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Concept Design for Hybrid Vehicle Power Systems

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***Abstract*— Hybridization implies adding a Secondary power source (e.g. electric motor and battery) (S) to a Primary power source (P) in order to improve the driving functions (e.g. fuel economy, driveability (performance)) of the vehicle. The fuel economy is strongly determined by the energy management strategy, which determines the power distribution between P, S and the Vehicle wheels (V). In this paper the influence of the specifications for P and S on energy management strategy (EMS) have been investigated. The final objective is to determine the minimum required specifications in order to design new hybrid drivetrain technologies and topologies for future hybrid vehicles.**

Keywords: energy management strategy, optimization, power systems, multi-objective design process

I. Introduction

A conventional drivetrain consists of a primary energy source (i.e. fossil fuel) and an energy converter, together also referred to as 'Primary power source' (P), which are connected to the wheels via a coupling, mechanical transmission, and differential. Hybrid technology implies adding a bi-directional energy accumulator, converter and transmission components referred to as 'Secondary power source' (S) in order to increase the integral driving functionality. The driving functions can comprise the fuel consumption, emissions, comfort, driveability (performance) and safety. S is able to exchange energy with the vehicle and is operated such that system/fuel efficiency is highest. The required specifications or design variables for S are accumulator size, power rating and average constant efficiency specifications (independent of power flow and operation point). The design process is focussed on determining the generic design specification for S, i.e., technology and topology independent. During this process optimal power distribution between S, P and V is realized. Based on these generic specifications, a technology designer is able to design new technologies for S. Not only the specifications for S and P but also the EMS plays an important role in the overall driving functions at vehicle level. The aim of the research presented in this paper is to investigate the influence of the power rating specifications for S and the efficiency specifications for P and S on the resulting EMS. The efficiency influence has been investigated by comparing the outcome of resulting EMS using average constant efficiency for S (with imaginary technology) and an actual S with power dependent efficiency (i.e. with a 60 V 10 kW electric permanent magnet motor combined with a 144 V 6 Ah NiMh battery). The hypothesis is that if the difference in influence between the actual power dependent component efficiency and the average constant efficiency for S is sufficiently small, the required combination of an average constant efficiency and other specifications (accumulator size and power ratings) for S fulfilling the required driving function improvement can be used to select and design new technologies for S.

II. Simulation Model and Method

The simulation model used is shown in figure 1. P is connected via a Transmission technology (T) to S and the Vehicle wheels (V). S is able to exchange energy with P and V. The bi-directional power flows for P, S and V are represented by P_p, P_s and P_v. P can be represented as a nonlinear static map, in which the fuel rate $\dot{m}$ $[g/s]$ is a function of the engine crank shaft power and speed.

$$\dot{m} = f(P_p, \omega_p) \text{ where } P_p = P_v - P_s \tag{1}$$

The objective is to optimize the power flow between the power sources over a defined drive cycle in order to

- Minimize the fuel consumption and emissions.
- Maintain state-of-charge of the accumulator within a certain range.
- Accomplish any drive power demand.

Therefore, the problem can be described as an optimization problem.

$$\min_{\underline{x}} J(\underline{x}) \text{ subject to } h(\underline{x}) = 0,\ g(\underline{x}) \leq 0 \tag{2}$$

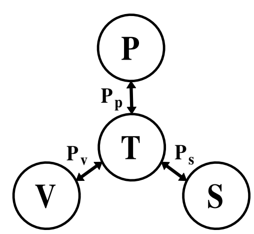

Fig. 1. Generic Hybrid Drivetrain Model: Primary (P), Secondary power source (S), Transmission technology (T) and Vehicle wheels (V)

with $h(\underline{x})$ equality and $g(\underline{x})$ inequality constraints. The cost function J is the total fuel consumption over the drive cycle as a function of the power flow of S, which is the control design variable.

$$J = \int_0^{t_{cycle}} \dot{m}(P_s(t), P_v(t), \omega_p(t))dt \qquad (3)$$

The influence of the power ratings of S has been investigated by changing the bounds or limitations on the operation range of S, the bounds on the energy level for S are fixed.

$$P_{s,min} \leq P_s \leq P_{s,max} \qquad (4)$$

$$E_{s,min} \leq E_s \leq E_{s,max} \qquad (5)$$

Furthermore, the optimization problem is subjected to an integral constraint, i.e. state-of-charge balance of accumulator, which leads to

$$\int_0^{t_{cycle}} P_s(t)dt = 0 \qquad (6)$$

The accumulator energy level evolution may be calculated with,

$$E_s(t) = E_s(0) + \int_0^{t_{cycle}} P_s(t)dt \qquad (7)$$

The optimization problem can be described as a multi-step decision problem in discrete-time format and therefore it can be solved by using the Dynamic Programming (DP) technique ([8]). The DP problem is solved by numerical discretization and interpolation of the state and control design values ([1]-[6]).

