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Research paper

Power-on shifting in dual input clutchless power-shifting transmission for electric vehicles

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ABSTRACT

The purpose of this paper is to study the practical application of a two motor electric vehicle powertrain utilizing a combination of fixed and multiple speed gear ratios. To realize power-on shifting without torque hole and maximize overall efficiency, a high-speed motor is adopted as the primary motor connecting to the multiple speed clutchless automated manual transmission and a low-speed high torque electric motor is employed as the assisting motor connected to the final shaft with fixed gear ratio. Motor torque and speed are controlled using improved model predictive flux control method in conjunction with synchronizer mechanism actuation to best fill the torque hole to improve both drivability and driving comfort. To evaluate the proposed system, a complete mathematical model is built and compared with a conventional single motor transmission system. The detailed transient dynamic results in terms of final shaft torque, acceleration and vehicle jerk demonstrate the effectiveness of the proposed powertrain.

1. Introduction

In order to fulfill the need to reduce exhaust emissions, strengthening the regulation of vehicle emissions has been a trend worldwide. This has been a driver to design more eco-friendly vehicles. As a result, the demand for electric vehicles and hybrid electric vehicles roars, pushing the development of international automotive industry to a new stage. To achieve the goal of making cleaner and more efficient vehicles without losing drivability and comfort, many innovative designs have been brought out and proved to be successful [1]. Prius earned its reputation by greatly reducing its fuel consumption in the meantime maintaining the smoothness in driving, but the eCVT transmission system in Prius is only for hybrid electric vehicle. There are also some successful pure electric vehicles such as Nissan Leaf, Mitsubishi iMIEV and early stage Tesla. They all adopt single fixed ratio transmission system which has the advantages of lower manufacturing cost, relatively smaller powertrain volumes and less drive-train mass [2]. The limitations of this kind of transmission are also obvious. Firstly, the dynamic performance is poor because the speed and torque range are compromised; secondly, overall operating energy efficiencies are lower as the motor has its own efficiency curve that varies with torque and speed.

To overcome the problems that single fixed ratio transmissions have encountered, the development of multi-speed transmission attracts considerable attention. It entitles electric vehicles to higher efficiency [3] and better longitudinal behavior [4]. For multi-speed transmission [5], manual transmission (MT) has the highest efficiency which is around 96%, the efficiency of automatic transmission (AT) is about 86% but it can transmit large torque as MT. Continuously variable transmis-

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sion (CVT) is famous for its smoothness but the overall efficiency is 85%. Based on the fundamentals of these transmissions, many novel configurations have been designed. In [6], detailed shifting mechanisms and control strategy for clutchless automated manual transmission (CLAMT) has been carried out, and the experiment results prove it is possible to remove the friction clutch of an AMT in the electric vehicle without compromising the dynamic performance. A planetary transmission is adopted in [7] to construct a seamless two-speed power split system. Walker et al. [8] introduce the dual clutch transmission to a pure electric vehicle and evaluate its detailed transient dynamic performance by both simulation and experiment. Fang et al. [9] bring out a new concept of uninterrupted mechanical transmission by modifying traditional planetary gearbox. In [10], a novel 4-wheel-drive two-speed electric vehicle layout is proposed. Two sets of electric drivetrains are designed for the axles and by controlling the behaviors of both drivetrains, torque hole compensation is achieved which both improves the drivability and the driving comfort. Besides the novelty in transmission configuration, many researchers improve the drivability and the comfort by adding a various numbers of motors [11]. In [12], an on-board configuration is brought and in [13], the motors are mounted on the wheels which will directly provide the required speed and torque.

Among the aforesaid configurations, automated manual transmission (AMT) is a promising solution to meet both requirements of dynamic performance and riding comfort, it has the advantages of high efficiency, low manufacture cost, and light in weight as a manual transmission and auto shifting ability as an automatic transmission [14,15]. But AMT also has its own drawbacks, which are the jerks during gear shifting, the excessive wear of the friction components and the torque interruption in the shifting process [6]. To improve the drivability, Galvagno et al. proposed torque assisted AMT in [16], it uses a servo-assisted clutch to replace the fifth gear synchronizer which will provide certain power while the engine is disconnected from the powertrain, but the assisted clutch doesn' t have its own power source which means it can' t eliminate the torque hole but alleviate it. In [17], a modified AMT called Inverse-AMT is proposed, it puts the friction clutch after the gears instead before them. Experiment results prove it to some extent solves the torque interruption problem.

