Optimal design of energy storage systems for hybrid vehicle drivetrains

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Abstract—Current hybrid drivetrain simulation packages are based on discrete (existing) system components and predefined system structures. Optimization of the performance of the hybrid drivetrain is then based on finding the most efficient control strategy of the primary and secondary power source and finally comparing the performance of the different candidate drivetrains. In this paper, the secondary power source components, part of the energy storage system (S), are modeled continuously, i.e., scalable to power and/or energy capacity needs. In this way, the size of the components of S can be added as an optimization parameter to a hybrid drivetrain design procedure.

Keywords: energy storage, hybrid drivetrain, multi-objective design problem, scalable model, SQP optimization, Penalty and Barrier functions

I. INTRODUCTION

In recent years several drivetrain simulation software packages have been developed, these packages can be used to develop hybrid drivetrain configurations and control strategies (e.g. ADVISOR [1], SIMPLEV [2], CarSim [3], HVEC [4], CSM HEV [5], V-Elph [6]) [7]. An optimal hybrid drivetrain design is obtained by optimizing a selected hybrid drivetrain configuration (e.g. series, parallel, series-parallel), to components and control. A drawback of the mentioned software packages is that they are based on a discrete set of (existing) drivetrain components, fixed in size (power, energy capacity). With the software tool QSS-Toolbox [8] it is possible to build drivetrain structures with scalable models for the Electric Machine (EM) and combustion engine. In this paper, in addition to scalable models for the EM, continuously scalable models will be constructed and evaluated for ultra-capacitor, battery, gas-pressurized tank, sub- and supercritical flywheel storage systems.

Hybridization of a vehicle drivetrain implies adding a Secondary power source (S, mostly a battery and an electric motor) to a Primary power source (P, usually an internal combustion engine). The objectives of a hybrid drivetrain are to improve the driving functions of a vehicle, i.e., fuel economy, emissions, driveability, comfort and safety. Hybridization allows performing brake energy recovery, downsizing the engine and optimizing the power flows over the different thermal, mechanical and electrical paths between the different power sources.

The NWO1 research programme “Impulse Drive” currently focuses on determining the required design specifications of the systems components for a hybrid vehicle fulfilling the required driving function improvements. The influence of the generic design specifications for the S on fuel economy and Energy Management Strategy (EMS) has been investigated in [9], the required vehicle driving function improvements serve to identify the system component specifications [10] [11].

The storage and conversion components, that provide the hybrid functionality, will be modeled continuously over their power and/or energy range in order to find an optimal design to a given control strategy. This will provide insights into (1) the solutions of the possible set of components necessary for the design of S, (2) quantification of the design trade-offs in achieving the objectives and into (3) the possibilities and limitations of the technologies that are under investigation. In order to be able to compare and evaluate performance of the hybrid drivetrain component designs, models will be generated of the efficiency, mass, volume and cost.

II. HYBRID S SYSTEM

The system that brings the hybrid functionality, i.e., S is defined as a system that can store and deliver energy to the drivetrain through one rotating mechanical drive shaft. Within this constraint, six different concept S system configurations have been identified, based on current technological possibilities, that will be analyzed and modeled further (see Table I). To be able to compare the Si designs (i = 1, ..., 6), each Si also has the design constraint of providing control over transmitted power flow regardless of the rotating speed or torque. Adding a Continuously Variable Transmission (CVT) to system S2 is thus necessary to be able to change torque for a required output power at a certain angular shaft speed.

Several of these systems have been modeled based on analytical models, a reference design was then constructed to identify the design and size scaling parameters zi. Scaling of look-up table based components is done by interpolation of properties (efficiencies, mass, volume) between discrete existing designs. A component cost model was constructed by literature investigation into manufacturing prices [12]. It is assumed that all dynamic effects of the components can be

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TABLE I
S system design concepts