III. Power specifications for S

In this section the influence of power rating specifications for S and efficiency specifications of P on the EMS will be discussed. The kinematical constraints and power losses imposed by T have been left out of consideration. The engine is only able to deliver positive torque. The vehicle is a typical midsized-passenger car equipped with a 1.6l petrol engine and the used drive cycle is the NEDC. Furthermore, the engine is assumed to be operated at operation points with the highest efficiency i.e. at the Optimal Operation Line (OOL). In figure 2, the required drive power P_v is shown. The second plot shows the energy specific fuel consumption at the OOL referred to as β_{OOL} [g/kWh] as a function of the engine crankshaft power P_p for the used 1.6l-petrol engine. The β_{OOL} has been determined from the nonlinear static engine map. From these graphs it can be seen that for drive powers up to approximately 10 [kW] corresponds to $> 80\%$ of the total required drive cycle energy (region I). At the same time the OOL of the engine shows a relative large sensitivity of the OOL to required engine power. For powers higher than 10 [kW] the fuel consumption sensitivity is much less (region II). Notice that for engine power higher than 45 [kW] mixture enrichment occurs thereby increasing the specific fuel consumption as a function of engine power. During the analysis the initial accumulator energy level is set to $E_s(0) = 50\% \cdot \Delta E_s$ with $\Delta E_s = (E_{s,max} - E_{s,min}) = 1[MJ]$ is assumed. In addition, a 10^{th} order polynomial fit function has been used in order to obtain a smoother function to calculate the fuel rate. The maximum deviation between the fitted function and the actual OOL is smaller than 3%. The fitted function $\beta_{OOL,fit}$ has three local minima (see figure 2). The S efficiency is assumed to be 100%. In the figures 3 and 4, the strategies for two different power ratings of 5 [kW] and 35 [kW] are shown respectively. The power ratings are the maximum motoring and generative power of S. From the strategies, it can be concluded that the optimal EMS focusses at operating the engine at power levels in which efficiency is higher (see figures 2, 3 and 4). This is accomplished by controlling the power flow in and out of the accumulator. If the power rating is sufficiently large

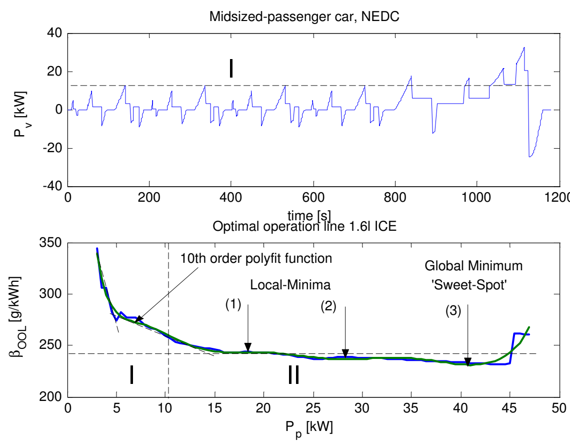

Fig. 2. Required drive power P_v and β_{OOL} as a function of required engine crankshaft power P_p

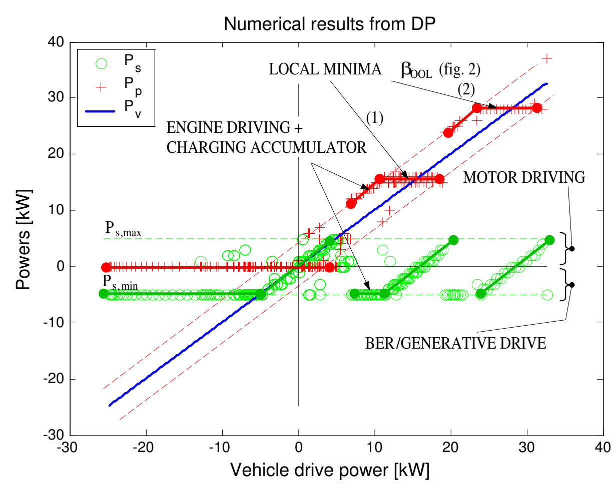

Fig. 3. EMS with max($|P_s|$) = 5 [kW], $\triangle E_s$ = 1 [MJ], η_s = 100%, BER = Brake Energy Recovery

