Efficiency Maximizing and Charge Sustaining Supervisory Control for Series Hybrid Electric Vehicles

Wassif Shabbir and Simos A. Evangelou

Abstract—A supervisory control system (SCS) that maximizes the overall powertrain efficiency of a series hybrid electric vehicle (HEV) is developed. A novel approach of formulating the overall power efficiency which considers the idling losses of the engine and also characterizes separately the charging and discharging efficiencies of the battery, is proposed. These features allow the mode of direct power transfer from engine to battery to be included in the optimization. In turn, this enables the formulation of an optimization problem with a charge-sustaining scheme for improved control. A dynamic model of a series HEV is used in the development and testing of the SCS. Simulations with standard driving cycles demonstrate the significant improvement in fuel economy and battery charge sustaining of the designed Efficiency Maximizing and Charge Sustaining Map (EMCSM) over a Thermostat control scheme.

I. INTRODUCTION

The automotive industry is undergoing a historical transition mainly due to two reasons: 1) an increasing awareness of climate change from consumers, manufacturers, regulators and policy makers; 2) an increasing demand and price for a finite supply of fossil fuels. It is predicted that by 2020 approximately 18% of new vehicles sold in Europe, and 7% in the US, will be HEVs [1]. Many technological challenges thus arise, one of them being the control of HEVs.

A feature common to all HEVs is the use of multiple energy sources in the powertrain. Invariably a SCS is required to make intelligent decisions on how to power the vehicle from its sources. A vast range of SCSs have been proposed in the literature, ranging from rule-based to optimization-based solutions [2]–[6]. However, most SCSs of the latter nature involve significant amount of computation and therefore they are not implementable in real time. This paper proposes a SCS which locally optimizes the efficiency of the powertrain, while enabling charge sustaining operation. The result of the optimization is stored as a map that can be accessed during driving at low computational cost. The control schemes designed in this paper build further on the work presented in [7] and patented in [8]. SCSs are often developed with simulations that are provided by vehicle models which include only steady-state characteristics. This results in the loss of important transient dynamics. The proposed SCS is developed and tested on a dynamic vehicle model that allows the analysis of operation during complex transient behavior.

In the next section the vehicle model is introduced and Section III analyzes the powertrain to determine the efficiencies of the energy sources. This analysis forms the foundation for the SCSs discussed in Section IV. Results are presented in Section V where the performance in terms of fuel economy is discussed. Finally conclusions are made in Section VI.

II. VEHICLE MODEL

The vehicle model described in [9] is used to design and simulate the SCSs presented in this work. It utilizes a series hybrid powertrain arrangement as shown in Fig. 1, and is capable of realistic transient response in the frequency range appropriate for standard driving. Its parameter set is representative of general-purpose passenger cars. The powertrain of the vehicle includes the motor-set which is an inverter driven Permanent Magnet Synchronous Motor (PMSM), mechanically connected to the wheels of the car via a continuously variable transmission. The motor-set is powered by a Primary Source of energy (PS) and a Secondary Source of energy (SS), all connected to a common DC bus from which energy transfer takes place. The PS contains a turbocharged 2.0L diesel engine, mechanically coupled to a Permanent Magnet Synchronous Generator (PMSG) which is electrically connected to a three-phase rectifier. The SS consists of a lithium-ion battery with the associated bi-directional DC-DC converter. Regenerative braking is possible by the PMSM behaving as a PMSG while capturing the kinetic energy from the wheels that eventually gets stored in the SS.

III. POWERTRAIN EFFICIENCY ANALYSIS

To facilitate the SCS in deciding how to manage the energy sources, it is critical that the powetrain efficiencies are well understood. This section will begin by analysing the PS followed by the SS, before formulating an overall efficiency.