Extensive study has proved that the two major parasitic loss sources in transmission system are friction clutch elements and electro-hydraulic actuators [18]. The overall efficiency is compromised by 4%–6% because of clutch drag and oil pumping. By comparison in [19,20], it is feasible to greatly minimize the reduction in overall efficiency for the transmission using clutchless variants. For a conventional vehicle which adopts internal combustion engine (ICE), the clutch in the AMT is inevitable because of the speed and torque adjustment delay caused by the poor controllability of the engine, which also entails long speed synchronization duration and exacerbates the wear of the friction plates. But it is not the case for electric vehicles [21], there are three reasons [6]. First, the inertia of a motor is much smaller than that of an ICE which makes it capable of changing speed swiftly. Second, due to the excellent low-speed control capability, by controlling the motor, the vehicles can be launched smoothly. Third, it' s easy to change the motor from torque mode to speed mode and vice versa. Therefore, after the synchronizer disengages the gears, the motor could change into speed mode which outputs little torque but reaches target speed immediately and then changes back to torque mode. Thus, the friction clutch is removed. Furthermore, because of the wide high-efficiency range, excellent speed regulation capability and fast torque response characteristics, transmission systems for EV need fewer gear ratios [22]. Zeroshift [23] is an example to remove friction clutch by re-designing the dog clutches to engage different gears without the need for speed synchronization. In [24], a series of controllable one-way clutches are employed to realize gear selection. In terms of the control strategy, [25] not only removes the friction clutch but also the synchronizer by refining the control algorithm. And in [26], the speeds and torques of the engine and motor are coordinately controlled to make it not necessary to have a clutch.

Aiming at designing a transmission system which could maximize energy efficiency, minimize emissions, and has certain drivability and comfort, this paper brings out a novel clutchless two motor power-shifting transmission where a single fixed ratio motor is utilized in parallel with a multi-speed transmission and second motor to balance the needs for improved motor efficiency in conjunction with power-on shifting capabilities. The structure of the system is presented below in Fig. 1.

The first motor drives the wheels through a multispeed transmission, with gear actuation achieved through a combination of motor speed control and synchronizer actuation [27]. This is a cost-effective and efficient method for achieving multispeed functionality without power-on shifting functionality. The second motor drives the transmission output shaft using a fixed reduction ratio and must be designed to achieve torque hole compensation through all of the gear shifts and also act as a driving motor under specified driving conditions. Such configurations have applications for both pure electric and hybrid electric vehicle powertrains. This would include HEV variants with a conventional engine upstream of EM1 would allow for both series and parallel operation of the vehicle.

In order to verify the gear shift quality of the proposed transmission system, robust testing criteria are crucial. In [28], a thorough investigation has been done to lay down the benchmark to assess shift quality which links both subjective ratings and objective measurements. And it conducts experiments on six different types of vehicles under six conditions such as launch, creep, hill start, abusive start and so on. Four pairs of words are brought out in [29] by trained drivers to depict the shift quality which are responsive/hesitant, smooth/rough, unperceivable/apparent and strong/weak. And it is proved in [30] these in-direct assessments could adequately reveal the objective criteria. Some researchers recommended [31] that the jerk shouldn' t exceed 10 m/s^3 in order not to be perceived by the driver, and others believe that the root mean square of the jerk also shouldn' t be larger than 2.83 m/s^3. In [32], vibration dose value is brought out as a standard industry metric which correlates well with human perception. Last but not least, shifting duration is also of great importance [33]. In the proposed transmission system, there are three main stages which are torque down of EM1 and torque up of EM2, speed synchronization and torque restore, as friction clutch is removed from this system, speed synchronization will directly influence the shift performance and it will take about half of the shifting duration.