1. INTRODUCTION

Increased environmental awareness, tightening emission norms and recent technological developments in the fields of electric motors, power electronics and batteries, have enabled car manufacturers to equip commercial passenger cars with hybrid-electric drivetrains. Several hybrid drivetrain topologies have been proposed over the last decades (see e.g. Ehsani (2014)). A few well known topologies are the series, the parallel and the series-parallel-hybrid topologies. For instance, the Toyota Prius is a well-known example of latter type of topologies.

The optimal design of a hybrid-electric drivetrain is a challenging task as various design objectives have to be considered, such as fuel economy, emissions (e.g. CO\textsubscript{2}, NO\textsubscript{x}, particles), vehicle acceleration performance, cost, comfort, safety, etc. (Silvas et al. (2017)). The achieved characteristics of a hybrid vehicle result from an interplay between the selected drivetrain topology, the component properties, the energy management strategy and the usage (i.e. the type of driving cycle). To cope with the dependencies between, there is a strong need for an integrated design methodology that combines topology design with control and sizing, enabling the selection of the optimal drivetrain for a specific type of vehicle (Silvas et al. (2015)).

Over the past decades, car manufacturers and academia have invested a lot of effort in determining optimal energy management strategies for hybrid drivetrains (Sciarretta and Guzzella (2007), Serrao et al. (2013)). These control strategies determine how power is split between the different sources during vehicle operation. Many different energy management strategies have been proposed, including heuristic strategies, and strategies based on numeric optimal control. Generally speaking, there are three basic approaches to address optimal control problems (Diehl et al. (2006)), (i) dynamic programming, (ii) indirect, and (iii) direct approaches.

Dynamic programming (DP) discretizes the state-time space and allows to compute the global optimal fuel economy of a given drivetrain configuration, even if it exhibits nonlinear characteristics (Sciarretta and Guzzella (2007)). However, DP suffers from the curse of dimensionality: the computational load and memory requirements grow exponentially with the number of states and inputs.

Indirect methods encompass the Pontryagin Maximum Principle, which forms the basis for the well-known Equivalent Consumption Minimization Strategy (ECMS) (Serrao et al. (2013)). The latter minimizes the weighted sum of the fuel power and the battery power instantaneously. Due to its simple nature, ECMS is well suited for real-time implementations. However, determining the optimal weighting factor can be cumbersome (Delprat and Hofman (2014)), which makes the method less suited for hybrid drivetrain design optimization.

Direct methods reformulate the continuous-time optimal control problem into a finite dimensional nonlinear programming problem, which can be solved using methods like the multiple shooting technique (Bock and Plitt, 1984). Direct methods offer the advantage that they can efficiently optimize control variables and system properties simultaneously. However, it is currently an active field of research to handle discrete variables and make these algorithms as such applicable to hybrid drivetrain optimization (Mauri et al. (2016)).
Recent studies, see e.g. Hofman et al. (2012) or Mohan et al. (2013), have shown that the drivetrain topology has a significant influence on the achievable vehicle performance. First approaches have been presented which allow the automatic generation of hybrid electric drivetrain topologies using constraint programming (Silvas et al. (2015)), heuristics (Bayrak et al. (2016)) or genetic algorithms (Bayrak et al. (2014)). These approaches are able to generate thousands of alternative topologies. However, a topology only describes how different types of components are interconnected. In order to assess the performance of a topology, the component properties have to be determined and a control strategy has to be designed. To the authors knowledge, effective methods which can automatically evaluate generic hybrid drivetrain topologies, are still lacking.

Ultimately, the goal of this research is to compare different HEV topologies. To this end, we propose a framework consisting of 3 steps, illustrated in Figure 1.

(1) Model Generation: given a topology, the gathered set of equations is ordered, resulting in a causal model.

(2) Model Evaluation: since HEVs are especially interesting in transient regimes, the topology is evaluated automatically over a time-varying speed trajectory. Dynamic Programming is used to calculate the controls to achieve minimal fuel consumption.

(3) Property Optimization: for a fair comparison, the component properties have to be tuned for each topology. To this end, model parameters like component sizes are improved by an optimization algorithm. The cost function encompasses, but is not limited to fuel cost. For example, component cost or gear shifting can be taken into account as well.

Items (1) and (2) are the novel contributions of this paper, and are discussed in detail in Sections 2 and 3 respectively. The optimization (3) is an important step, but it is not our main focus. The combined steps (1), (2) & (3) provide a general framework that is capable of automatically evaluating HEV topologies. In this paper, we show two well-known example topologies. Section 2 discusses the causal model extraction by means of a series hybrid, while a parallel hybrid example is evaluated and optimized in Section 4.

2. MODEL GENERATION FROM A TOPOLOGY DESCRIPTION

In this section, as a running example, the series hybrid topology of Figure 2 is considered. The Internal Combustion Engine (ICE) supplies mechanical power to the generator (EM1). Assisted by the battery (B) via the powersplit (PS), electrical energy $P_{EM2}$ is transferred to the Electrical Motor (EM2), driving the wheels (W), which must follow a speed and torque trajectory $\{\omega_W, T_W\}$.

2.1 Object-Oriented Library

As depicted in Figure 2, a topology comprises of components and connections. The components inherit their equations from an object-oriented component library, which currently encompasses the building blocks of a series-parallel topology, but can be readily extended with additional components or technological variations.

The HEV component library contains all information to describe the individual components. For each component, ports are defined that describe how the component can be connected to other components. When the ports of two components are connected, they define one or more topological equations. For example, the mechanical connection between the Internal Combustion Engine (ICE) and the generator (EM1) defines two topological equations: $\omega_{ICE} = \omega_{EM1}$ and $T_{ICE} + T_{EM1} = 0$.

Also, the component equations are defined in the library. For each equation, multiple causal forms are implemented. For example, the combustion engine defines a relation $f(\omega_{ICE}, T_{ICE}, F)$. Depending on the causality, the fuel $F$ may be computed from the speed $\omega_{ICE}$ and torque $T_{ICE}$. Alternatively, $\omega_{ICE}$ or $T_{ICE}$ can be the output of this equation. The various causal directions are all defined in the component library. That is, $f(\omega_{ICE}, T_{ICE}, F)$ is implemented three times in the ICE component: $\omega_{ICE} = f_{\omega_{ICE}}(T_{ICE}, F)$, $T_{ICE} = f_{T_{ICE}}(\omega_{ICE}, F)$ and $F = f_{F}(\omega_{ICE}, T_{ICE})$.

When gathering the equations from the topological description, the equations are initially unordered and given in an acausal form, i.e. they express a relation between
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