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Perspective

Electric vehicles' powertrain systems architectures design complexity

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A B S T R A C T

Strict emission regulations and energy scarcity have ushered in a new era of automotive technology. Utilizing electric power as a second source of energy or an alternative to fossil fuel energy has been the center of attention for decades. Implementing electric energy in vehicles' powertrain systems requires new system architecture and rigorous methods for decision-making in a multi-disciplinary design procedure. Accordingly, the challenge is to define the design requirements and the economic feasibility of the final product.

1. Introduction

The term "electrified vehicles" (EVs) refers to a broad category of vehicles utilizing electrical power in their powertrain system. The share of electric power utilized in the powertrain system and the powertrain system's architecture are the two basic methods for the classification of electrified vehicles. Simple technologies like start/stop or regenerative braking systems or even more complex technologies like battery packs, fuel cells, and E-Motor can be implemented to integrate electrical power into the powertrain system. Therefore, an electrified vehicle can be categorized as a micro-hybrid, mild-hybrid, full hybrid, and battery electric vehicle (BEV) depending on the percentage of electric power and technology level, which is more likely consumer-oriented [1]. Micro hybrid vehicles utilize 5-10 % electric power in their powertrain by implementing technologies such as internal combustion engine (ICE) start/stop. Therefore, they do not use electric power to generate traction, it is utilized to assist the powertrain by optimizing the running time of the ICE [2]. The share of electric power increases up to 25 % in a mild hybrid vehicle by implementing an E-Motor to assist the ICE for traction generation. Mild hybrid vehicles cannot run only on electric power, so the E-Motor contributes to traction generation and has responsibility for energy harvesting as a regenerative brake. Full hybrid vehicles implement up to 80 % electric power for traction generation and can be run on either electric mode or ICE mode or on both modes (i.e., hybrid mode). The different architectures of full hybrid vehicles, which are discussed in the next section, increase the overall efficiency of the powertrain by providing different combinations of electrical and mechanical power for traction generation. The last one is BEVs, which utilize electricity as the only energy source for traction generation. Although the overall efficiency of the BEV's powertrain is much higher than conventional ICE, specific component arrangements in its powertrain are required for optimum performance. These configurations are discussed in the next section.

2. EV's Powertrain Systems Architectures

The architecture of the energy flow from energy storage to the traction force at the wheels can be used to classify a full hybrid electrified vehicle. In general, hybrid electric vehicles (HEV), by having two propulsion systems and energy storage systems, can be classified as parallel, series, and parallel-series (power-split) hybrids depending on how the two systems are configured. In parallel architecture, ICE's and E-Motor's output shafts are connected to the wheels through a transmission system, so each of them can be utilized separately and simultaneously for traction generation. The powertrain architecture of a mild hybrid vehicle is quite similar to a full hybrid parallel architecture, but electric power cannot be considered the sole power source for traction generation in a mild hybrid in contrast with a full hybrid parallel architecture. In a series-hybrid setup, the ICE is only connected to a generator to charge the battery pack, limiting the use of the ICE's power to just generate electricity and dedicating the E-Motor power for traction generation. The electrical part of the series hybrid powertrain is quite the same as BEVs from the technological point of view but may differ from each other in terms of sizing, considering the amount of required output traction and charging method. In parallel-series design (i.e., power-split), by implementing a specific coupling mechanism, the ability to charge the battery pack with ICE (e.g., the same charging method in series hybrid) is added to the parallel design. This connection mechanism offers a wide range of options for regulating the ICE and E-Motor power so that both earlier configurations are possible. To increase the range of full hybrid vehicles, solutions such as a larger battery pack and the ability to charge the battery pack directly from the electricity grid have been devised as known Plug-in hybrid electric vehicles (PHEV). Plug-in charging capability is applicable to all aforementioned architecture of full hybrid vehicles. Different architectures of full hybrid electric vehicles are illustrated in Figure 1 [3]. PHEVs minimize vehicles' fuel consumption and decrease the emission level, especially on daily trips, by having a larger battery pack that provides a longer all-electric range. A series hybrid vehicle with a large battery pack and plug-in charging option can be categorized as a range-extended BEV, such as BMW i3.

BEV's powertrain system can come in a variety of design concepts. Although E-Motors typically have higher efficiency compared to ICEs, this advantage is greatly reduced in low-speed and low-torque operating conditions. For this reason, gearbox or multi-motor designs are utilized to boost the powertrain's flexibility addressing BEV's major issues like range anxiety. Even though a multi-speed or continuous variable transmission (CVT) gearbox for BEVs improves the powertrain's efficiency in various use-case scenarios [4], a multi-motor arrangement can be a more practical way to increase the adaptability of a fully electric powertrain [5]. Most of the technologies implemented in EVs are mature enough to meet performance and efficiency targets. Despite all these technological breakthroughs, electrified vehicles still face significant barriers to market penetration, including range anxiety. The above-mentioned configuration's primary goal is to increase the powertrain's overall efficiency. However, it should be noted that adding additional parts meant the need for a more sophisticated technique of coupling and more effort for improving the powertrain component sizing and energy control strategy. The performance of a vehicle is greatly influenced by the proper selection of key powertrain parameters. It stands to reason that proper component size optimization will be essential to achieving the necessary performance, energy efficiency, and reasonable lifecycle cost of EVs.

