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Research paper

Efficiency comparison of electric vehicles powertrains with dual motor and single motor input☆

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ABSTRACT

Two novel dual motor input powertrains are proposed to improve the energy efficiency of electric vehicles (EVs). The first powertrain is based on a dual motor with planetary gear transmission (DMPGT), which connects two motors to the sun gear and ring gear respectively, and the carrier is engaged with output shaft. Two band brakes equipped on the sun gear and ring gear can realize three driving modes. The second powertrain is based on a dual motor with parallel axle transmission (DMPAT). It also provides three driving modes through switching on and off the two motors. To evaluate the two proposed powertrains, they will be compared with the widely adopted single motor with 1-speed and with 2-speed powertrains. The gear ratios of the powertrains are selected aiming at the vehicle dynamic performance, while the gear or mode shifting is designed to maximize the efficiency of EVs through an instantaneous optimization algorithm. The simulation results of the two proposed powertrains in three typical driving cycles demonstrate that the EVs equipped with both DMPGT and DMPAT have a higher overall efficiency than the EVs equipped with single motor input powertrain.

1. Introduction

Electric vehicles (EVs) have been considered as a very promising alternative to traditional vehicles to reduce the transportation greenhouse gas emission. However, the relatively short driving range of most commercialized EVs limits their popularization. Before the energy density of battery to be significantly increased, improving the overall efficiency of powertrain is a practical and cost-effective way to increase the driving range of EVs. At the same time, the improvement of powertrain efficiency for EVs enables less electricity energy consumption.

The multi-speed transmissions have been widely used in traditional internal combustion engine (ICE) vehicles for two reasons. Firstly, the multi-speed transmissions provide a better dynamic performance for ICE vehicles, e.g. higher top speed, faster acceleration, and smooth starting. Secondly, it enables the ICE work in the high efficiency region through a reasonable gear shifting operation, which reduces fuel consumption. However, there are few commercialized EVs equipped with a multi-speed transmission powertrain. The electric motor is able to provide constant maximum torque from zero to base speed, as well as their max rotational speed is high. In consequence, the single-speed transmission is capable to provide a satisfied

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dynamic performance [1–3]. On the other hand, the drivetrain mass, volume, losses and cost can be effectively reduced by using a central motor drive equipped with a single-speed transmission, which represented a cost-effective solution [4].

Although the multi-speed transmission is not necessary in terms of dynamic performance for EVs, it can improve the overall efficiency of powertrain so as to increase the driving range. The motors suffer lower efficiency in the regions of low torque and low speed, so introducing the multi-speed transmission into EVs may enable the motor work in a higher efficiency region. There have been some researches demonstrating that an electric motor equipped with a multi-speed transmission can reduce the energy consumption of EV [5–7]. According to the powertrain structures in traditional ICE vehicles, the possibility of implementing different transmissions into EV powertrain have been investigated, e.g. automated manual transmission (AMT), and automatic transmission (AT), dual clutch transmission (DCT), and continuously variable transmission (CVT).

Ren et al. [8] demonstrated that CVT could improve the overall energy consumption 5–12% depending on the driving cycle. However, the efficiency of the transmissions was not considered in their model. The CVT suffers lower efficiency than other transmissions due to the mechanical layouts and principles, so the actual improvement of overall efficiency should be lower than the given values. Hofman et al. stated that the CVT was typically the most energy efficient transmission type if the transmission efficiency of all the transmission types was equal assumed. When the relatively low efficiency of CVT itself is considered, the CVT is even less energy efficient than the single-speed transmission [9]. More investigation of EVs equipped with CVT can be referred to [10,11]. For the EVs equipped with stepped multi-speed (more than 2 gears) transmission, the AMT is widely used due to its relatively high efficiency. Tseng and Yu [12,13] investigated the feasibility of adopting a clutchless AMT in an electric vehicle with a gear shifting control strategy to achieve smooth gear shifting. However, the torque interruption during the gear shifting was inevitable. Roozegar et al. [5] investigated the gear-shifting of a multi-speed transmission for EVs with optimum performance under functional constraints. The multi-speed transmission was realized by a multi-stage planetary gear set and its control strategy was relatively complicated. More studies about the multi-speed transmission for EVs can be found in [14,15].