enough, the engine is operated at 'Sweet-spot', which is the global minimum of $\beta_{OOL,fit}$. From the sensitivity analysis of the vehicle drive power P_v and the β_{OOL} of the engine follows that at low required drive powers it can be preferable to shut-off the engine and driving the vehicle only by the secondary power source in order to avoid part load (see figure 2). From the results of DP in figure 3 it can be seen that the vehicle is propelled by the secondary power source for required drive powers P_v up to approximately 5 [kW] avoiding some of the part load. This is equally to the chosen maximum power rating of S. In figure 5, the State-of-Charge (SoC) $= E_s/\Delta E$ evolution including the cumulated fuel costs [g] has been depicted. It can be seen that the optimized strategy keeps the accumulator SoC within the $15\% - 50\%$ range for max($|P_s|$) = 5 [kW] and $\triangle E_s = 1$ [MJ]. In the first 80% of the total drive cycle more than 60% of the obtainable brake energy with a max($|P_s|$) of 5 [kW] is available for charging the accumulator ([7]). However, for approximately 80% of the total drive cycle, the accumulator SoC tends to decrease over time due to motor driving.

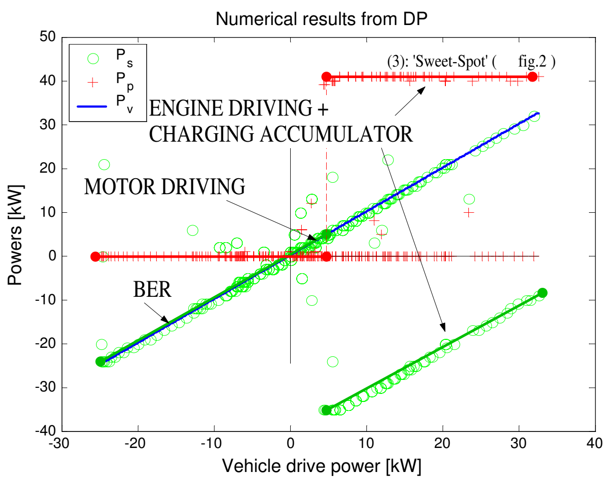

Fig. 4. EMS with max($|P_s|$) = 35 [kW], $\triangle E_s = 1$ [MJ], $\eta_s = 100\%$, BER = Brake Energy Recovery

IV. Efficiency specifications for S

In this section the influence of the efficiency of S and P on the EMS from DP will be discussed. The secondary power source is assumed to be an electric permanent magnet motor with maximum power specification of 10 [kW]. The bi-directional energy accumulator is assumed to be a NiMh battery (1.2 [V] x 6 cells x 20 modules) with a current capacity of 6 [Ah]. The static efficiency maps for the electric machine and battery have been derived from the Advanced Vehicle Simulator (ADVISOR) of the National Renewable Energy Laboratory (NREL) of U.S. Department of Energy. During this analysis the engine and the electric machine are both assumed to be operated at the operations points with highest efficiency. In figure 6, the block diagram for the power flows of S is shown. The total efficiency is the product of the battery efficiency and the electric machine efficiency.

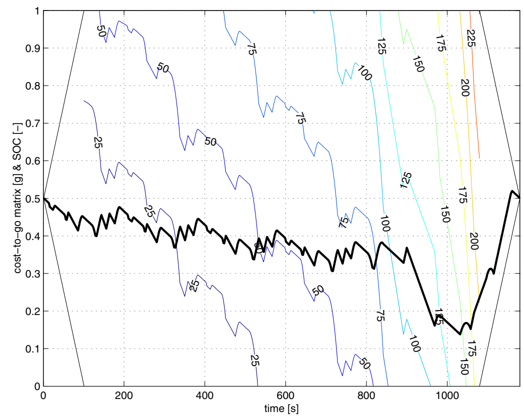

Fig. 5. State-of-Charge evolution and cost-to-go matrix [g], max($|P_s|$) = 5 [kW], $\triangle E_s = 1$ [MJ], $\eta_s = 100\%$

$$\eta_s = \eta_{battery} \cdot \eta_{em} \tag{8}$$

During this analysis the influence of η_s and the average constant efficiency of S, i.e.,

$$\bar{\eta}_s = \frac{1}{P_{s,max} - P_{s,min}} \int_{P_{s,min}}^{P_{s,max}} \eta_s \, dP_s \tag{9}$$

