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A two-phase control algorithm for gear-shifting in a novel multi-speed transmission for electric vehicles

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ABSTRACT

In light of the current low energy-storage capacity of electric batteries, multi-speed transmissions (MSTs) are being considered for applications in electric vehicles (EVs), since MSTs decrease the energy consumption of the EV via gear-shifting. Nonetheless, swiftness and seamlessness are the major concerns in gear-shifting. This study focuses on developing a gear-shifting control scheme for a novel MST designed for EVs. The main advantages of the proposed MST are simplicity and modularity. Firstly, the dynamics model of the transmission is formulated. Then, a two-phase algorithm is proposed for shifting between each two gear ratios, which guarantees a smooth and swift shift. In other words, a separate control set is applied for shifting between each gear pair, which includes two independent PID controllers, tuned using trial-and-error and a genetic algorithm (GA), for the two steps of the algorithm and a switch. A supervisory controller is also employed to choose the proper PID gains, called PID gain-scheduling. Simulation results for various controllers and conditions are reported and compared, indicating that the proposed scheme is highly promising for a desired gear-shifting even in the presence of an unknown external disturbance.

1. Introduction

Due to a much lower impact on the environment, hybrid electric vehicles (HEVs) and electric vehicles (EVs) appear as proper substitutes for internal-combustion-engine vehicles (ICEVs). Nevertheless, since the energy-storage capacity of electric batteries is much lower than that of their ICE counterparts, EVs are not yet established as viable substitutes. Therefore, to achieve longer running time on a single charge of the electric battery, the efficiency of EVs should be improved. Research has shown that by applying a multi-speed transmission (MST) in EVs, thus providing the desired power in more than one way, one can attain a higher efficiency through gear-shifting [1–4].

There are various types of MSTs for EVs, initially designed for ICEVs, such as automated manual transmissions (AMTs) [5–7], automatic transmissions (ATs) [8–10], dual-clutch transmissions (DCTs) [11–13], and continuously variable transmissions (CVTs) [14,15]. The presence of clutches or torque converters are vital for gear-shifting in ICEVs, since ICEs cannot operate below certain speeds and their speed control is quite challenging. On the other hand, electric motors (EMs) are speed-controllable in a wide range of operating speeds. Hence, novel MSTs can be designed for EVs, without any clutches or torque converters to disconnect the EM from the transmission during gear-shifting. In fact, EM and clutches can be adopted as control inputs in the EV transmissions to make gear-shifting seamless and swift. Since gear-shifting affects

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the dynamic performance, passenger comfort, and drivability[1] of the vehicle, the main objectives during gear-shifting are seamlessness, swiftness, increased drivability, vibration-elimination, cancellation of output-torque interruption, and improved efficiency. Extensive research has been conducted on each of the above-mentioned goals [16–19].

Different strategies have been employed for gear-shifting control and estimation in ATs and DCTs [20]. For instance, applying the time-optimal hybrid minimum principle, Pakniyat and Caines [21,22] found the minimum acceleration time required for reaching a speed of 100 km/h from rest. Next, the authors obtained the optimal gear ratios, the optimal gear-shifting instants and the optimal control inputs. Based on the dynamics model and gear-shifting objectives, an optimal shifting control strategy, including a PID controller and a robust two degree-of-freedom (dof) controller, was developed by Meng et al. [23] for an AT for automotive applications. Further, Rahimi et al. [24,25] estimated the unmeasurable states and the unknown inputs for a seamless two-speed transmission for EVs. Then, based on the estimation results, an observer-based backstepping controller was developed to achieve seamless gear-shifting, while tracking the optimal trajectory corresponding to the minimum shifting time [26]. Walker et al. [27] proposed a new scheme, namely, the integrated powertrain control of both the engine and the clutches, for reducing shift transient responses in DCTs. Design, modelling and estimation of the unmeasurable loads and states of a novel MST designed for EVs were studied by our team based on the Kalman filter, the Luenberger observer and neural networks (NNs) [28,29]. Moreover, to assure acceleration and jerk continuity, the optimal trajectory for a swift and seamless gear-shifting was found employing polynomial transition functions [30]. Although intensive research has been conducted on MSTs for EVs, there are still lacunae in design, modelling, and gear-shifting strategies and control.

This paper reports on the development of a two-phase gear-shifting control algorithm for a novel modular MST designed for EVs. The main advantages of the proposed MST are simplicity and modularity. Firstly, the dynamics model of our proposed MST is devised. Then, the proposed control algorithm for gear-shifting is described, for achieving a swift, seamless shift. Using trial-and-error and a genetic algorithm (GA), different PID controllers are tuned and compared to find the appropriate control inputs for each phase of the proposed gear-shifting algorithm. In fact, for shifting between each two gear ratios in the transmission, i^{th} to j^{th}, a separate two-step control set is developed. Such controllers are called PID gain-scheduling, which means different gains have been tuned for the PID controllers. The proper gains will be selected by a supervisory controller. Simulation results indicate that the approach is highly encouraging for a smooth and swift gear-shifting.

An outline of the paper follows. Section 2 is devoted to the mathematical model of the proposed MST designed for EVs. The proposed gear-shifting algorithm and tuning of the corresponding controllers are discussed in Sections 3 and 4. Simulation results are reported and compared in Section 5.

2. Mathematical model of the proposed MST for EVs

As shown in Fig. 1, in the proposed MST designed for EVs, all sun gears are connected to the same shaft. Also, there is only one carrier for all planetary gear sets. In the underdrive gear train, as represented in Fig. 1(a), the sun gears are installed on the input shaft, while the shaft connected to the carrier is the output. The overdrive gear train, as indicated in Fig. 1(b), operates the other way around. Different speed ratios are achieved by engaging the corresponding clutch. In fact, the gear-shifting process includes releasing the engaged clutch and engaging another one.

One can combine both overdrive and underdrive gear trains into a single transmission, as illustrated in Fig. 1(c). In the combined transmission, two friction clutches should be employed between carrier and planet gears in both gear trains, $\mathrm{C}_{\mathrm{f}}^{\mathrm{i}}$ and $\mathrm{C}_{\mathrm{f}}^{\mathrm{o}}$, in order to lock the free overdrive or underdrive gear train when the associated clutch is engaged. In fact, only one of the friction clutches is closed, depending on the overdrive or underdrive mode. The combined transmission has $m + n$ main gear ratios, when only one of the gear trains is operating, as well as $m \times n$ median gear ratios when both gear trains are engaged at the same time. Note that, in median gear ratios, one ring clutch is engaged from each side of the transmission; both friction clutches are released. Thus, the total number of speed ratios in the proposed combined transmission, including the direct drive mode, is

$$j = m + n + m \times n + 1 \tag{1}$$

The main advantage of the proposed transmission is modularity. In other words, the designer can determine the numbers of the underdrive and overdrive modules, including a planetary gear set and a clutch, separately, according to the application and the number of gear ratios required. We are prototyping the proposed MST designed for EVs. As depicted in Fig. 2, our transmission testbed includes a four-stage planetary gear set, consisting of two overdrive and two underdrive gear ratios. The dynamics model of a two-speed transmission, represented in Fig. 1(d), is investigated below.

Let $\mathbf{q}, T, V, L, \Pi$ and Δ denote the vector of generalized coordinates, the kinetic energy, the potential energy, and the Lagrangian of the system, the power supplied to the system and the system dissipation function, respectively, the Lagrange equation is then given by

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[1] No generally acceptable definition of the term can be cited, but it usually includes the qualitative evaluation of a powertrain, such as the degree of smoothness and steadiness.