Energy-efficient Straight-line Driving Torque Vectoring for Electric Vehicles with Disconnect Clutches and Unequal Front/Rear Motors

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Abstract. This paper investigates potential of energy efficiency improvement for electric vehicle (EV) equipped with unequal front/rear-axle e-motors and disconnect clutches under straight-line driving conditions. First, a static optimization of front/rear torque distribution is performed for various driving cycles, which provides insights into energy efficiency gains and optimal powertrain operation including optimal torque switching curve for two- and four-wheel drive modes. Disconnect clutches enable inactive motors to be switched off when operating in the 2WD mode to avoid their drag losses. A dynamic programming (DP)-based optimization of torque vectoring control trajectories is carried out to find the globally optimal energy saving potential. For clutch durability reasons, the number of clutch state changes is minimized along with energy consumption. Finally, a rule-based (RB) control strategy is proposed and verified against the DP Pareto optimal frontier benchmark for different certification driving cycles.

Keywords: Electric Vehicles, Four-wheel Drive, Unequal Motors, Disconnect Clutches, Energy Efficiency, Torque Vectoring, Optimization, Control.

1 Introduction

Electric vehicles (EV) can conveniently be realized in multiple e-motor configurations. These configurations are characterized by control redundancy that can be exploited to improve vehicle dynamics [1] and reduce energy consumption [1, 2]. For instance, the energy efficiency can be improved for straight-line driving by using two-wheel-drive (2WD) mode for low-torque demands, while switching to all-wheel drive (AWD) mode for mid-high torque demands [1]. Further energy efficiency gains can be achieved by avoiding the drag losses of inactive motors in the 2WD mode through disconnecting those motors via dog clutches [3].

EV torque vectoring literature is mostly focused on powertrains with no disconnect clutches and equal motors [4]. It is analytically proven in [5] that, under those conditions, the equal front/rear torque distribution is optimal in the AWD mode occurring above a vehicle velocity-dependent torque demand switching curve. When concerning the use of disconnect clutches, the optimization problem becomes dynamic, and a global optimum can be found offline by using a dynamic programming algorithm [6, 7]. The DP benchmark can closely be approached by using rule-based (RB) control [6].

When concerning unequal front/rear motors, the optimal control problem becomes more complex, and it is solved in [8, 9] for the no-disconnect case. The main aim of this paper is to extend the numerical optimization and RB controller design studies from [6] to the disconnect case, in order to gain insights into optimal behavior and check the RB strategy applicability in this more general design task.

2 Model

The considered EV powertrain consists of two unequal pairs of e-motors (M/G$_1$ of 55 kW at front axle, and M/G$_2$ of 111 kW at rear axle), which are represented by the efficiency and maximum torque maps shown in Figs. 1b and 1c, and adopted from an extended-range EV from [12]. The motors are connected to wheels via single-speed transmissions and dog clutches (Fig. 1a).

The EV powertrain is represented by a backward-looking model [6, 11], which apart from the kinematic relations accounts for the tire and transmission losses. The front/rear torque distribution is defined by the torque distribution control input σ: $\tau_{w,f} = \sigma\tau_{w,t}$, $\tau_{w,r} = (1-\sigma)\tau_{w,t}$, where $\tau_{w,t}$ is the total torque demand calculated from the vehicle longitudinal dynamics model fed by the velocity/acceleration profile defined by a simulated driving cycle. The only dynamics within the model relates to clutch state equation $\mathbf{c}(k+1) = [0\ 0\ 0\ 0]\cdot\mathbf{c}(k) + \mathbf{I}\cdot\mathbf{c}_R(k)$, where $\mathbf{c}$ and $\mathbf{c}_R$ are binary vectors of clutch sta and clutch state reference, respectively, and k is the sampling step. The model includes $\mathbf{c}$- and $\mathbf{c}_R$-related e-drive transient losses corresponding to clutch connect synchronization and clutch-disconnect motor stopping process [6, 11]. The vehicle mass is increased compared to model in [6] to account for larger-size rear motors and provide wider-torque range utilization of motors for given, certification driving cycles.