on the EMS following from DP will be investigated. The same engine and vehicle type as described in the previous section has been used. The temperature effects and transients (due to high internal capacitance) of the battery have been ignored. In figure 7, the generative/motoring power transfer curves of S are shown for different SoC levels $\in \{10\%, 90\%\}$. These curves are obtained from the nonlinear static maps for S as shown in figures 8 and 9. It can be seen that the generative efficiency is higher than the motoring efficiency. The constraints for S (e.g. maximum battery charge power, electric machine output power) described as in the optimization problem can be expressed as a nonlinear look-up table function of P_s. The optimal operation line for S (for the electric motor and battery combination) has been determined and used in the optimization problem, with the assumption that the influence of the SoC within the range of 40%-60% can be neglected. In figure 10, the power dependent efficiency for S and the histograms for

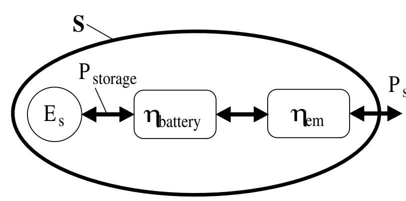

Fig. 6. Block diagram of power flows for S

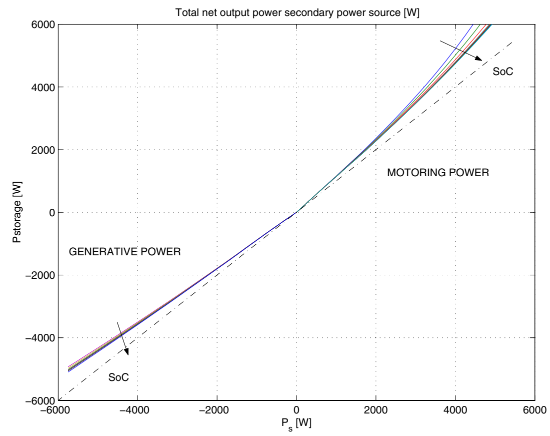

Fig. 7. Power flow P_s as a function of $P_{storage}$ for different SoC $\in \{10\%, 90\%\}$

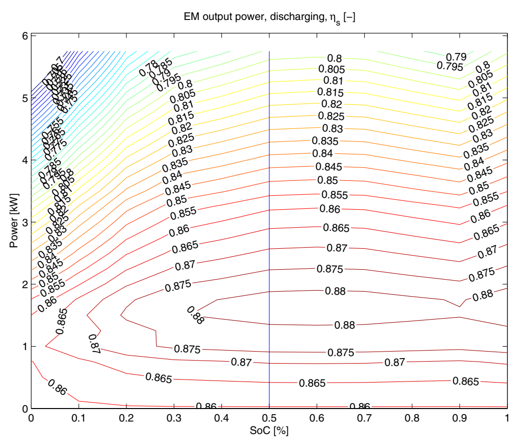

Fig. 8. Motor drive efficiency η_s as a function of $P_s > 0$ and SoC, maximum efficiency at $\approx 50\%$ SoC

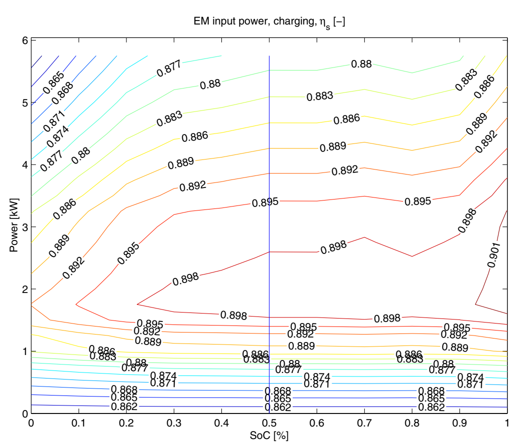

Fig. 9. Generator efficiency η_s as a function of $P_s < 0$ and SoC, maximum efficiency at $\approx 50\%$ SoC

η_s, and $\bar{\eta}_s$ are shown. If the power independent efficiency for S is used, the strategy tends to charge the battery

