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Design, modelling and estimation of a novel modular multi-speed transmission system for electric vehicles[☆]

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ABSTRACT

The efficiency of electric vehicles (EVs) should be improved to make them viable, especially in light of the current low energy-storage capacity of electric batteries. Research demonstrates that applying a multi-speed transmission (MST) in an EV can reduce the energy consumption of the vehicle through gear-shifting. However, for effective gear-shifting control in MSTs, first of all, the model of the transmission is required. Moreover, reliable methods should be employed for estimation of the unmeasurable loads and states of the system, under model-based control. This study establishes the mathematical model and estimation algorithms for a novel MST designed for EVs. The main advantages of the designed MST are simplicity and modularity. After devising the dynamics of our proposed transmission, the Kalman filter, the Luenberger obsever and neural networks (NNs) are used to estimate the states, the unknown arbitrary disturbance and the unknown clutch torque applied to the system. Simulation results demonstrate that the proposed approach is suitable for estimation purposes. Experiments were conducted using an in-house prototyped transmission testbed, to validate the simulation results and assess the estimation algorithms.

1. Introduction

The main problem with internal-combustion-engine (ICE) vehicles is pollution. We thus need to find an appropriate substitute for them, with a much lower impact on the environment. Hybrid electric vehicles (HEVs) and electric vehicles (EVs) are two appropriate substitutes. Nonetheless, due to the current low energy-storage capacity of electric batteries, EVs have failed to gain popularity. Hence, it is required to improve the efficiency of EVs, to achieve longer running time on a single charge of the battery. Research demonstrates that by applying a multi-speed transmission (MST) in EVs, we can decrease the energy consumption of the vehicle, since the desired power is provided in more than one way in an MST. In fact, this way, the electric motor (EM) can operate on the high-efficiency regions for longer periods. However, the overall efficiency improvement depends on the gear ratio values and the number of gear ratios in the MST, as well as the chosen driving cycle [1–7].

Automated manual transmissions (AMTs) [8–10], automatic transmissions (ATs) [11–13], dual-clutch transmissions (DCTs) [14–16], and continuously variable transmissions (CVTs) [17,18] are various kinds of MSTs. The above-mentioned MSTs were initially designed for ICE vehicles. However, EMs are speed-controllable in a wide range of speeds, compared to their ICE counterparts. Therefore, novel transmissions can be designed for EVs, without a clutch or torque converter to disconnect the motor from the transmission during gear-shifting; consequently, the losses are minimized. Instead, the EM is an element to be controlled to make gear-shifting swift and seamless [11,19]. Gear-shifting affects drivability[1], passenger comfort, dynamic performance, and efficiency. Thus, the main objectives in gear-shifting are seamlessness, swiftness, increased drivability, vibration elimination, output-torque interruption cancelation, and improved efficiency. There has been extensive research on each of these targets [20–25]. One of the main gear-shifting algorithms, mostly adopted in ATs and DCTs, is based on separating and controlling the torque and inertia phases distinctly [20,26]. However, since the power transmission paths are permanently connected in EVs, torques and speeds are always related to

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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.

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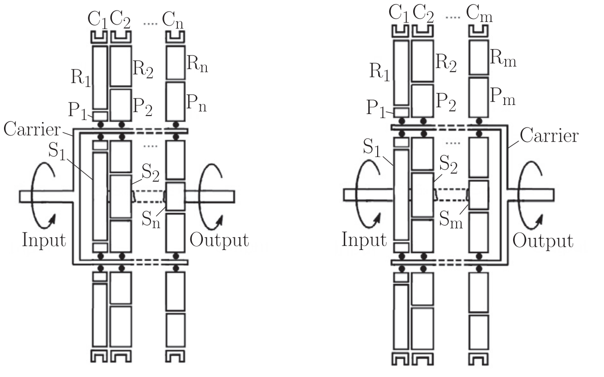
each other. Accordingly, the above-mentioned phases should not be controlled independently [7,19]. Using polynomial transition functions to guarantee the continuity of the velocity, acceleration and jerk, the optimal gear-shifting in MSTs for EVs was investigated, which led to a swift, seamless shift [27].

