

Control Variables Optimization and Feedback Control Strategy Design for the Blended Operating Regime of an Extended Range Electric Vehicle

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Abstract

In an authors' previous SAE publication, an energy management control strategy has been proposed for the basic, charge-depleting/charge-sustaining (CD/CS) regime of an Extended Range Electric Vehicle (EREV). The strategy is based on combining a rule-based controller, including a state-of-charge regulator, with an equivalent consumption minimization strategy. This paper presents an extension of the control strategy, which can provide a favorable vehicle behavior in the more general blended (BLND) operating regime, as well. Dynamic programming-based control variables optimization is first conducted to gain an insight into the vehicle optimal behavior in the BLND regime, facilitate the feedback control strategy development/extension, and serve as a benchmark for the control strategy verification. Next, a parameter optimization method is applied to find optimal values of critical engine on/off thresholds. Finally, the control strategy is verified against the optimal benchmark for several repetitive certified driving cycles, and the results are compared with those obtained for the basic CD/CS regime.

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INTRODUCTION

Extended Range Electric Vehicles (EREVs) are aimed to combine advantages of electric vehicles such as high efficiency, low level of noise, zero level of gas emissions, and low price of energy, and those of hybrid electric vehicles (HEV) such as high specific energy density and wide vehicle range. The considered vehicle power train (the Chevrolet Volt application) has four basic operating modes [1, 2, 3]: electric vehicle (EV), two-motor electric vehicle (TMEV), series HEV (SHEV), and series-parallel HEV (SPHEV) modes. The basic EREV operating cycle includes (i) the charge depleting (CD) regime (EV and TMEV operation) that is active until a battery is discharged to some predefined low value, and (ii) charge sustaining (CS) regime (additionally, SPHEV and SHEV are active) in which the battery state-of-charge (SoC) is sustained at the reached low value [4]. If the vehicle driving range is known in advance, and it exceeds the vehicle all-electric-range (AER), the battery could be discharged more gradually by combining all operating modes during whole operating cycle (blended operating regime, BLND) [5]. In this way, more control freedom is introduced and the potential for power train losses and energy consumption reduction is further increased.

In order to exploit this potential, the BLND regime-controlled vehicle requires a more sophisticated energy management control strategy, which should be tuned and verified by using the related benchmark obtained through off-line control variable optimization studies.

In [6] BLND control of PHEV power train is realized by adaptation of equivalent consumption minimization strategy (ECMS) weighting factor using a PI controller, in order to force the SoC to follow a SoC reference trajectory. The reference [5] proposes a Pontryagin Minimum Principle (PMP)-based instantaneous optimization strategy, which results in BLND operation as an optimal/preferable type of operation. The same reference also deduces optimal SoC trajectories for different scenarios of road grade. Similar to [6], the paper [7] deals with ECMS control and adaptation of equivalent consumption weighting factor using tangent functions in dependence of the SoC deviation from reference trajectory. In [8] the engine on/off power thresholds have been optimized through an analytical approach applied to a simplified control strategy and a simplified PHEV model, in order to improve the performance in the blended mode. Dependence of the engine-on threshold and a maximum distance that can be traveled using the BLND operation is investigated in [9].

In the authors' previous publication [4], a practical and easy-to-tune rule-based controller is combined in a smooth manner with a multi-phase ECMS control strategy to provide a favorable EREV performance in the CD/CS operating regime. The SoC is explicitly sustained by means of a proportional+deadzone-type SoC controller. Consequently, the basic CD/CS strategy can be readily extended for the BLND regime through a proper shaping of the SoC reference trajectory. However, in order to achieve consistent performance in the BLND regime (always better than in the CD/CS regime in terms of fuel economy gain), it has been found out that the engine on/off thresholds should be tuned by off-line parameter optimization.

The paper is organized as follows. First, a backward-type EREV power train model and the basic CD/CS control strategy have been described. Next, a dynamic programming (DP)-based control variable optimization is conducted for the case of CD/CS and BLND regime. The insights gained through control variable optimization and the results of numerical controller-parameter optimization are used to extend the control strategy to exploit the features of optimized vehicle behavior in the BLND regime. Finally, the control strategy is verified against the optimal DP benchmark for several certified driving cycles, and its performance is compared with that of the basic CD/CS strategy.

