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Research paper

Gear-shifting in a novel modular multi-speed transmission for electric vehicles using linear quadratic integral control

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ABSTRACT

The efficiency of electric vehicles (EVs) can be improved by applying multi-speed transmissions (MSTs), while ensuring that gear-shifting is swift and smooth. This paper establishes a gear-shifting control algorithm for a novel MST, with the advantages of simplicity and modularity, designed for EVs. Firstly, the mathematical model of the proposed MST is derived. Next, the control algorithm developed for gear-shifting is clarified, which guarantees seamlessness and swiftness. The system under study is over-actuated, with end constraints on some control inputs. Therefore, for acceleration and jerk continuity, while satisfying the input terminal constraints, one input is suggested to be changed independently, based on a 2-3 blending polynomial. Then, the new fully-actuated system is controlled using a linear quadratic integral (LQI) controller, which is an extension of the linear quadratic regulator (LQR) for tracking problems. Simulation results indicate the effectiveness of the proposed control algorithm in the presence of unknown external disturbances.

1. Introduction

Electric vehicles (EVs) suffer from the current low energy-storage capacity of electric batteries. Hence, to improve the efficiency of EVs, multi-speed transmissions (MSTs) are being considered for applications in EVs [1–4]. This way, since the power provided by the electric motor (EM) is transmitted to the wheels by different gear ratios, the maximum operating efficiency can be achieved for various conditions via proper gear-shifting.

Automated manual transmissions (AMTs) [5–7], automatic transmissions (ATs) [8–10], dual-clutch transmissions (DCTs) [11–13] and continuously variable transmissions (CVTs) [14,15] are different kinds of MSTs for EVs. The above-mentioned transmissions were initially designed for internal-combustion-engine vehicles (ICEVs). However, in ICEVs, since the engine cannot operate below certain speeds, and their speed control is quite challenging, clutches or torque converters are essential to disconnect the engine from the transmission system during gear-shifting. On the contrary, one can remove such clutches or torque converters in designing MSTs for EVs, since the speed of EMs can be controlled in an extensive range. In fact, in EVs, to make gear-shifting seamless and swift, the torque provided by the motor can be employed as an independent control input [16]. Gear-shifting affects drivability of the vehicle, dynamic performance and passenger's comfort. Hence, the key goals during gear-shifting are seamlessness, swiftness, vibration-elimination, cancellation of output-torque interruption and increased drivability. There has been intensive research on the above-mentioned targets [17–20].

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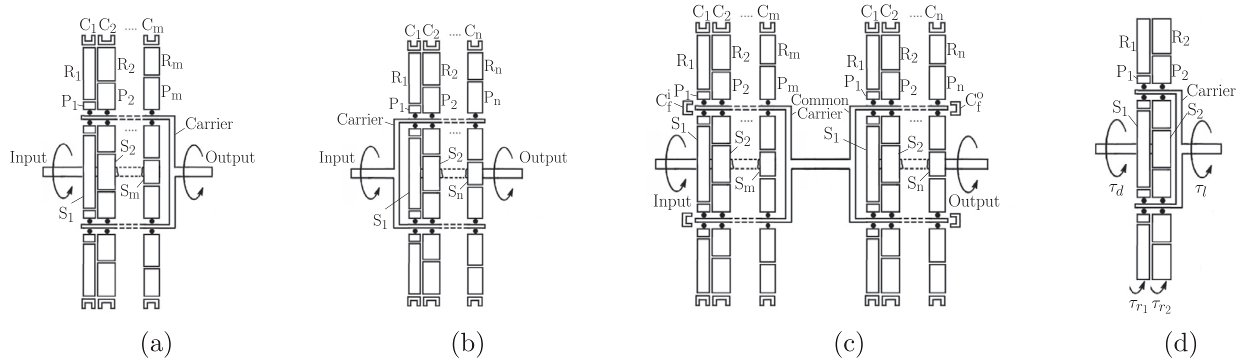

Fig. 1. Multi-stage planetary gear sets: (a) underdrive gear train; (b) overdrive gear train; (c) combined MST; and (d) a two-stage planetary gear set.

