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Design and control of a novel two-speed Uninterrupted Mechanical Transmission for electric vehicles

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ABSTRACT

Conventional all-electric vehicles (EV) adopt single-speed transmission due to its low cost and simple construction. However, with the adoption of this type of driveline system, development of EV technology leads to the growing performance requirements of drive motor. Introducing a multi-speed or two-speed transmission to EV offers the possibility of efficiency improvement of the whole powertrain. This paper presents an innovative two-speed Uninterrupted Mechanical Transmission (UMT), which consists of an epicyclic gearing system, a centrifugal clutch and a brake band, allowing the seamless shifting between two gears. Besides, driver's intention is recognized by the control system which is based on fuzzy logic controller (FLC), utilizing the signals of vehicle velocity and accelerator pedal position. The novel UMT shows better dynamic and comfort performance in compare with the optimized AMT with the same gear ratios. Comparison between the control strategy with recognition of driver intention and the conventional two-parameter gear shifting strategy is presented. And the simulation and analysis of the middle layer of optimal gearshift control algorithm is detailed. The results indicate that the UMT adopting FLC and optimal control method provides a significant improvement of energy efficiency, dynamic performance and shifting comfort for EV.

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1. Introduction

With the increase of environmental pollution, global warming and shortage of oil resources, government departments have promulgated stricter regulation on fuel economy and emissions. Meanwhile, the electric vehicles have brought the advantages of zero emissions, independence on crude oil and high energy efficiency, receiving significant attention from vehicle constructors and consumers.

Taking a back look at the development of the EV, its history contains three stages [1–3]. Since 1834, when the EVs were invented, till the early twentieth century, the EV experienced the first crucial period of its development. It was during this time when many companies in North America and Europe produced and sold EVs rather than internal combustion engine vehicles (ICEV). Nevertheless, the EV developed slowly due to the limitation of battery technology, while the technology and manufacture of IECV went through a period of rapid development. For this reason, the EV was replaced by the ICEV since the

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1930s. Until the early 1970s, when the oil crisis and environmental problems appeared, some countries started to look for alternatives to the ICEV. Consequently, the EVs, as well as the hybrid electric vehicles (HEV) and the fuel cell vehicles (FCV), return to the limelight.

The EVs have more advanced sources and more intelligent management of energy than conventional fossil-fueled vehicles. However, the EVs need to improve the overall cost effectiveness so as to feature stronger competitiveness in the market. There are three major issues of EV that need attention, which is the optimization of battery performance and management, the improvement of propulsion efficiency and the distribution of charging facilities [4,5].

According to the propulsion system optimization of EV, a lot of work has been done, including the research focusing on architectures and modeling for energy management, the study on advanced electrical power system of EVs in [6,7], as well as the comparison between different electrical motor drivelines in [8]. Moreover, the work on the subject of EVs' transmission system is proceeding in this field. In [9–14], current research works suggest that replacing the conventional single-speed reducer with more applicable transmission system may significantly improve the performance of EVs. The conventional manual transmission (MT) and the continuously variable transmission (CVT) have been compared with the single-speed reducer through modeling and simulation for the EVs over several standard drive cycles. The two-speed automated manual transmission (AMT) is introduced to the EVs by the simulation as well as the experiments on a test bench in [14–16], and an inverse AMT is studied with the dry clutch located at the rear of the transmission so that the traction interruption of traditional AMT can be canceled[17]. A two-speed dual-clutch transmission (DCT) is also implemented in [18]. Besides, a new structure of two-speed gearbox is designed by adding a one-way sprag clutch to the traditional two-speed MT in [19,20]. While the implementation of AMT in EV can improve the energy efficiency, the power interruption during gearshift results in poor comfort performance due to the restriction of mechanism and principle. Hence, a smooth gearshift is necessary and crucial for the transmission system of EV [21]. In this paper, a novel two-speed transmission system is presented, taking advantages of its mechanical construction and realizing a seamless gearshift. Compared to the transmission system developed from conventional MT in [19–21], the novel transmission system presented in this paper achieves a more compact packaging and it is easier to control.

The two important issues of the transmission control system are gearshift decision making and gearshift control. In the area of gearshift decision making, fuzzy logic technique has been used in AT to infer the driver's intention to accelerate in [22–24]. In AMT, both the driver's intention and the road load have been estimated by using the vehicle velocity, accelerator pedal position and its changing rate through a fuzzy logic module in [25–27], and the torque and speed of engine have been also used to evaluate the engine working condition in [28]. Besides the parameters mentioned above, the relative accelerator pedal position has been defined to help evaluating the driver's expected accelerating performance, which colligated the driving condition and the driver's intention in [29,30].

In the area of gearshift control, research works on the optimization of gearshift control have been carried out on various transmissions. Considering the uncertainties of the driver inputs and vehicle constructions [29], H_∞ control and LMI (linear matrix inequality) approach can be introduced into the gearshift controller and provide better performance [30–33]. The optimal control method has been applied in clutch engagement of vehicles in [34–36] and has also been used for the gearshift command in the hybrid electric vehicles in [34,37,38]. The dynamic programming method and optimal control method have been used to derive the control law in an explicit form by minimizing the performance measure during the gearshift process of AT in [22].

In this paper, aiming at improving the dynamic performance during gearshift, ensuring the choice of shift point more appropriate and reducing energy consumption, the recognition of driver intention based on the method of fuzzy logic control and the optimal control algorithm of gearshift are implemented in the transmission control system of EV.

In the next two sections, the mechanical layout and mathematical model of the transmission system are presented, including the states of two gears and gearshift process. In Section 4, a transmission system controller with three layers is developed, and the principle of control methodology during gearshift is discussed in detail. Finally, performance of the proposed control system of the novel transmission is presented in Section 5 through a set of simulation results.

2. Structure and principle of the novel transmission system

2.1. Transmission structure

Between the three critical factors of automatic transmission design, including dynamic, economic and comfort performances, it turns out to be the key and difficult point to reach a compromise. The development of the novel two-speed UMT aims at achieving higher efficiency and better dynamic performance as well as improving shift quality, by applying an improved control approach in a transmission with new structure. In this section, the mechanical structure of the UMT is described in detail.

The UMT adopts a single-stage epicyclic gear system and an uninterrupted gearshift system. The structure of the transmission is somehow similar to the conventional AT, but there are two significant differences. Torque convertor is normally used in conventional AT, but not adopted in the presented UMT, due to its relatively low efficiency. Besides, the gearshift system of the UMT uses electric actuators, while conventional AT uses hydraulic actuators. The former has the advantage of simple structure, easy deployment and quick response.

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