<table>
<thead>
<tr>
<th>$S_i$</th>
<th>$S$ system</th>
<th>Components and Modeling</th>
<th>Layout</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_1$</td>
<td>Super-critical flywheel with electrical CVT</td>
<td>Flywheel: analytical model, scalable to power profile Electrical CVT: scalable to power, empirical model</td>
<td></td>
</tr>
<tr>
<td>$S_2$</td>
<td>Sub-critical flywheel with mechanical V-belt CVT</td>
<td>Flywheel: analytical model, scalable to power profile CVT: discrete, empirical model</td>
<td></td>
</tr>
<tr>
<td>$S_3$</td>
<td>Nickel Metal Hydrid (Ni-MH) battery with PM motor and Inv</td>
<td>Battery: scalable to power profile, empirical model Motor: scalable to power, empirical model</td>
<td></td>
</tr>
<tr>
<td>$S_4$</td>
<td>Valve Regulated Lead Acid (VRLA) battery with PM motor and Inv</td>
<td>Battery: scalable to power profile, empirical model Motor: scalable to power, empirical model</td>
<td></td>
</tr>
<tr>
<td>$S_5$</td>
<td>Super capacitor with PM motor and Inv</td>
<td>Super capacitor: scalable to power profile, empirical model Motor: scalable to power, look-up table based</td>
<td></td>
</tr>
<tr>
<td>$S_6$</td>
<td>Compressed air energy storage (CAES) with hydraulic control valve and gear pump</td>
<td>Pressure tank: analytical model, scalable to power profile Pump: scalable to power</td>
<td></td>
</tr>
</tbody>
</table>

PM = Permanent Magnet, EM=Electric Machine, FW=Flywheel, CVT=Continuously Variable Transmission, GPT=Gas-Pressurized Tank, INV=Inverter

neglected within the simulation resolution of one second, so static models are used.

III. DESIGN OPTIMIZATION METHOD

The design of the S systems can be regarded as a multi-objective optimization problem. $S$ configurations will be optimized with respect to efficiency, mass, volume and cost:

$$ T = \min_{\bar{x}} \{1 - \eta(P, \bar{x}), M(\bar{x}), V(\bar{x}), \varepsilon(\bar{x})\}, $$

$$ s.t. \ h(\bar{x}) = 0, \ g(\bar{x}) \leq 0 $$

(1)

With $T$ the objective function value, $\bar{x}$ the vector containing design variables of $S$, $\eta$ the efficiency, $P$ the output power profile $P(t)$, $M$ the total mass of $S$, $V$ the total volume, $\varepsilon$ the cost, $h$ the equality constraints and $g$ the inequality constraints. To obtain one single objective function the weighted sum method [13] is one of the most common methods, used to solve multi-objective design problems. The method has been adopted in this research, the weight factors $\alpha_\eta$ are therefore introduced together with normalization factors $M_{\text{max}}$, $V_{\text{max}}$ and $\varepsilon_{\text{max}}$:

$$ T = \min_{\bar{x}} \alpha_\eta(1 - \eta) + \alpha_M \frac{M}{M_{\text{max}}} + \alpha_V \frac{V}{V_{\text{max}}} + \alpha_\varepsilon \frac{\varepsilon}{\varepsilon_{\text{max}}}, $$

$$ s.t. \ h(\bar{x}) = 0, \ g(\bar{x}) \leq 0 $$

(2)

The factors $\alpha_n$ ($\sum \alpha_n = 1$) can be used by a designer to identify what criterion is most important, e.g., for a city bus the mass and volume are less relevant, compared with a passenger car, so $\alpha_M$ and $\alpha_V$ can be set lower then $\alpha_\varepsilon$ and $\alpha_\eta$. A Sequential Quadratic Programming (SQP) algorithm will be used to find minima of the objective function $T$. Several constraints cannot be explicitly written in the design parameter set $\bar{x}$ (e.g. State-of-Charge) and a Penalty and Barrier function will be used to include these in the objective function. Calculating the Hessian based on look-up table based models can be problematic since the objective function is then discontinuous at several points. Further, introducing weighted objectives and Penalty and Barrier techniques, Pareto optimality can no longer be guaranteed regardless of a discontinuous objective function. An optimization technique that can cope with this problem is Dynamic Programming (DP), however this technique has not been explored further. Instead, the SQP search algorithm will be started at different starting points $\bar{x}_0$ for each $S_i$ system to obtain a robustness sensitivity of the minimized design $\bar{x}^*$. Several minima are expected to be found for each $S_i$ system, depending on the choice of optimization parameters. An overview of the design process and a flowchart for the optimization procedure are shown in figure 1.

