Mechanism and Machine Theory 94 (2015) 96–118

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

Seamless dual brake transmission for electric vehicles: Design, control and experiment

Mir Saman Rahimi Mousavi *, Ali Pakniyat, Tao Wang, Benoit Boulet

Department of Electrical and Computer Engineering, McGill University, 817 Sherbrooke St. West, Montréal, QC H3A 0C3, Canada
Centre for Intelligent Machines, McGill University, 817 Sherbrooke St. West, Montréal, QC H3A 0C3, Canada

ARTICLE INFO

Article history:
Received 13 January 2015
Received in revised form 25 May 2015
Accepted 7 August 2015
Available online 29 August 2015

Keywords:
Two-speed seamless transmission
Electric vehicle
Dynamical modeling
Pontryagin Minimum Principle
Backstepping controller

ABSTRACT

Transmission is one of the crucial elements of a motor vehicle's driveline that affects efficiency and dynamic performance of the vehicle. This paper studies the dynamical modeling, controller design, and experimental validation of a two-speed transmission for electric vehicles which has a specification of seamless gear shifting. The transmission incorporates a two-stage planetary gear set with common sun and common ring gears and two braking mechanisms to control the flow of power. The dynamical modeling of the driveline of an electric vehicle equipped with such a transmission is derived by exploiting the torque balance and virtual work principle. Thereafter, the Pontryagin Minimum Principle is applied to design an optimal shifting controller. This controller keeps the output speed and the output torque of the driveline constant during the gear shifting operation while minimizing the shifting time and the dissipation of energy caused by the internal brakes. Since the optimal control law provided by the Minimum Principle is open loop, a backstepping controller is designed to provide a stabilizing feedback law based on the optimal control inputs. Simulation and experimental results demonstrate the ability of the proposed transmission to exhibit smooth shifting without excessive oscillations in the output speed and torque.

1. Introduction

Increasing fuel cost and environmental concerns have pushed the automotive industry to gradually replace internal combustion engine (ICE) vehicles with hybrid electric (HEV) and fully electric vehicles (EV). However, the energy density of electric batteries is much less than that of fossil fuels. Thus, by changing the source of power from internal combustion engine to electric motor, it is required to minimize the losses in the driveline in order to maximize the range of EVs. Pure electric vehicles in the market are mostly equipped with single ratio transmission with a trade-off between efficiency and dynamic performance, such as maximum speed, acceleration, and gradability [1]. Research indicates that using multi-speed transmission for EVs can reduce the size of the electric motor and provide an appropriate balance between the efficiency and the dynamic performance [1–5]. Currently used multi-speed transmissions for EVs such as Automated Manual Transmission (AMT), Automatic Transmission (AT), Dual Clutch Transmission (DCT), and Continuously Variable Transmission (CVT) were initially designed for ICE vehicles [6]. Since ICEs cannot operate below certain speeds and their speed control during gear changes is not an easy task, the presence of clutches or torque convertors is inevitable for start-ups, idle running and gear changing. This, however, is not the case for EVs as electric motors are speed controllable in a wide range of operating speeds. This difference provides an opportunity for designing novel transmissions for EVs [4,5].

* Corresponding author at: McConnell Engineering Bldg., room 503, Department of Electrical and Computer Engineering, McGill University, 817 Sherbrooke St. West, Montréal, QC H3A 0C3, Canada.
E-mail addresses: mir.rahimimousavi@mail.mcgill.ca, saman@cim.mcgill.ca (M.S. Rahimi Mousavi), pakniyat@cim.mcgill.ca (A. Pakniyat), tao.wang6@mcgill.ca (T. Wang), benoit.boulet@mcgill.ca (B. Boulet).