A. Primary Source of Energy

The key variables of the PS are the speed and torque of the internal combustion engine (ICE), as their product provides the power of the PS \((P_{PS})\). To investigate the impact of these variables on the PS efficiency for any given power demand, a test-model is used to load the PS with a varying amount of power for a certain engine speed \((\omega_{ICE})\) to measure the generated power together with the fuel consumption under steady-state conditions. The efficiency \(\eta_{PS}\) is defined as

\[
\eta_{PS}(P_{PS}, \omega_{ICE}) = \frac{P_{PS-out}}{P_{PS-in}(P_{PS}, \omega_{ICE})} \cdot \frac{P_{PS}}{P_{PS}}
\]

where \(\dot{m}_{fuel}\) is the fuel mass flow rate and \(Q_{HV}\) is the lower heating value of the fuel.
Tests are performed for power demands from 0 kW to 40 kW in 1 kW increments and engine speeds from 800 rpm to 2275 rpm in 25 rpm increments. The results (Fig. 2) demonstrate that the PS generally becomes more efficient with an increasing power demand and that the maximum efficiency is found at 25 kW (1550 rpm). It is clear that a significant amount of data points have been omitted in the Figure. The data points at very low power requirements are neither operationally feasible or the model is not validated in that range. Furthermore, the engine has some internal control on the air fuel ratio that essentially limits the power in that range. Further, the engine has some internal control on the air fuel ratio that essentially limits the power input at any engine speed, in order to reduce emissions [8].

In our investigation the ICE cannot be switched off and will instead idle at 800 rpm when it is not being used. This means that the vehicle will often have the PS delivering zero output power while consuming a finite amount of fuel to overcome the friction losses when idling. In terms of efficiency this is expressed as 0% but this value is not very helpful for the control. For this reason, it is chosen to store the power input of the PS (PS−in), which is the power associated with the fuel, as expressed in the denominator of Eq. 1. The input PS power at various engine speeds for zero output power is shown in Fig. 3. The input PS power for all the data points in Fig. 2 is also stored.

B. Secondary Source of Energy

Strictly speaking, the SS is an energy buffer, rather than an energy source. It receives energy from the PS either directly (by charging) or indirectly (by regenerative braking). It is therefore not straightforward to express the efficiency as an instantaneous value. The conventional approach is to express it as the energy charge-discharge efficiency, coulombic efficiency or the voltaic efficiency [10], [11]. However, they all suffer from an inaccuracy: the underlying assumption of these types of efficiency is that the battery will be charged and discharged at the same power level. Consequently, when evaluating the efficiency of the battery at a discharge of, e.g. 10 kW as compared to 20 kW, it is not the actual instantaneous efficiency being compared, but rather it is a comparison with two different assumptions being made for the two cases. The assumptions are that the battery was charged with 10 kW in the past if discharging at 10 kW, and 20 kW if discharging at 20 kW. Clearly the past charging should be already fixed, and not determined by present and future discharging levels. To address this, the efficiency is separated into charging efficiency and discharging efficiency, where the former is defined as

\[ \eta_{\text{bat-charge}} = \frac{P_{\text{bat-charge}}}{P_{\text{bat-in}}} \]

\[ = \frac{V_{\text{bat-OC}} \cdot I_{\text{bat}}}{V_{\text{bat}} \cdot I_{\text{bat}}} \]

\[ = \frac{V_{\text{bat-OC}}}{V_{\text{bat}}} \]

in which \( P_{\text{bat-charge}} \) is the power being stored in the battery. This power is obtained by multiplying the current, \( I_{\text{bat}} \), with the open-circuit voltage of the battery, \( V_{\text{bat-OC}} \). \( P_{\text{bat-in}} \) corresponds to the power sent to the battery at its ports, while \( V_{\text{bat}} \) is the voltage at the same ports. Similarly the discharging efficiency can be formulated as

\[ \eta_{\text{bat-discharge}} = \frac{P_{\text{bat-out}}}{P_{\text{bat-discharge}}} \]

\[ = \frac{V_{\text{bat}} \cdot I_{\text{bat}}}{V_{\text{bat-OC}} \cdot I_{\text{bat}}} \]

\[ = \frac{V_{\text{bat}}}{V_{\text{bat-OC}}} \]

where \( P_{\text{bat-out}} \) is the power delivered by the battery at its ports, and \( P_{\text{bat-discharge}} \) is the power consumed by the battery internally. The latter power is obtained by multiplying the current with the open-circuit voltage of the battery.

