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Research paper

Modelling and control of a novel two-speed transmission for electric vehicles

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ABSTRACT

Multiple speed transmissions adopted by electric vehicles (EVs) provide the probability of further improving the global efficiency of the drivetrain, as well as extending limited driving range for the fixed power storage. This paper proposes a novel two-speed transmission for an electric vehicle (EV), which is capable of realizing power-on gear shifting by operating the band brake to lock or unlock the one-way-clutch. The band brake controlled by the actuator provides a smooth and efficient gear shifting. To achieve power-on gear shifting, three alternative control strategies are proposed and applied in this novel two-speed transmission system. To verify the transient behaviour during the gear shifting, the EV powertrain equipped with the proposed two-speed transmission is undertaken. Firstly, a mathematical model is developed, including the electric motor, the proposed two-speed transmission, the vehicle, etc. Then, model-based alternative power-on gearshift strategies are developed, and a torque-based gearshift closed-loop controller with the desired speed trajectory is proposed. The vehicle jerk and the friction work are taken as the foremost metrics to evaluate the gearshift quality. The simulation results demonstrate that all strategies can achieve power-on gearshifts. The disadvantages and advantages of these strategies are exhibited clearly, which provides beneficial knowledge and reference to the researchers engaged in the development of the transmission controller.

1. Introduction

Conventional internal combustion engine (ICE) vehicles have made significant contributions to the progress of modern society by meeting many of the requirements for mobility, but it causes high consumption of fossil fuel and environmental degradation [1]. Consequently, EVs have been widely accepted as a potential alternative for the current conventional ICE vehicles to expedite sustainable and green transportation [2]. They are distinguished by superior features such as high-efficiency and a more flexible powertrain as well as reducing emissions. As the most promising transportation, EVs attract attention from all over the world.

For an ICE vehicle, the operating range of the engine is limited so the vehicle cannot be driven over a wide speed range. This is the reason why transmission is still indispensable in the modern vehicle industry [3]. Compared to ICE, the speed and torque of electric motors are more controllable with outstanding dynamic performance [4]. By employing advanced control schemes, electric motors can present a high constant torque within the base speed scope and then enter a constant-

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power region for higher speed. An EV may not gain as many benefits from using multi-gear transmissions as that for an ICE vehicle. Commercial EVs are widely equipped with single speed transmissions [5], due to the trade-off between cost and the complexity of the system. Considering the increasing demand for higher efficiency and performance, integrating multiple speed transmissions has been regarded as an alternative technology to improve the EV's performance. Research results in [5–7] indicate that the performance of electric vehicles is improved, and the customers' cost is reduced from a long-term sight when the multiple speed transmissions are added to EVs.

Since ICE requires idle speed and its speed is difficult to control in gear shifting process, clutches or torque converters between ICE and transmissions are necessary for start-ups, idle speed, and gearshift. However, the operating speed of electric motors for EVs can be easily controlled in a wide range. This benefit of electric motors provides an opportunity to redesign transmissions for EVs, with removing clutches or torque converters from the traditional transmissions [8]. Currently the configurations of multi-speed transmissions utilized in EVs, e.g. clutchless automated manual transmission (CLAMT) [9,10], dual motor multi-speed EV transmission [11], continuously variable transmission (CVT) [12,13], inverse automated manual transmission (I-AMT) [5,6], dual clutch transmission (DCT) [14,15], and planetary transmission [16,17], derive from those of the traditional transmissions initially designed for ICE vehicles. Both merits and demerits exist in each layout. In terms of CLAMT, it is of great merits due to its lower cost, simpler to control and higher efficiency than other sorts of gearboxes such as CVT, DCT and planetary transmission [18]. However, the torque interruption in the shifting gear process is inevitable as the electric motor has to be de-energized to assist the disengagement of the synchronizer mechanisms in the gearshift process. Alternatively, dual motor multi-speed EV transmission addresses torque interruption problem by compensating the torque hole with another motor during the gear changing events. However, this configuration adds extra costs with twin motors and increases control complexity. Furthermore, CVT suffers from low efficiency due to the way the torque is transferred in the transmission. Considering that efficient operating points of electric motors are sufficient enough, a CVT is not necessary for EVs [19]. Planetary transmission and DCT variants overcome the limitation of torque interruption through the utilization of the clutch-to-clutch gearshift approaches, which has been validated in many studies such as [20,21].

The clutch-to-clutch gearshift control has been discussed variously in many types of research. Since engaging the clutch is required to meet different metrics, as minimizing the gearshift duration; minimizing the friction work and ensuring small vehicle jerk, optimization-based algorithms, such as model predictive control [22] and back-stepping technique [23], are essential for this problem. Different from the optimal schemes which simultaneously formulate multiple control objectives by penalty functions, another controller design method is also suitable for clutch engagement control, where the clutch control is considered as a speed tracking control problem. The control aim is to ensure the clutch slip speed track the reference trajectory well. The speed reference trajectory is often designed based on experience, depicted in the form of fifth exponential decay [24], and the form of the cubic polynomial [25]. And, dynamic programming method is also utilized to design the reference trajectory in the study [26]. In order to track the reference trajectory accurately, various controllers are widely developed, such as sliding mode control [27], robust adaptive control [28] and prediction function control [29]. However, these studies are only based on single particular gearshift strategy to design the controller. They missed the difference from different gearshift strategies that will have effects on gearshift quality.

In this study, a two-speed transmission is proposed to meet the increasing demand for EVs, including higher efficiency and performance and lower cost. First, the dynamic model of proposed transmission equipped EV is built. Then, to achieve power-on gearshift, model based gearshift control strategies are proposed for the novel two-speed transmission. Finally, the simulation results demonstrate that the power-on gearshift can be achieved in the proposed transmission. This article is standing out in similar papers with two major contributions to the existing literature. First, a novel two-speed transmission is proposed, taking advantages of its mechanical layout to achieve power-on gearshifts by controlling a band brake to block or unblock the one-way-clutch, which makes the gearshift control easier than similar transmissions mentioned in [14–17]. Second, model based alternative power-on gearshift strategies are developed and investigated for the proposed transmission. Simulation results clearly show the differences from these gearshift strategies, which provides beneficial knowledge and reference to the researchers undertaking the development of the transmission controller.

The remainder of this paper is divided into the followings: Section 2 shows the layout and working principles of the transmission. The characteristics of the proposed two-speed transmission are depicted in detail. Section 3 presents the powertrain system modelling, including the kinematic model of the transmission and the comprehensive powertrain model. Section 4 illustrates the detailed development of the alternative power-on gearshift control strategies for the novel two-speed transmission. Simulation results are provided in Section 5 to demonstrate the performance of the different power-on gearshift strategies.

2. The layout and working principles of the transmission

2.1. The transmission layout

The novel two-speed transmission is shown in Fig. 1. The powertrain system of the EV consists of an electric motor, a two-speed transmission, final drive, differential, half shafts, and wheels. As shown in the figure, the input of the transmission is the small sun gear, which is connected to the electric motor through the input shaft. The output of the transmission is the ring gear which is attached via the final drive and differential to the wheels.