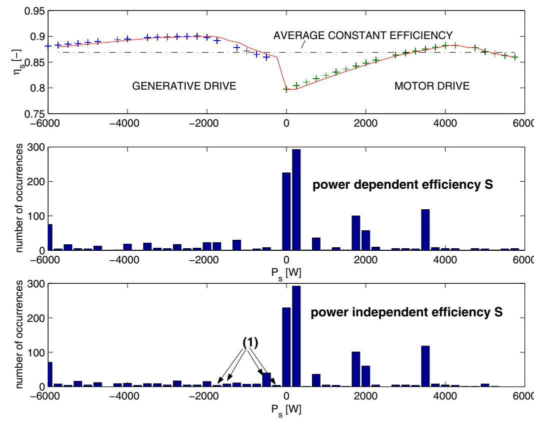

Fig. 10. $\eta_s(P_s)$, Histograms for η_s, $\bar{\eta}_s$

slightly more over the drive cycle (referred to (1) in fig. 10). The difference between $\bar{\eta}_s$ and the generator efficiency η_s is smaller than the difference between $\bar{\eta}_s$ and the motor efficiency η_s. The SoC level (see figure 11) is kept for both simulations within range of 40%-50%. In figure 12,

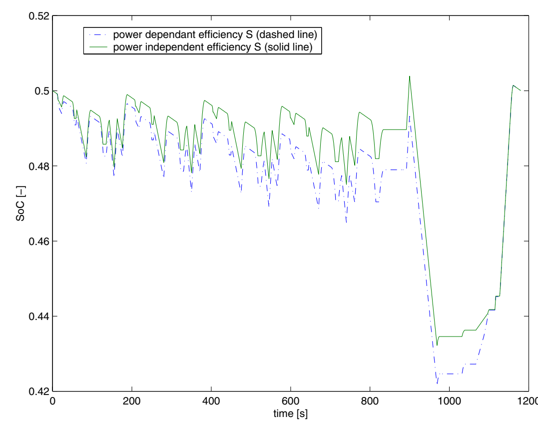

Fig. 11. SoC evolution with average constant efficiency $\bar{\eta}_s$ and power dependent efficiency η_s for S

the power distribution for the engine is shown. It can be seen that the resulting strategy focusses on operating the engine at higher efficiency levels (local maxima) as much as possible depending on the required drive power and the maximum power ratings of S. For required vehicle drive powers between the local maxima of η_p, the vehicle is generatively driven by S, forcing the engine to be operated at a higher efficiency level. However, for required vehicle drive powers up to approximately 4 [kW], the vehicle is almost fully electrically driven. The difference in influence on the fuel economy and EMS between the actual power dependent component efficiency and the average constant efficiency for S is small. The total fuel consumption with $\bar{\eta}_s$ is approximately 0.3% higher. The maximum difference in the SoC level, which occurs at the minimum SoC level, is

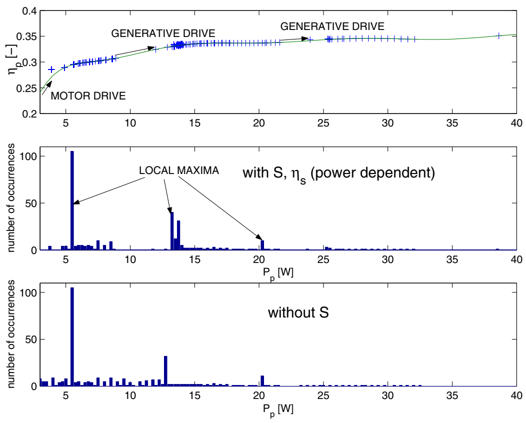

Fig. 12. $\eta_p(P_s)$, Histograms for η_p with S & η_s, and η_p without S (i.e. $P_p = P_v$)

approximately 43% - 42% $\approx$ 1%. The required combination of an average constant efficiency and other specifications (accumulator size and power ratings) for S fulfilling the required driving function improvement may be used in order to select and design new technologies for S.

V. Conclusions

The influence of the power rating specifications for S and the efficiency specifications for P and S on the EMS have been investigated. The influence of the power ratings of S has been investigated by changing the bounds or limitations on the operation range of S, the bounds on the energy level for S were fixed. It can be concluded that the EMS is strongly determined by the power rating specification of S and the efficiency of the engine. The optimal EMS focusses at operating the engine at power levels in which efficiency is higher depending on the required drive power and the maximum power ratings of S. This is accomplished by controlling the power flow in and out of the accumulator. The difference in influence on the fuel economy and EMS between the actual power dependent component efficiency and the average constant efficiency $\bar{\eta}_s$ for S is small. The total fuel consumption with $\bar{\eta}_s$ is approximately 0.3% higher. The maximum difference in the SoC level, which occurs at the minimum SoC level, is approximately 1%. The required combination of an average constant efficiency and other specifications (accumulator size and power ratings) for S fulfilling the required driving function improvement may be used in order to select and design new technologies for S.

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