If the objective is to compare the efficiency of the PS and SS, it is not sufficient to only consider the discharging efficiency of the SS as it neglects the future losses from
replenishing the consumed SOC. This can be best addressed by including a correction factor $v$ reflecting the average charging efficiency, considering both SS and PS losses. It also takes into account the amount of energy charged through regenerative braking, which is essentially free for the SS. This correction factor $v$ could be estimated in real time during driving, but as its dynamics are very slow it is considered a constant for the purposes of this work. Note that the efficiencies in Eq. 2 and 3 above only consider the battery. The overall efficiency of the SS is expressed as

$$\eta_{SS}(P_{SS}, SOC) = \begin{cases} \frac{P_{bat-charge}}{P_{SS}} & P_{SS} < 0 \\ \frac{P_{bat-discharge}}{P_{SS}} \cdot v & P_{SS} \geq 0 \end{cases} \quad (4)$$

where the DC-DC converter losses have also been considered. $P_{SS}$ is the power demanded by the SS.

To determine this efficiency function, multiple simulations are run where power levels in the range of -30 kW to 30 kW are investigated for SOC values in the range of 50% to 80% (with intervals of 1 kW and 1% SOC). Since constant power loading of the battery does not result in steady-state operation, the data collected correspond to the instantaneous values of the relevant variables at the consistent time of 6 sec from the initial loading time, for all cases. The results are presented in Fig. 4. As expected, the SS is most efficient at low magnitudes of power. Furthermore, it is interesting to note that the charging becomes slightly more efficient at lower SOC levels, while discharging becomes slightly more efficient at higher SOC levels. Thus, if efficient operation is encouraged, charge sustaining is indirectly taking place to some extent. Finally, the case of zero output power is also obtained but not included in Fig. 4. Instead it is included in a map of the power flow of the battery, as defined by Eq. 5.

### C. Total Efficiency

Having obtained the efficiencies for both the PS and the SS, the combined total efficiency can be calculated as

$$\eta_{tot}(P_{PS}, P_{SS}) = \frac{P_{out}}{P_{in}} = \frac{P_{PS} + P_{SS}}{\eta_{PS} + \eta_{SS}} = \left(\frac{P_{PS} + P_{SS}}{P_{SS} \cdot \eta_{PS} + P_{SS} \cdot \eta_{PS}}\right)$$

However, computing the efficiency above does not account for the case of zero output power from either of the sources, as that will simply make the corresponding efficiency zero, and thus make $\eta_{tot}$ undefined. Instead the efficiency can be expressed in terms of the input powers for the energy sources as discussed in the previous sub-section. Also, the individual powers of the sources can be expressed as a fraction of the total power requested by the motor, $P_M$, according to

$$u = \frac{P_{PS}}{P_M}, \quad (7)$$

$$P_{PS} + P_{SS} = P_M, \quad (8)$$

giving a single decision variable $u$ to determine both $P_{PS}$ and $P_{SS}$. Thus the total efficiency can be formulated as

$$\eta_{tot}(u, \omega_{ICE}, P_M, SOC, v) = \frac{P_{out}}{P_{in}} = \frac{P_{PS-in} + P_{SS-in} + u, \omega_{ICE}, P_M, SOC, v}{P_M} \quad (9)$$

### IV. Supervisory Control Systems

Having obtained expressions for the total efficiency of the energy sources, intelligent decisions can be made by the SCS. This section presents two new control strategies that utilize the previous analysis to maximize the efficiency at any given time, while one of these goes further to operate in a charge sustaining fashion. Finally, a separate control scheme is introduced for benchmarking purposes.