IV. RESULTS

Table I concepts optimizations have been performed in order to identify the sensitivity of the solutions to the chosen weighting, i.e., $\alpha_M = 0.2$, $\alpha_V = 0.2$, $\alpha_\varepsilon = 0.2$ and $\alpha_\eta = 0.4$. The results will discussed in this section.

A. Design evaluation of concept designs

The influence of a continuous discharge and charge power profile on the average efficiency of the optimized systems as shown in Table I has been investigated. This has been done by sequentially changing the nominal power rating and the duration time $t_d$ (resulting in different required energy
storage capacities) (see Fig. 2). The initial SOC value is 1 assumed. The results regarding the average system efficiency are shown in Fig. 3. In Fig. 3 is shown, that only $S_4$ or the VRLA with a PM has an average efficiency lower than 60% for nominal power ratings higher than approximately 5 kW-6.5 kW. All the other systems have an average efficiency larger than 70% for nominal powers between 5 kW-25 kW and energy storage levels of 0.1 MJ-2 MJ. It can also be seen that the efficiencies of $S_1$, $S_3$ and $S_4$ are more sensitive to nominal power rating than energy capacity compared to $S_2$ and $S_5$.

![Fig. 2. Power profile used for investigation of design responses (average efficiency)](image)

For the rest of this section, only the storage devices from the $S$ systems are considered, so conversion components are removed (i.e., EM, CVT).

In Fig. 4, it can be seen that the efficiency of the super-critical or High Speed (HS) and the sub-critical flywheel system or Low Speed (LS) Flywheel systems decrease with increase in duration time and decrease of nominal power rating. Additionally, the efficiencies of VRLA and the UC decrease with increase of duration time and increase of nominal power rating. Furthermore, the Ni-MH battery efficiency is independent on duration time variation, because the efficiency is dependent on SOC-level, which has a small fluctuation due to the significant larger energy capacity compared to the other systems. However, the battery efficiency decreases with increase of nominal power rating.

![Fig. 4. Influence of the nominal power rating and duration time $t_d$ on the average efficiency for the different storage components. CAES storage is omitted, the tank has 100% efficiency in the modeling.](image)

In the Fig. 5, the specific power as a function specific energy storage capacity for the different optimized storage systems is shown. The obtained density values can be compared with average data available in literature (areas are indicated by the colored rectangles). As can be seen in Fig. 5 for the LS flywheel system, the power density decreases significantly compared to a relative small decrease of energy density with increase of duration time. At shorter duration times and higher power demands the LS flywheel is more efficiently (see Fig. 4). The flywheel is optimized such that the bearing friction and air drag losses are minimized, which minimizes the maximum flywheel speed, which results in a larger flywheel mass.

![Fig. 5. Specific power as a function specific energy storage capacity for the different optimized $S$ systems](image)
B. Optimization of $S$ using a 20 kW power cycle