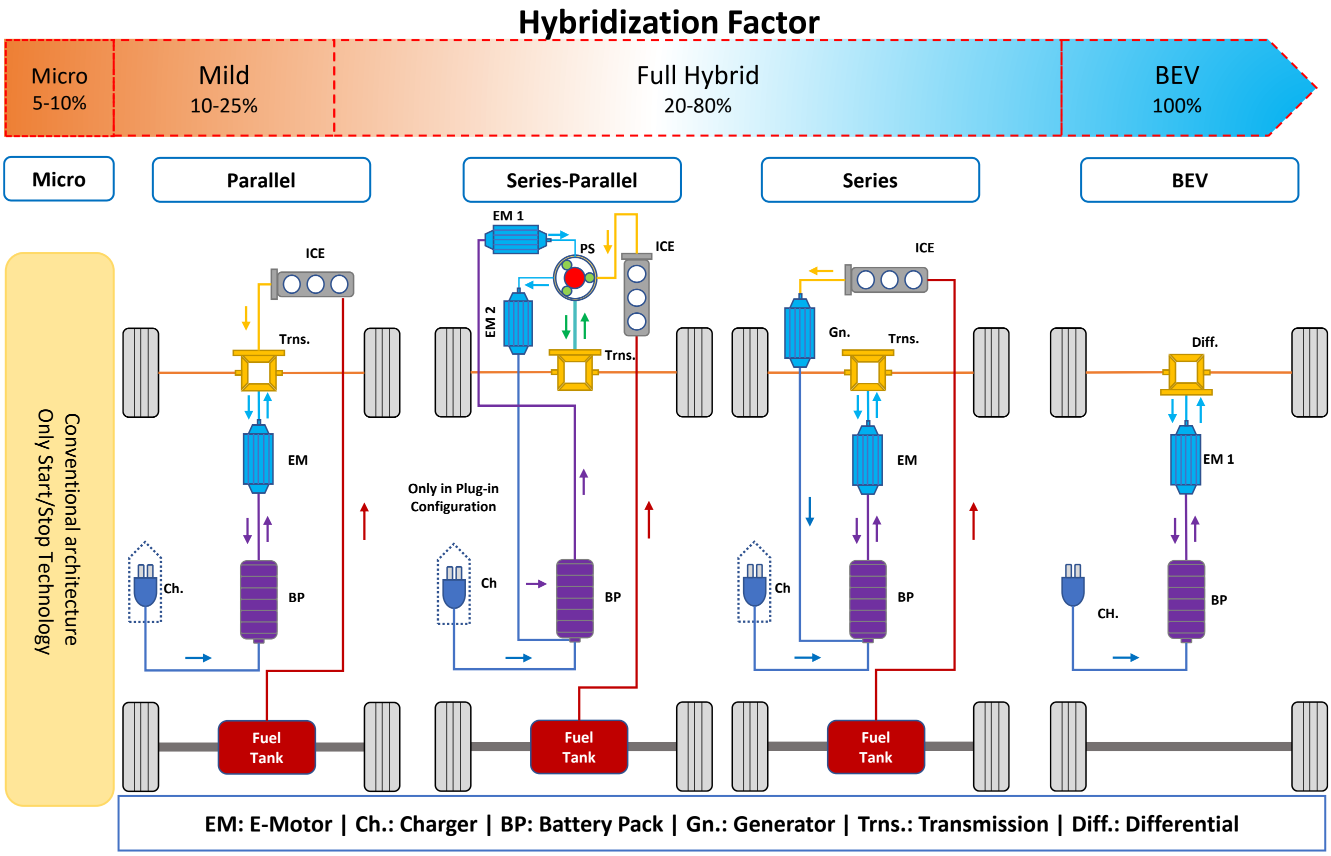

Figure 1. Share of electric power in powertrain and architecture of electrified vehicles

The component sizing is influenced by not only the powertrain architecture of the vehicle but also a vast variety of other aspects, such as the anticipated driving cycle, operating environment, and powertrain control strategy, to name a few. Energy control strategies play a key role in electrified powertrain design. Although in the case of HEVs, the energy control strategy should manage two separate energy systems to achieve the best efficiency while preserving deriving performance and comfort, in the case of BEVs there is only one energy system, so they differ from each other. Despite all the advancements in the abovementioned technologies, technologies related to EVs have a small share compared to other technologies related to ICEs. For instance, these technologies were utilized on just 7% of vehicles in the United States in 2020, Figure 2 [6].