#### A. Efficiency Maximizing Map (EMM) Control

The fundamental principle of the EMM control is to operate the energy sources such that the efficiency $\eta_{tot}$ is maximized. As it is clear from the definition of this variable in the previous sub-section, it depends on three defined variables ($P_M, SOC$ and $v$) and two decision variables ($u$ and $\omega_{ICE}$). The objective is thus to produce a map for the optimal decision variables given the defined variables, according to

$$EMM: [u_{opt}, \omega_{ICE-opt}] = f(P_M, SOC, v). \quad (10)$$

The optimization problem can be formulated as

$$P_EMM \left\{ \begin{array}{l} \max_{u, \omega_{ICE}} \eta_{tot} \\ 0 \leq u \leq \frac{P_{PS-in}}{P_M} \end{array} \right. \quad (11)$$

and can be solved through a simple iterative process, where every feasible combination of values for the defined and the decision variables are tested (the range of $u$ is set by the $P_M$ of interest and $P_{PS-in}$ (33 kW), and $\omega_{ICE}$ is evaluated within its feasible range, with decision variables appropriately discretized). As this procedure is performed off-line, computational time is not an issue. Once this optimization is performed, the EMM control map is obtained.

The optimal power share factor $u_{opt}$ with varying power demand and correction factor $v$ is shown in Fig. 5. It can be seen that the effect of $v$ is very significant, and that lower values encourage the use of the PS (higher power share factor $u$). Note also that the control chooses a power share factor.
larger than one for low power demand, which means that the PS will provide more power than the motor requires and the excess power will be used to charge the battery. This allows the PS to operate at a more efficient region, while also charging the battery efficiently, rather than wasting fuel on idling losses. Calculations are also made to investigate the dependence of \( u_{\text{opt}} \) on SOC-levels, and as can be expected from the efficiency plot of the SS in Fig. 4, the effect of the SOC is very small. Fig. 6 shows the optimal selection of the engine speed \( \omega_{\text{ICE}} \) with varying \( v \) values, and as lower \( v \) values lead to higher usage of the PS, it can also be seen that the optimal engine speed requests are higher.

The total efficiency \( \eta_{\text{tot}} \) that is realized by this selection of decision variables \( u \) and \( \omega_{\text{ICE}} \) is presented in Fig 7. It might be expected that the efficiency should be very high at low power requirements as the battery is very efficient in that range, but this is not the case as the idling losses of the engine more than cancel out this advantage. It can also be seen that for small values of \( v \) for which SS usage is discouraged and PS usage is encouraged, the efficiency at high power demands is approximately that of the PS alone.

### B. Efficiency Maximizing and Charge Sustaining Map Control (EMCSM)

The EMM control has no inherent constraints in terms of SOC, so the battery could end up depleted or overcharged and permanently damaged. To address this, a charge sustaining factor \( k \) is included in the control design, which encourages the battery to be charged at low SOC values and discharged at high SOC values. This bias is introduced in the expression of total efficiency, by weighting the \( P_{SS-in} \) as in Eq. 12. For \( k > 1 \), the SS discharging power becomes heavier, causing it to be reduced by the optimization algorithm. Simultaneously the SS charging power becomes heavier, but since it is a negative quantity, this actually encourages further charging of the battery (as \( P_{SS-in} \) is always positive and we are aiming to minimize the denominator). Conversely, for smaller \( k \) values, the discharging of the SS becomes more attractive and charging less desirable. The new objective is not only to maximize the efficiency but also to keep the SOC levels within a certain range. The upper limit of SOC in this case has been chosen to be 80\% to allow a buffer for regenerative braking, as well as to avoid very high SOC that accelerates degradation of the battery. Similarly a lower limit of 50\% is chosen to limit the depth of discharge to 30\%, as it is exponentially related to battery degradation. Thus, the new optimization problem to be solved can be expressed as

\[
P_{EMCSM} \begin{cases} 
\max_{u,\omega_{\text{ICE}}} \eta_{\text{CS}} \\
0 \leq u \leq \frac{P_{PG-max}}{P_{PG}} \\
50 \leq SOC \leq 80
\end{cases} \tag{13}
\]