The influence of a power demand to the $S$ resulting from fuel economy optimization has been used in order to select a $S$ system fulfilling the design targets as an example result. The optimal power distribution between $P$ (Primary power source), $S$ (Secondary power source) and $V$ (Vehicle propulsion power) has been obtained by minimizing the fuel consumption, maintaining SOC within a certain range, and accomplish any drive power demand [9]. The optimization problem can be described as a multi-step decision problem in discrete-time format and therefore it can be solved using the Dynamic Programming (DP) technique. The maximum power rating of $S$ is set to 20 kW. The vehicle is assumed to be a mid-sized passenger car (1360 kg), and the engine is a 1.6 l SI operated at the optimal operation line. The drive cycle is the NEDC. Furthermore, during these simulation the efficiencies of $S$ and $T$ are assumed to be 100%. The results are shown in Fig. 6. In Fig. 9, it can be seen that power flow out of the $S$ is controlled such that $P$ is operated as much as possible at levels in which the engine efficiency is higher. The optimal power demand from $S$ has been used to optimize the different $S$ systems as shown in Table I using the SQP algorithm. The initial SOC level is 0.9 assumed. A spider diagram is shown in Fig. 8 for comparison of different optimized $S$ systems to design criteria: efficiency, mass, volume and cost. Immediately, it can be seen that sub-critical flywheel system or Low Speed (LS) Flywheel, Compressed Air Energy Storage Tank (CAES), Ultra-Capacitor (UC) with PM EM are not feasible solutions, caused by too high mass, volume or cost respectively. The VLRA with a PM EM and the super-critical or High Speed (HS) flywheel system are rejected caused by too low average efficiencies of 50.1% and 52.5% respectively. Therefore, the combination of a Ni-MH battery with an energy capacity of approximately 9 kWh and a 20 kW PM EM is the most suitable solution fulfilling the design targets. The SOC evolution and the power losses of this system are shown in Fig. 7. The discrepancy between the SOC levels at the end of cycle between the imaginary $S$ simulated without losses (blue line) from DP and the $S$ consisting of the Ni-MH and PM EM (magenta line) is caused by the energy losses. The mass, volume, cost price and average efficiency are optimized to 141 kg, 31 dm$^3$, 2.9 € and 81.8% respectively for the complete system. The battery solely has a mass of 100 kg and an output power of 22.4 kW corresponding to a 0.22 kW/kg and 90 Wh/kg for the power and energy density. The power and energy density of the battery pack of the new Toyota Prius is respectively increased and decreased to approximately 0.52 kW/kg and 33 Wh/kg. Adapting the fitted parameters for battery module mass and volume as a function of the current capacity in the mass and volume model can easily be done for state-of-the-art technology in mass production once available. It should be noticed that the maximum allowable battery voltage and the battery configuration (series or parallel connected) is of influence on the amount of required battery energy capacity and nominal power rating. In this paper, the batteries are assumed to be connected in series reducing the internal battery losses due to lower current losses. Furthermore, no constraints are set to the maximum battery voltage.

![Optimal power distribution between $P$, $S$ and $V$](image)

**Fig. 6.** Optimal power distribution between $P$, $S$ and $V$ (Primary power source, Secondary power source and Vehicle power load, respectively). Topology and transmission are optimal and are assumed lossless.

![Optimized Ni-MH battery with PM EM](image)

**Fig. 7.** Optimized Ni-MH battery with a PM EM ($S_3$ of Table I), $P_s$, $SOC$ and $P_{loss}$ are shown as function of time.

V. Conclusion

Different $S$ system concepts have been introduced that can provide hybrid functionality when coupled via an transmission technology to a hybrid drivetrain. Within the presented optimization framework, performance in terms of mass, volume, price and efficiency can be compared and evaluated between the six presented $S$ system models. In this paper, a continuous charge and discharge power demand on the different $S$ design have been investigated. Most of the discussed $S$ systems are dependent on the nominal power rating and the duration time of the signal. Except the Ni-MH battery, which is independent on the duration time, due to its high internal capacity. The
sizing of the battery systems can be done solely on the power requirements from the storage device. Since, storage capacity of batteries is sufficient for single-storage system. Batteries are often used in their most efficient SOC range (SOC ∈ [30%–80%]). The other storage components (flywheels, ultra capacitors, compressed air energy storage) are sized based on storage capacity and not on power ratings. In addition, generally the full storage capacity available to deliver the required power profile (SOC ∈ [0–1]) is used. From the optimized S designs using a 20 kW power demand to the S, the battery systems are favorable, however the battery packs can be considered heavy and voluminous for hybrid vehicle application. Splitting up the S into two power levels (low and high) and designing corresponding technologies to its purpose it is expected that the overall losses, mass and volume of the S can be reduced. Nonetheless, the Ni-MH battery pack has a high efficiency over large part of its working range and low sensitivity to the efficiency with varying power- and energy capacity needs. Some aspects are not taken into account in this research, e.g. lifetime expectancy. The models can however be expanded easily with these aspects. Future work will focus on the applicability of the different S systems to different vehicle classes. In addition, the optimized S system will be used to determine the ratio specifications in combination with a chosen P and V following from optimal operation of these component over a defined drive cycle. Once these specifications are determined the transmission technology can be selected and designed.

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