EREV POWER TRAIN MODEL AND CONTROL STRATEGY

Modeling and power flow analysis of the EREV transmission [1] is explained in details in [3, 10]. The next subsection briefly describe the backward power train model that is further used for the purpose of control variables optimization and feedback control strategies verification. Also, the previously developed control strategy is described, which was proven to be very close to globally (DP) optimal results in the CD/CS operating regime [4].

Backward Model of EREV Power Train

Fig. 1 shows a functional scheme of the considered Extended Range Electric Vehicle (EREV) transmission [1, 3]. Apart from the internal combustion engine (ICE), two electric machines (M/G1 and M/G2), battery, and planetary gear, this transmission also includes three clutches (F1, F2, and F3), which are responsible for switching between various operating modes.

Depending on the clutch state (cf. Table 1), the transmission can operate either in modes where the electric driving is solely used and battery charge is depleting (Charge Depleting regime - CD), or in modes where the hybrid operation is active and battery charge is sustaining (Charge Sustaining regime - CS). More specifically, there are five characteristic power train operating modes [1, 3] which can be divided into three specific groups. In the first group, characterized by no power split, clutch F1 is locked (F1 = ON), and clutch F2 is open (F2 =

OFF). Thus, the ring gear is locked, the planetary gear is reduced to a standard two-port gear, and the M/G2 machine speed is directly proportional to the power train output speed ω_{cd} . Here, the engine clutch F3 is used to switch between electric vehicle mode (EV, F3 = OFF) or series hybrid electric vehicle mode (SHEV, F3 = ON), where the latter also includes the engine start operation. The second group of operating modes includes the power split feature (F1 = OFF, F2 = ON), where clutch F2 connects the M/G1 machine to the planetary gear, thus combining both electric machines and making their speeds dependent on each other and the output speed ω_{cd} . Again, depending on the state of engine clutch F3, this results in series-parallel operating mode (SPHEV, F3 = ON), or two-machine electric vehicle mode (TMEV, F3 = ON). The third group relates to the power train idle mode, where clutches F1 and F2 are open, while F3 can be locked for charging the battery (BC) or starting the engine, or open for fully idle mode.

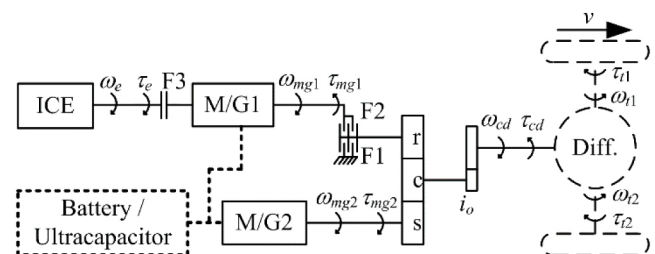


Figure 1. Principal schematic of considered EREV power train.

Table 1. Characteristic modes of EREV power train operation.

MODE	F1	F2	F3	Regime	Power split	S_{mode}
EV	ON	OFF	OFF	CD	NO	0
SHEV	ON	OFF	ON	CS	NO	3
TMEV	OFF	ON	OFF	CD	YES	1
SPHEV	OFF	ON	ON	CS	YES	2
BC	OFF	OFF	ON	CS	n/a	n/a
Idle	OFF	OFF	OFF	n/a	n/a	n/a

The transmissions speed and torque steady-state equations are shown in Table 2 for different operating modes [1, 3]. Fig. 2 shows the block diagram of backward model of the considered transmission, where the equations from Table 2 are integrated into the Mechanical transmission block.

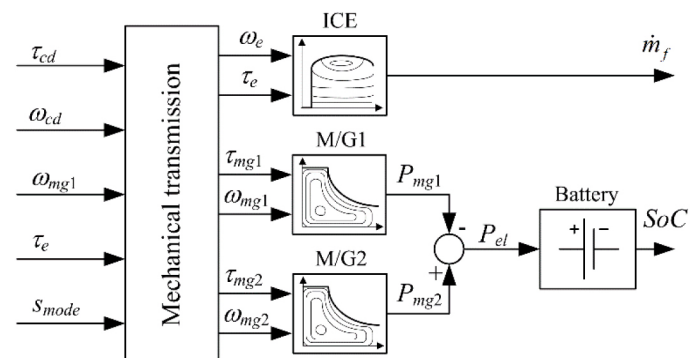


Figure 2. Block diagram of simple quasi-static backward model of EREV system.