To ensure operation within this SOC range the charge sustaining factor \( k \) is shaped as shown in Fig. 8. The lower values of SOC are associated with a high \( k \) value, encouraging the SCS to charge the battery, as discussed above. Similarly, at high SOC values, the \( k \) value is low and thus encourages the battery to be discharged. There is a flat region around 65\% where no modification is desired. The exact shape of this factor can easily be adapted and tuned.
$$\eta_{CS}(u, \omega_{ICE}, P_M, SOC, v) = \frac{P_M}{P_{PS-in} (u, \omega_{ICE}, P_M) + k(SOC) \cdot P_{SS-in}(u, P_M, SOC, v)}$$ (12)

C. Thermostat Control

The Thermostat control strategy (also called On-off control) is a simple, robust SCS that achieves a good fuel economy [12]. It is the most conventional control strategy for series HEVs and is a suitable benchmark for the EMM and EMCSM control. The basic principle is to run the PS at its optimal point and have the SS act as an equalizer, as

$$P_{SS} = P_M - P_{PS-opt}.$$ (14)

However, to ensure stable transitions the PS is used just below its peak efficiency (23 kW rather than 25 kW at 1550 rpm). This mode of operation is valid until the SOC reaches its upper threshold (80%), at which point it enters a mode of SS-only operation. This mode quickly depletes the SS and once the SOC hits the lower threshold (50%) it returns to operate the PS at its optimal point. For the purpose of stable operation some additional rules are introduced: the PS stops providing power if the motor is using regenerative braking, to avoid overcharging the battery; the PS is instructed to assist with 14 kW in case the power demand surpasses 16 kW; when in battery-only mode; and some delays are included to avoid oscillations and unstable transitions.

V. Results

The implemented SCS can now be simulated to investigate operation and performance. A $v$ factor value of 0.30 has been selected for all tests to allow reliable comparison of fuel economy, which will be discussed at the end of the section.

A. Power Profiles

Simulations are run for three different drive cycles: the NYCC is low-speed urban driving; the UDDS is high-speed urban driving; and the EUDC is European highway driving. The EUDC cycle is relatively short and shows most clearly the mode of operation of the SCS, so only results of this drive cycle are presented here. Also, the difference in operation between the EMM and EMCSM is barely noticeable when observing the load profile, so only EMM is shown. Figs. 11 and 12 illustrate the power time histories for the PS, SS and motor-set for the Thermostat and EMM control respectively.

The key characteristic of the Thermostat Control is the sharp transition profile for the PS power, which is typically operated at its optimum point. However, due to the additional protective rules, the PS will stop providing power in the case of regenerative braking. The SS power varies from negative to positive to balance the difference between the motor-set power and the PS power. The EMM control on the other hand has less extreme transitions. The SS is used for both charging and discharging in a more balanced way, while the Thermostat charges it for much of the drive cycle. It should be noted that the vehicle model does not include any start-stop system, so the Thermostat control suffers more idling losses than the designed control schemes.
VI. Conclusions

Two supervisory control strategies have been developed for a series HEV. The EMM control presented is an improvement upon previous work, where key upgrades include redefining the SS efficiency such that the discharging efficiency is separated from the charging efficiency. This allows the consideration of battery efficiency without the assumption that the battery is charged and discharged at the same power. Also, the idling losses of the PS have been considered, to further strengthen the accuracy of the SCS. The EMCSM control, which uses a modified EMM, is equipped with the ability to bias the operation of the energy sources such that the SOC is kept close to the initial SOC, and within set thresholds. While the control could be further tuned, it is already delivering significant reductions in fuel consumption.

Both the developed SCSs outperform the Thermostat control in fuel economy and SOC deviation is reduced significantly, contributing to sustainable driving.

REFERENCES