3 Optimization and Control

The static optimization relies on a search over a grid of σ values, which is aimed at minimizing the battery power consumption. The results shown in Fig. 2a for the clutch disconnect case suggest that it is optimal to use the weaker, front motors ($\sigma = 1$; FWD) if the torque demand is lower than the torque switching curve (cyan; cf. EREV optimization results in [12]), which is close to the maximum torque curve for the FWD mode (red). Otherwise, all-wheel drive (AWD) is optimal, where σ mostly takes values in the range from 0.2 to 0.5, thus meaning that the torque is distributed towards stronger, rear motors. When not considering the disconnect clutches, the optimized σ-maps turn out to be very similar to those shown in Fig. 2a. These results contrast with those obtained for equal motors (M/G1 all; [10]), where equal distribution ($\sigma = 0.5$) is optimal for AWD mode and the torque switching curves are distinctively different depending on whether the disconnect clutches are used or not. This is partly because the equal torque distribution is not feasible for high torque demands in the case of unequal motors (those larger than $4\tau_{m,1,max}h_1$, see Fig. 2a). For instance, the torque distribution ratio at the maximum wheel torque demand is determined by $\sigma_{max} = 2\tau_{m,1,max}h_1/(2\tau_{m,1,max}h_1 + 2\tau_{m,2,max}h_2)$, which gives $\sigma_{max} = 0.2317$.

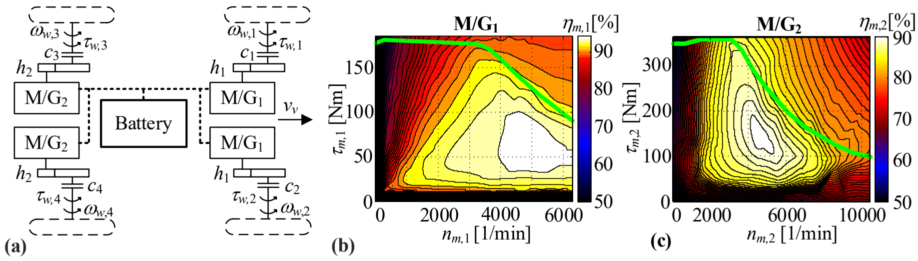

Fig. 1. Principal schematic of EV powertrain with unequal front/rear e-motors (a), given by efficiency maps and maximum torque curves (b, c).

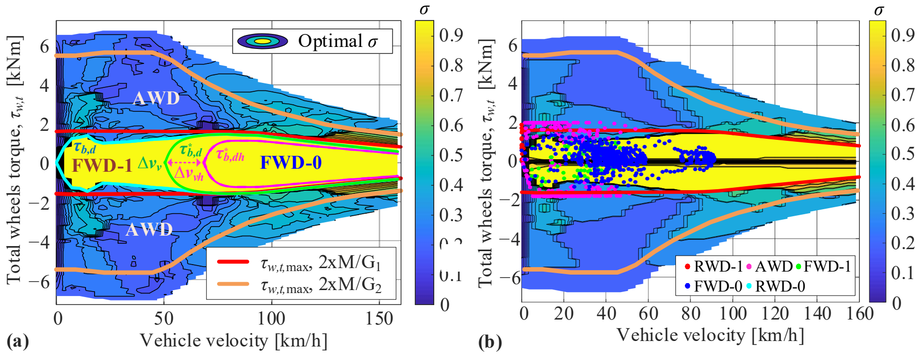

Fig. 2. Optimized torque distribution ratio map for clutch disconnect case (a) and DP optimization results corresponding to control setting denoted by orange-circle point in Fig. 5a.

Using the disconnect clutches introduces clutch state dynamics and related transient losses in the optimization problem. To establish a globally optimal benchmark for control strategy design and verification, offline optimizations of control trajectories $\sigma(k)$ and $\mathbf{c}_R(k)$ are performed by using the dynamic programming (DP) algorithm from [6, 10]. For the clutch durability and also drivability reasons, the energy consumption minimization cost function is extended with a term that penalizes the number of clutch state changes, with the corresponding weighting factor K_{sw} [10].