Table 2. Transmission steady-state equations for different operating modes [10].

MODE:	ω_{cd}	τ_{cd}
EV, SHEV	$\frac{1}{i_o(h+1)}\omega_{mg2}$	$i_o(h+1)\tau_{mg2}$
SPHEV, TMEV	$\frac{1}{i_o(h+1)}(\omega_{mg2} + h\omega_{mg1})$	$i_o(h+1)\tau_{mg2} = i_o(h+1)h^{-1}(\tau_e - \tau_{mg1})$
MODE:	ω_e	τ_e
EV	0	0
SHEV	ω_{mg1}	τ_{mg1}
SPHEV	ω_{mg1}	$h\tau_{mg2} + \tau_{mg1}$
TMEV	0	0

The engine and electric machines from Fig. 1 are represented in the model in Fig. 2 with the nonlinear specific fuel consumption and efficiency maps, respectively, which are shown in Fig. 3 along with the engine and electric machines maximum torque curves denoted by bold green lines [3].

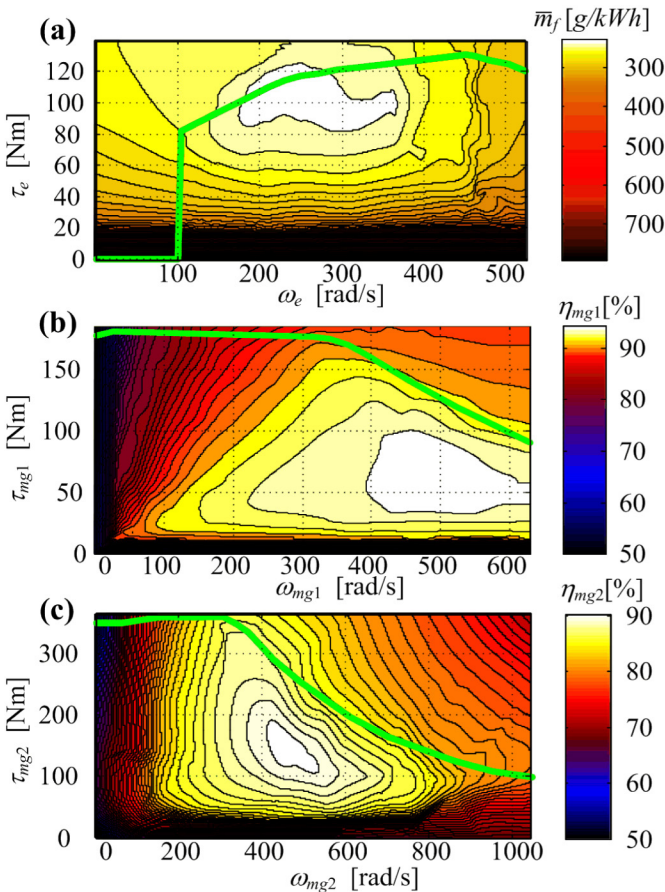


Figure 3. Torque limit curves and efficiency plots for engine (a), M/G1 machine (b), and M/G2 machine.

The only state-variable of the backward model in Fig. 2 relates to the battery State-of-Charge (SoC), where the battery dynamics is described by the following well-known state equation [11]:

$$\frac{dSoC}{dt} = \frac{\sqrt{U_{oc}^2(SoC) - 4R(SoC, i)P_{batt}} - U_{oc}}{2Q_{max}R(SoC, i)}, \quad (1)$$

with U_{oc} denoting the open circuit voltage, R the internal resistance, and Q_{max} the battery capacity, and $0 \leq SoC = Q/Q_{max} \leq 1$. In the model used in this paper (Fig. 4), the voltage U_{oc} is made dependent on the SoC [11], while the internal resistance R is made dependent on the current sign, $\text{sgn}(i)$ (i.e. different values are used for charging and discharging). The battery power in (1) is calculated as

$$P_{batt} = P_{mg2} - P_{mg1} = \eta_{mg2}^{k_2} \omega_{mg2} \tau_{mg2} - \eta_{mg1}^{k_1} \omega_{mg1} \tau_{mg1}, \quad (2)$$

where $\eta_{mg1,2}$ is the efficiency of the M/G1 and M/G2 machines, and the coefficient $k_{1,2}$ is equal to -1 or 1 depending on whether an electrical machine operates as a motor or generator, respectively.