Considering the plenty proposals of multi-speed transmission for EV, the 2-speed transmission shows the best balance between the advantages of a multiple-speed transmission system and the simplicity of a compact and lightweight drivetrain. Single-speed transmission, 2-speed DCT and CVT based EVs were compared in reference [16], which showed that 2-speed DCT was more likely to enable the motor run at the high efficiency region and consume less energy. To investigate shifting control of EVs system equipped with a DCT transmission, a 2-speed DCT electric powertrain was developed in [17]. Both the simulation and experimental studies of the shift transient behavior of 2-speed DCT equipped EV powertrains was undertaken in [18]. A series of power-on and power-off shift control strategies were developed for gear shifting. When AT is implemented in EVs, the torque convertor could be removed to improve its efficiency. Shin et al. [19] designed a 2-speed AT for EVs by using two planetary gears. The proposed 2-speed AT had higher efficiency than traditional hydraulic AT, because it did not contain viscous and pumping losses in the torque converter. More investigations of 2-speed AT for EVs can be found in references [20,21]. Some novel 2-speed AMT was proposed to overcome the power interruption. Sorniotti et al. [1] presented a 2-speedAMT, and at the same time, a similar architecture was reported in references [22,23] which were called as inverse automated manual transmission (I-AMT), since the clutch was located at the rear of the transmission so that the traction interruption of traditional AMT could be avoided. Compared with the single-speed transmission, the 2-speed I-AMT shows greater performance in terms of acceleration time, maximum speed and energy economy.

In the aforementioned references, only one motor is integrated in the powertrains. However, the function of 2-speed transmission also can be realized by implementing dual motor structures to eliminate the power interruption during gear shifting. When two down size motors are applied as a replacement for the original single motor with large power, the torque utilization factor of the motor driving can be increased, and potentially the operating efficiency along driving cycles can be improved [24]. Yu et al. [25] designed a powertrain for two-axle four-wheel-drive EV to improve the energy efficiency, driving stability for an Utility Vehicle, in which two motors were used with two AMTs to drive the front and rear axle respectively. A four-speed, dual motor parallel drivetrain design was presented in references [4,24] which works on the principle of two double-speed transmissions, each driven by a separate motor connected to a sole secondary shaft. This drivetrain architecture provides increased flexibility of the electric motor operating tracks, theoretically beneficial for the overall efficiency of the system regardless of the driving conditions. An energy consumption and performance comparison between the parallel dual motor powertrain, a conventional single-speed powertrain and a double-speed powertrain was provided. Liang et al. [26,27] also investigated the power-on shifting and power sharing strategy for a similar dual input clutchless transmission on EVs. Besides the parallel axle structure, the planetary gear train was also used in dual motor powertrain. A dual motor propulsion system based on differential torque transmission was proposed in [28], which was focused on the driving ability analysis but there was no investigation of fuel economy performance. Urbina Coronado et al. [29,30] proposed a dual motor propulsion system with planetary gear train, including the epicyclical differential gear train and bevel differential gear train. Simulation results indicated that the dual motor powertrain architecture improved the overall efficiency and extended its driving range. A dual-motor driving system was proposed in [31], which was based on a planetary gear set with clutch and brakes. This system consists of several working modes by controlling the activation of clutch and brakes to achieve torque-speed coupling between the two motors, which improves the high performance range of the motors and increase the driving range. A similar mechanism termed dual-motor coupling powertrain was proposed in [32], in which a planetary gear unit coupled the speed of two motors, and another shaft-fixed gear unit coupled the torque of two motors.