pre-defined evaluation criteria.

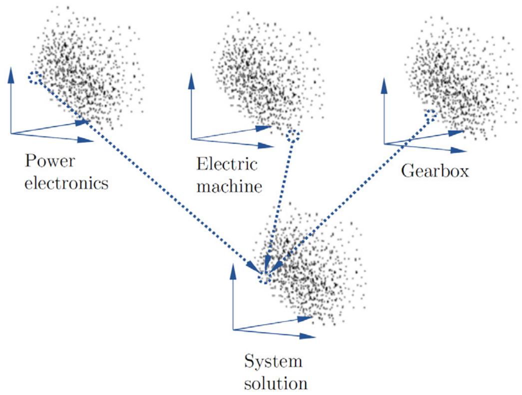

Fig. 10. System synthesis concept of the optimization approach [19]

In this way, the Pareto-fronts provide a multi-dimensional representation of the result of the multi-objective optimization process. As known from Pareto-fronts, the optimal result is not unambiguously defined, but depends on a trade-off as a function of the evaluation criteria [25]. In this way, it is up to the involved engineers and experts to select the final system configuration. The introduced approach supports decision making by provision of suggested, optimal design solutions considering the main criteria efficiency, performance, costs and package. Fig. 11 shows an exemplary optimization result, displayed as 3*D*-Pareto front, which contains the evaluation criteria *Package metric*, *Relative costs* and *Losses*, respectively drivetrain efficiency. Each dot in the diagram represents one found optimal solution. The best possible trade-offs between package metric and costs are displayed as circles.

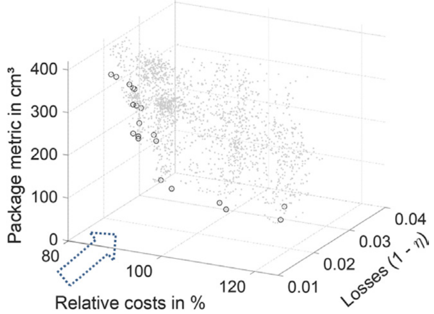

Fig. 11. Exemplary optimization result: 3*D*-Pareto front showing the evaluation criteria package metric, relative costs and efficiency [18]

CONCLUSIONS

1. The layout process of electric axle drives is performed on system level by involvement of component characteristics and their integration under consideration of pre-defined development targets, e. g. performance, efficiency, packaging and costs. In addition, various boundary conditions have to be incorporated, e. g. customer demands, legislative aspects and vehicle-related factors. In this way, the development process involves a broad range of influencing parameters and periphery conditions and thus includes a multi-dimensional optimization problem.

2. The present work introduces a systematic implementation of electric axle drive development into state-of-the-art development processes in the automotive industry and points to the importance of the early design phases in propulsion system layout and optimization. Integrated into the standardized processes of mechatronics systems development, an approach for multi-objective optimiza-

tion is introduced, that supports the handling of the occurring complex interactions of various design-related parameters. The introduced systems engineering synthesis is based on component-specific Pareto-optimal designs with the target to optimally handle performance, efficiency, package and costs for given system requirements. The results are displayed as Pareto-fronts of electric axle drive system designs variants, from which decision makers are able to choose the best suitable solution.

3. In this way, the introduced approach provides a methodological procedure to support decision making starting in the early layout phase with the target to improve effective systems engineering in electric axle drive development processes.

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Received: 08.10.2019
Accepted: 29.11.2019
Published online: 06.12.2019