To give a thorough understanding of the final product characteristics, the design of EVs requires cross-domain engineering as well as multiscale and multiphysics simulation. New products are becoming more and more reliant on software due to the use of sophisticated simulation tools to create a product that complies with the specifications. Model-Based System Engineering (MBSE) provides a basis to integrate several design domains by using modeling approaches to logically translate needs into specifications of a final product. An MBSE design approach can provide a decision-making framework not only for EV design and production but also for defining the required specifications of each product subsystem.

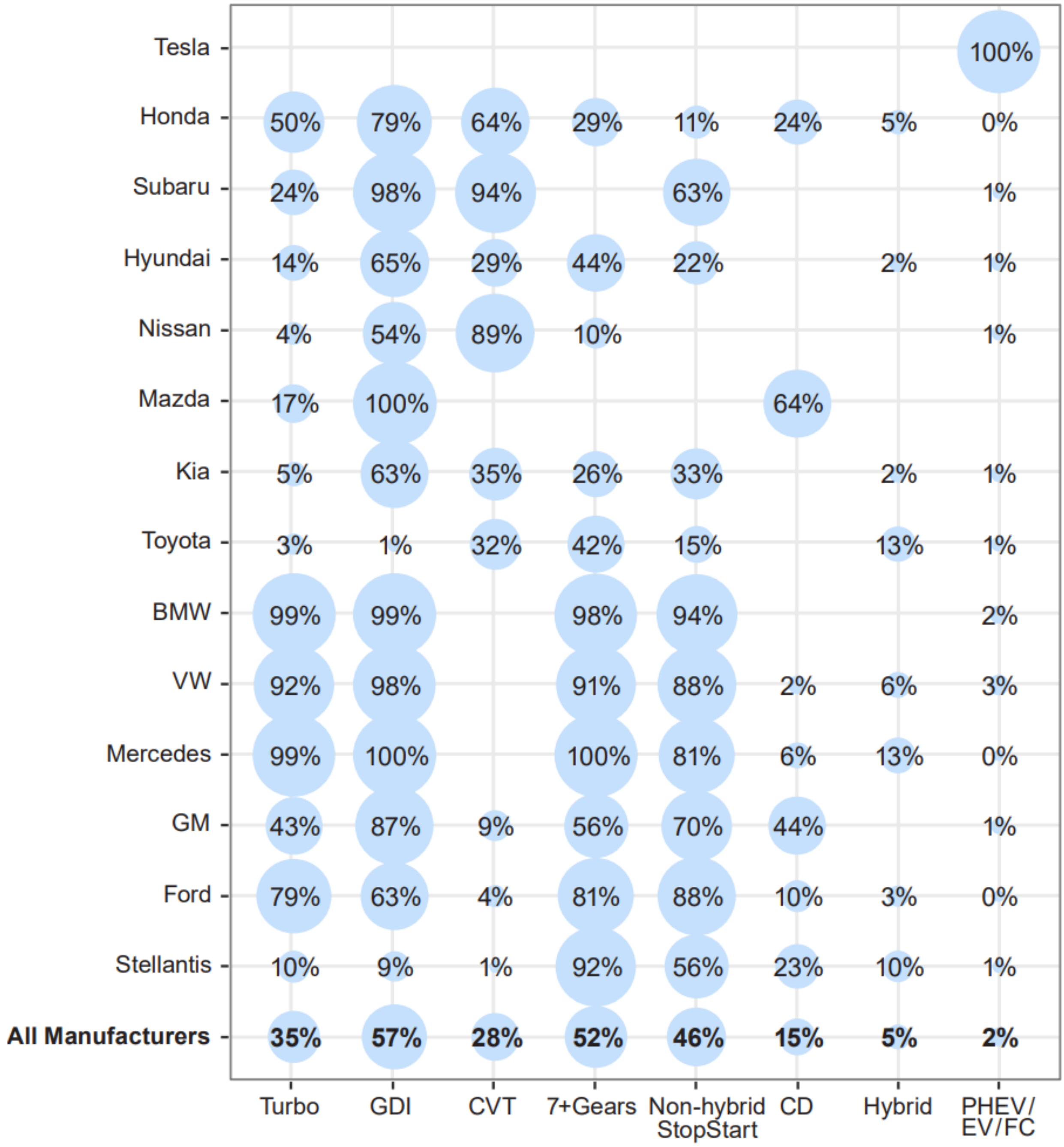

Figure 2. Manufacturer Use of Emerging Technologies for Model Year 2020 [6]

3. Conclusion

By and large, the design complexity of an electrified powertrain can be introduced as complexity in the control strategy and sizing of the components. This complexity is not only affected by the number and architecture of the powertrain's components but also by the diversity of its operational conditions. The design complexity should be considered as a barrier to the market penetration of EVs; thus a holistic framework, such as MBSE, is required to have a compromised solution for a right-design strategy.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Conflict of interest

The authors declare no potential conflict of interest.

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