The RB control strategy, which is originally proposed for the powertrain with equal motors [6, 11], is somewhat adapted for the considered powertrain with unequal motors. It sets the AWD operating mode with the fixed $\sigma = 0.3$ (instead of $\sigma = 0.5$) for torque demands above the torque switching curve (cyan), while setting the FWD ($\sigma = 1$), otherwise (see Fig. 2a). The FWD mode is further divided into regions where the opposite-axle (rear) e-motors are connected (FWD-1) or disconnected (FWD-0), with the note that unlike in [6, 11] there are no separate switching curves for these two cases. This rule is motivated by DP optimization results shown in Fig. 2b, which indicate that the RWD clutches should remain connected in the FWD mode under low-velocity (urban-like) condition, in order to reduce the clutch switching frequency including related transient losses. The FWD-1/FWD-0 boundary curve ($\tau^*_{b,d}$; green) has a two-parameter exponential form and it is supplemented with a hysteresis ($\tau^*_{b,dh}$; magenta) to suppress the number of clutch state changes [6, 11].

4 Results

Different control strategy variants are simulated over various certification driving cycles and compared based on the battery energy consumption (Table 1). The baseline strategy without clutch disconnect functionality, given in the first row of the table, simply iterates σ over the fine-resolution set $\{0, 0.01, \ldots, 1\}$ at each simulation time step, to find the optimal value minimizing the energy consumption. Narrowing σ to only three discrete values $\{0, 0.35, 0.97\}$, selected on the basis of the static optimization results from Fig. 2a, leads to around only 1% higher energy consumption while simplifying the implementation. Adding clutch disconnect option within the static optimization in each simulation time step, and thus enabling FWD-0 and RWD-0 operating modes, improves the energy consumption up to 6% when compared to the baseline case (the third row of the table, cf. similar results given in [10, 11] for the case of equal motors). The DP optimization accounting for transient losses further improves the results, with the percent margin shift of up to 2% for dynamic driving cycles (UDDS and US06), and negligibly (around 0.2%) for quasi-stationary cycles (HWFET and NEDC).

Table 1. Battery energy consumption [kWh] of control allocation and DP for various certification driving cycles.

METHOD	Disconnect	WLTP	UDDS	US06	HWFET	NEDC
Control allocation ($\sigma \in \{0,0.01,\ldots,1\}$)	No	4.5189 (0%)	1.9941 (0%)	2.8620 (0%)	2.9525 (0%)	1.9178 (0%)
Control allocation ($\sigma \in \{0,0.35,0.97\}$)	No	4.5521 (+0.7%)	2.0089 (+1.2%)	2.8949 (+1.2%)	2.9703 (+0.6%)	1.9309 (+0.7%)
Control allocation ($\sigma \in \{0,0.35,1\}$)	Yes	4.3777 (−4.1%)	1.9904 (−2.6%)	2.7827 (−2.6%)	2.7827 (−5.9%)	1.8126 (−5.7%)
DP, $^*K_{sw} = 0$ ($\sigma \in \{0,0.1,\ldots,1\}$)	Yes	4.3130 (−4.6%)	1.9064 (−4.4%)	2.7547 (−3.7%)	2.7713 (−6.1%)	1.8048 (−5.9%)

$^*K_{sw} = 0$ relates to case of no clutch switching penalization within DP optimization.

Fig. 4 shows the DP Pareto optimal frontiers (blue circles) obtained for $\sigma \in [0, 0.1, \ldots, 1]$ and a wide range of K_{sw} values. The same figure shows the Pareto filtered frontiers corresponding to RB control strategies with and without hysteresis included (see [6, 11] for methodology details). The battery energy consumptions are expressed relative to the right-most minimum-energy Pareto frontier point ($K_{sw} = 0$). The number of clutch state changes can be reduced by up to 80% via increase of K_{sw} with a minor increase of energy consumption. Introduction of hysteresis brings consistent improvement of results, which is most pronounced for the dynamic driving cycles (UDDS and US06; Fig. 4). The full-RB vs. DP relative energy consumption increase around the Pareto frontier knee point (i.e., in the region where the clutch switching frequency is well suppressed) is typically around 2%. This is somewhat inferior to the performance of the powertrain with equal motors, where the energy consumption increase margin is around 1% (see comparative results shown in Fig. 5). This implies that the expected benefit of predictive control would be higher for the case of unequal motors (see [6, 10, 11] for details of model predictive control approach and related results).