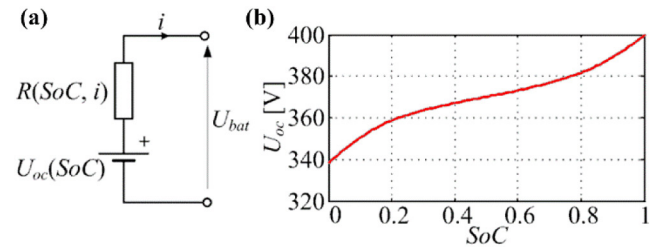


Figure 4. Battery equivalent electrical circuit (a) and open circuit voltage vs. state-of-charge dependence (b).

EREV CD/CS Control Strategy

The basic modes of EREV operation are charge depleting (CD) and charge sustaining (CS) regimes. The vehicle is driven in the CD regime until the SoC reaches some predefined value (30% in this paper), and afterwards it is switched to the CS regime in order to sustain the SoC. Consequently, there are two different control strategies: (i) CD regime strategy (electric driving only) and (ii) CS regime strategy (hybrid electric driving). The CD regime includes EV and TMEV operating modes, while the CS regime supports all operating modes (EV, TMEV, SHEV, and SPHEV).

Both, CD and CS strategies consist of two parts: (i) optimal operating mode determination, and (ii) instantaneous optimization of power train operating points for the chosen operating mode and the given driver demand inputs and physical constraints on power train torque and speed variables. Fig. 5 outlines operating modes regions in the output torque vs. vehicle velocity map, whose borders have been obtained by means of offline analyses and dynamic programming optimization tool [4, 12] (cf. [2]). In the case of CD regime's EV and TMEV modes, the powertrain operating point is set with the aim to satisfy the driver torque demand, and at the same time to maximize the overall powertrain efficiency.

case of hybrid modes (SPHEV and SHEV), the (engine) operating point is chosen according to the RB+ECMS methodology described in the next subsection.

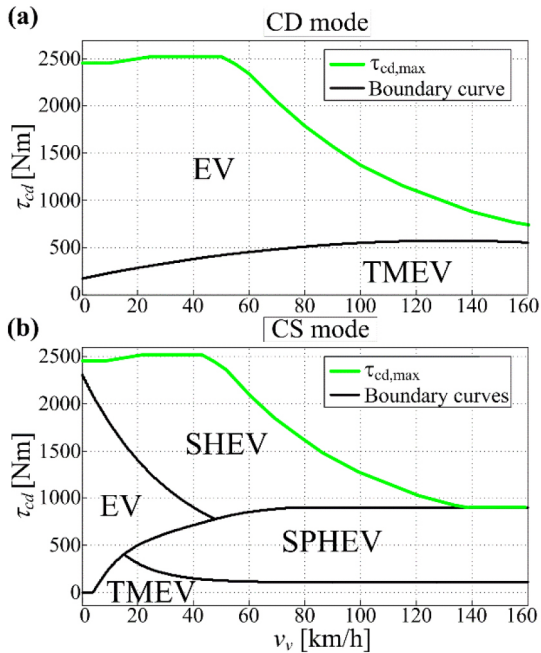


Figure 5. Operating modes and associated regions for the case of CD regime (a), and CS regime (b).

Hybrid Modes Control Strategy

Since the engine, M/G1 machine and M/G2 machine speed and torque variables are coupled through the planetary gear kinematics model and the driver demand (Table 2), it is found to be sufficient to assign only two independent control variables (here the engine speed and engine torque) for the given vehicle velocity and torque demand. The rule-based (RB) control strategy (see Fig. 6a, [4]) consists of a proportional-like SoC controller, engine start/stop logic, and engine operating point calculation. Note that engine start/stop logic contains hysteresis aimed to avoid frequent engine on/off switching.