Many approaches have been applied for design, modelling, and gear-shifting control and estimation in MSTs [21]. For instance, Pakniyat and Caines [22,23] employed the time-optimal hybrid minimum principle to reach a certain speed from rest in minimum time. The same authors also found the optimal gear-shifting instants, the optimal gear ratios, and the optimal control inputs. Considering gear-shifting goals, Meng et al. [24] established an optimal shifting control algorithm, i.e., the combination of a PID and a robust controller, based on their dynamics model. Moreover, Mousavi et al. [25] and Alizadeh et al. [26] estimated the unmeasurable states and the unknown inputs of a transmission for EVs. Next, using the estimation results, these authors built an observer-based backstepping controller to attain a seamless shift [27]. Based on the integrated powertrain control of both the engine and the clutches, a new strategy was introduced by Walker et al. [28] to improve the gear-shifting transient response in DCTs. Design, mathematical modelling and estimation of the unmeasurable loads and states of a novel MST designed for EVs was investigated employing the Kalman filter, the Luenberger observer and neural networks (NNs) [29,30]. Further, applying polynomial transition functions, the optimal trajectory for gear-shifting was found, which guarantees velocity, acceleration and jerk continuity [31]. Although there has been extensive research on MSTs for EVs, there are still lacunae in gear-shifting algorithms and control.

In this paper, a gear-shifting control algorithm is developed for a novel modular MST designed for EVs. The designed MST has the advantages of simplicity and modularity. Firstly, after a brief description of the proposed MST, its dynamics model is established. Then, after stating the gear-shifting problem, the proposed control algorithm for a swift, seamless shift is explained. From a control point of view, the system under study is over-actuated, i.e., the number of control inputs is greater than the number of outputs. Besides, there are terminal constrains on some of the control inputs. Hence, it is suggested to change one of the inputs independently based on a 2-3 blending polynomial, which, besides meeting the end constraints, guarantees the continuity of the acceleration and jerk at the ends of the gear-shifting interval. Next, for controlling the new fully-actuated system, a linear quadratic integral (LQI) controller is employed, which is an extension of the linear quadratic regulator (LQR) for tracking problems. Simulation results demonstrate that the proposed control algorithm is very promising for a seamless, swift shift in the designed MST, even in the presence of unknown disturbances.

An outline of the paper follows. In Section 2, the proposed MST designed for EVs is briefly described. The mathematical model of the transmissions is derived in Section 2.1, while the gear-shifting problem is explained in Section 2.2. The proposed gear-shifting control algorithm is discussed in Section 3. Simulation results are reported in Section 4.

2. The proposed MST designed for EVs

First, the mathematical model of the proposed MST designed for EVs is derived using a Lagrangian formulation. Next, the gear-shifting problem is discussed.

2.1. Mathematical modelling

All planetary gear sets in the proposed MST designed for EVs share the same carrier, as represented in Fig. 1. As well, all sun gears on each side of the transmission are installed on the same shaft. In the underdrive gear train, the sun gears and the carrier are connected to the input and output shafts, respectively, as depicted in Fig. 1(a), while the overdrive gear train operates the other way around, as shown in Fig. 1(b). To achieve the desired speed ratio, the corresponding clutch should be engaged. For shifting between speed ratios, the engaged clutch should be released and another one should be engaged. The underdrive and overdrive gear trains can be combined into one single transmission, as indicated in Fig. 1(c). In the new MST, two friction clutches, C_f^i and C_f^o, are applied between carrier and planet gears to lock the free overdrive or underdrive gear train. The main advantages of the proposed MST designed for EVs are modularity and simplicity. The mathematical model of a two-speed underdrive gear train, illustrated in Fig. 1(d), is now derived using a Lagrangian formulation.