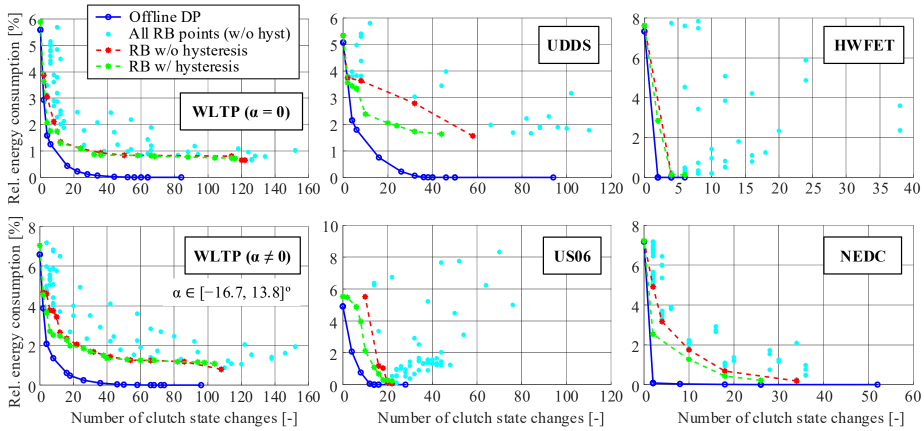

Fig. 4. Pareto optimal frontiers obtained by DP optimization, and RB control with and without hysteresis (a realistic non-zero road slope profile α is optionally appended to WLTP cycle).

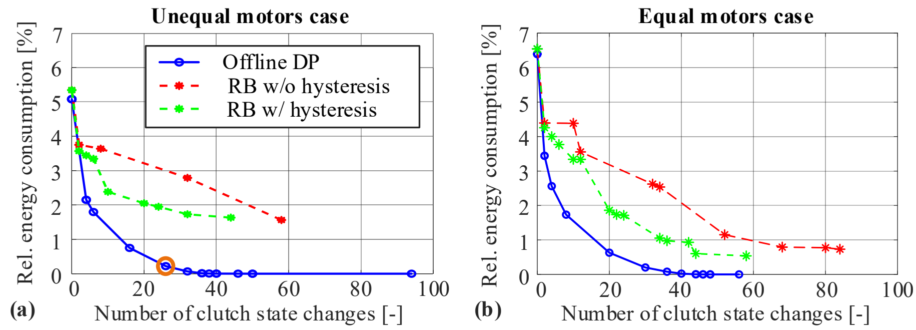

Fig. 5. DP and RB control Pareto optimal frontiers for powertrains with unequal (Fig. 4) and equal motors [11] (UDDS driving cycle).

5 Conclusion

An analysis of energy-efficient straight-line driving torque vectoring for electric vehicles equipped with unequal front/rear e-motors and disconnect clutches has been presented. The emphasis was on comparison of control strategy specifics and related performance with respect to the basic case of equal motors.

Control allocation optimization has revealed that there is an optimal velocity-dependent and clutch state-unaffected torque switching curve, below which it is optimal to operate with front (weaker) motors only (front-wheel-drive, FWD), while all motors are activated, otherwise (all-wheel-drive, AWD). The optimal values of AWD front/rear torque distribution ratio lie in the range from 0.2 to 0.5 depending on the torque demand and velocity (unlike the value of 0.5, i.e. equal distribution, in the case of equal motors). It has been shown that the AWD torque distribution ratio can be fixed to a single value (0.35 for the particular vehicle) and still approach the optimal results (with the energy consumption increase margin of up to 1%). When enabling the clutch disconnect option, the energy consumption can be reduced by up to 6%, which is similar margin as in the case of equal motors.

Apart from the energy consumption criterion, the number of clutch state changes has also been considered for clutch durability reasons. Globally optimal and offline-obtained dynamic programming (DP) results have shown that the number of clutch state changes can be reduced by up to 80% with negligible influence on energy consumption. The previously proposed rule-based (RB) control strategy has been adjusted for the powertrain with unequal motors. The RB control performance approaches the DP benchmark energy consumption within the margin of 1% for a majority of considered driving cycles, while in the worst-case of UDDS cycle this margin increases to around 2%. Although small, these values are about doubled when compared with those observed for the powertrain with equal motors, which leaves a certain room for performance improvement through applying more sophisticated predictive control strategies.

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