The engine operating point optimization is aimed to minimize the equivalent fuel consumption defined by [4, 13]

$$\dot{m}_{eq} = \dot{m}_{fuel} + \dot{m}_{batt}(P_{batt}, \eta_{batt}, A_{ek}), \quad (3)$$

where the battery power flow is accounted for by the so-called battery equivalent fuel rate $\dot{m}_{batt}$ and combined with the actual engine fuel consumption rate $\dot{m}_{fuel}$, and where P_{batt} is the battery charging/discharging power given by Eq. (2), η_{batt} is the battery efficiency and A_{ek} is the engine specific fuel consumption. The driver and battery power demands (P_d and P_{batt} , respectively) are used to determine the engine power demand P_e^* . The 1D-ECMS optimization minimizes the equivalent fuel consumption (3) over the constant engine power curve $P_e = P_e^*$, thus satisfying the engine power demand and ensuring the SoC sustainability (Fig. 6a, [4]). When the SoC is around the target value, it is possible to give the ECMS more freedom in order to reduce the fuel

consumption. Thus, 2D-ECMS, which minimizes the equivalent fuel consumption (3) over the 2D region in the engine speed vs. torque map, can be applied. Finally, a 2D-ECMS is smoothly combined with RB+1D-ECMS through a SoC error-dependent weighting function $W(e_{SoC})$ (see Figs. 6b, [4]). Both optimizations are conducted by using the Hooke-Jeeves directional search algorithm. A simple linear search is initially performed over the coarsely discretized 1D or 2D target region, thus minimizing the possibility that the directional search algorithm ends up in a local minimum. This combined, final strategy is denoted below as RB+ECMS. When the SoC starts to significantly differ from its target value, the RB+1D-ECMS takes dominance over the 2D-ECMS due to its ability to preserve the SoC sustainability while still using the ECMS (of 1D type).

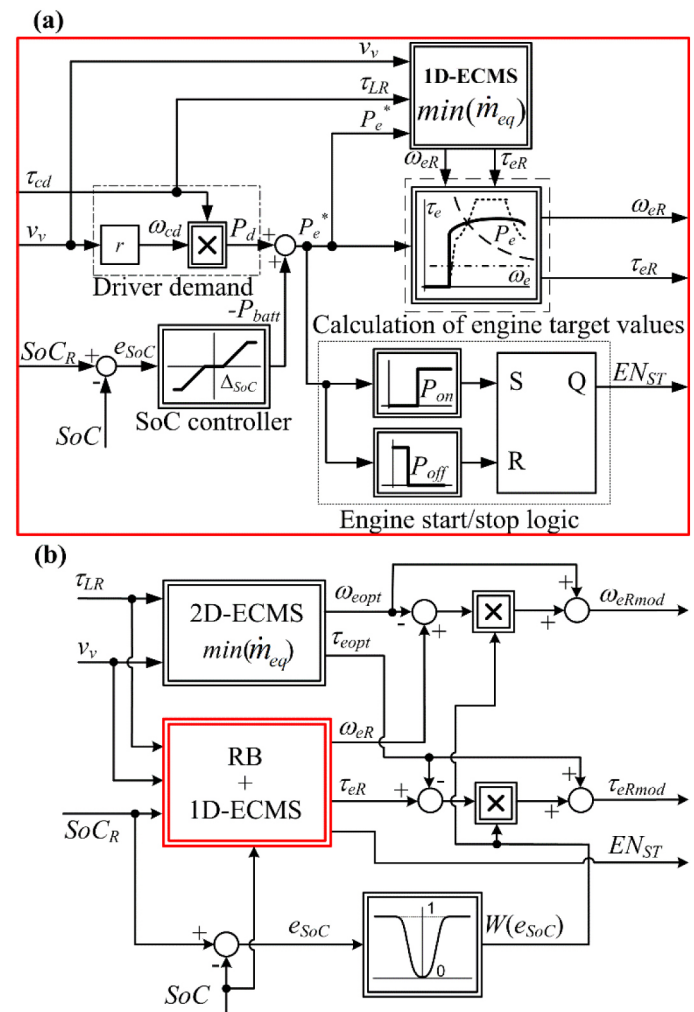


Figure 6. Block diagram of combined RB controller and 1D-ECMS (a), and block diagram of combined RB+1D-ECMS controller extended with 2D-ECMS.

Verification Results

Table 3 shows comparative results of RB+ECMS and DP optimization for CD and CS operating regimes. For CD regime, electrical energy consumptions expressed in SoC decrease are compared, and for CS regime fuel consumptions are compared. The CS regime results from Table 3 are illustrated