For appropriate gear-shifting, an accurate real-time monitoring of the unmeasurable states, the unknown disturbance and the unknown inputs of the transmission are required. Liu et al. [28] employed a combination of the auxiliary particle filter and the iterated extended Kalman filter (APF-IEKF) to estimate the tire-road friction coefficient using the existing sensors. Furthermore, a deterministic Luenberger observer, a stochastic Kalman–Bucy filter, and a fading-memory Kalman filter were designed by Rahimi et al. [29–31] to estimate the unmeasurable states and the unknown inputs for a seamless, two-speed clutchless AMT for EVs. Then, based on the estimation results, an observer-based backstepping controller was established for a seamless gear-shifting in an EV, while following the optimal trajectory associated with the minimum shifting time [32]. Combining the model-based observer, the unknown input observers, and the adaptive output torque observer, a novel algorithm was developed to estimate the torque of the clutches during gear-shifts for a DCT [33]. Although there has been intensive research on MSTs, there are still lacunae in the design, mathematical modelling and estimation.

The mathematical modelling and estimation algorithms of a novel MST designed for EVs are developed in this paper. The main advantages of the designed MST are simplicity and modularity. Firstly, the kinematics and dynamics model of our proposed transmission system are established via a Lagrangian formulation. Then, after finding the process and the measurement models, the Kalman filter, the Luenberger observer and neural networks (NNs) are applied to estimate the unmeasurable states, the unknown arbitrary disturbance and the unknown clutch torque applied to the system. For the assessment of the estimation algorithms, various disturbances, such as linear, parabolic, sinusoidal, and arbitrary, are applied to the system. Results demonstrate that the Kalman filter has a better performance than the two other methods. In fact, compared to NNs, the Kalman filter is more precise, since it is based on a mathematical model. Also, compared to the Luenberger observer, the Kalman filter considers the covariances of the noise of both the process and the measurement models. Moreover, according to the error covariance, the Kalman gain is updated during the estimation, while the Luenberger gain remains constant. Using an in-house prototyped transmission testbed, some experiments are also conducted to validate the model and the estimation algorithms.

An outline of the paper follows. Section 2 is devoted to the mathematical model of the proposed MST designed for EVs. Estimation of the tranmission is discussed in Section 3. Section 4 provides simulation results. Experimental work is reported in Section 5.



(a) Overdrive gear train (b) Underdrive gear train

Fig. 1. Multi-stage planetary gear sets.

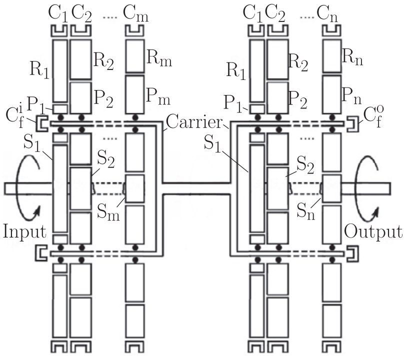


Fig. 2. A combined multi-speed transmission system.

2. Mathematical model of the proposed MST for EVs

The proposed MST designed for EVs is depicted in Fig. 1. As shown in the figure, all sun gears are installed on the same shaft. As well, all planetary gear sets share the same carrier. In the overdrive gear train, the input shaft is connected to the carrier, while the output shaft is connected to the sun gears. The underdrive gear train operates the other way around. As mentioned, the main advantages of the proposed MST are simplicity and modularity. In other words, depending on the application and the number of gear ratios required, the appropriate number of modules, including a planetary gear set and a clutch, can be added to the transmission. The EM is connected to the input shaft. By engaging a clutch, the corresponding speed ratio is achieved in the output. In fact, for switching between gears, the engaged clutch should be released and another one should be engaged. The resultant external disturbance is applied to the output shaft.

The overdrive and underdrive gear trains can also be combined to develope a single transmission, as represented in Fig. 2. In the new transmission, two friction clutches are required between the carrier and one of the planet or sun gears in both gear trains, C_f^i and C_f^o, in order to make the free overdrive or underdrive gear train act as a rigid body when the corresponding clutch is closed. In fact, depending on the operation mode required, i.e., underdrive or overdrive, one of the friction clutches is engaged, the other released. The new transmission supports $m+n$ main gear ratios, when one of the gear trains is operating and the other is disengaged, as well as $m \times n$ median gear ratios when both gear trains are controlled simultaneously. In median gear ratios, one ring clutch in engaged from each side and both friction clutches are released. Therefore, including the direct drive mode, the total number of speed ratios in the proposed transmission is

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

The most significant benefit of the proposed transmission is that the designer can determine the numbers of the underdrive and overdrive modules independently, according to the application and the desired number of gear ratios. Note that in each gear ratio, the others can be treated as a rigid body. The kinematics and dynamics of a two-speed transmission, as well as the external disturbance applied to the transmission are investigated below. The parameters used here are defined in Table 1.