http://dx.doi.org/10.1016/j.mechmachtheory.2015.08.003
0094-114X/

AMT is of great interest because of its lower weight and higher efficiency in comparison with other types of transmissions such as AT, CVT and DCT [7–9]. However, the torque interruption during gear changing operation, which comes from the disengagement and re-engagement of the transmission to the electric motor or engine, reduces passenger comfort and lifetime of the synchronizers. Gear shifting and drivability improvement of a clutchless AMT for EVs are addressed in [10] via a sliding mode controller that reduces the gap of torque interruption (shifting time). The same problem is tackled in [11] by using a combination of state-feedback and H_∞ robust controllers to provide an optimal speed synchronization. A comparison between a fixed-ratio transmission and a novel two-speed I-AMT (Inverse Automated Manual Transmission) with rear mounted dry clutches is made in [3] and dynamic programming is used to design the optimal gear ratios for the first and second gears in order to minimize the energy consumption for urban and sub-urban drive cycles. It is indicated that efficiency and dynamic performance of a two-speed AMT transmission with optimal gear ratios are much better than those of a single speed transmission.

In contrast to AMT, DCT has the special feature of eliminating the output torque interruption during gear shifts, but they have lower efficiency and higher weight [12–14]. A two-speed DCT transmission for electric vehicles is studied in [15] and an open-loop shifting controller is presented. The results demonstrate that the vibration of the output torque is not considerable and the torque hole is almost eliminated.

Continuously variable transmissions (CVTs) provide continuous change of the gear ratio. The principle used by CVT transmission is to keep the source of power (electric motor or engine) in the most efficient point while changing the gear ratio in order to get different combinations of the torque and speed. However, since the set of efficient operating points for electric motors is rich enough multiplicity of gear ratios or a continuously variable transmission are not necessary for EVs [16–19].

Similar to DCTs, planetary-gear-based ATs have the ability to eliminate the output torque interruption during the gear shift operation. However, due to the existence of torque convertors and hydraulic systems in ATs, they generally have lower efficiency in comparison with other types of transmissions and they are not of great interest for EVs. Although the presence of torque convertor provides passenger comfort and increases drivability, the output power of the transmission can be decreased due to internal slippage inside the torque convertor when it is not completely locked-up [6,20–23].

This paper proposes a compact two-speed clutchless seamless transmission in order to meet a desirable efficiency, performance, and drivability for EVs. This transmission is comprised of a dual-stage planetary gear set with common ring and common sun gears. The ratio of the pitch diameter of the ring gear to the sun gear in the input and output sides are different in order to provide two different gear ratios. A special feature of planetary gear trains is the possession of high power density due to the torque distribution over several gears which provides a compact design [6]. Two friction brakes are considered to direct the flow of power during gearshift through the control of the speed of the sun and the ring gears such that a fast and smooth gear change is achieved. The proposed design is such that the transmission is perpetually connected to the electric motor and final drive and there is no clutch or torque converter to disconnect this mechanical coupling.

The gear shift control through torque and inertia phases is the conventional control strategy employed for ATs and DCTs [24]. The control of the proposed transmission through these phases is studied in [4]. Because of the perpetual connectedness of the power transmission paths in this transmission, torques and speeds are always dependent on each other through the transmitted power. Hence, the control strategy can be further improved such that the control strategy would not be required to be distinctly separated into the torque and inertia phases. This forms the basis for the controller design in this paper.

Fig. 1 shows the schematic view of the driveline of an electric vehicle equipped with the proposed two-speed transmission. As can be seen in Fig. 1, the input of the transmission is the carrier of the first stage of the two-stage planetary gear set, which is attached to an electric motor. The output of the mechanism is the carrier of the second stage which is connected via the final drive to the wheels. Two different gear ratios can be obtained by braking the sun or the ring gears. As explained in more detail in Section 4 the control of the brakes can be made in such a way that the gear shifting would be seamless and without any torque interruption. Fig. 2 shows a 3D exploded view diagram of the proposed transmission. Here, for brevity, the terms sun, ring and planets are used instead of sun gear, ring gear and planet gears, respectively.

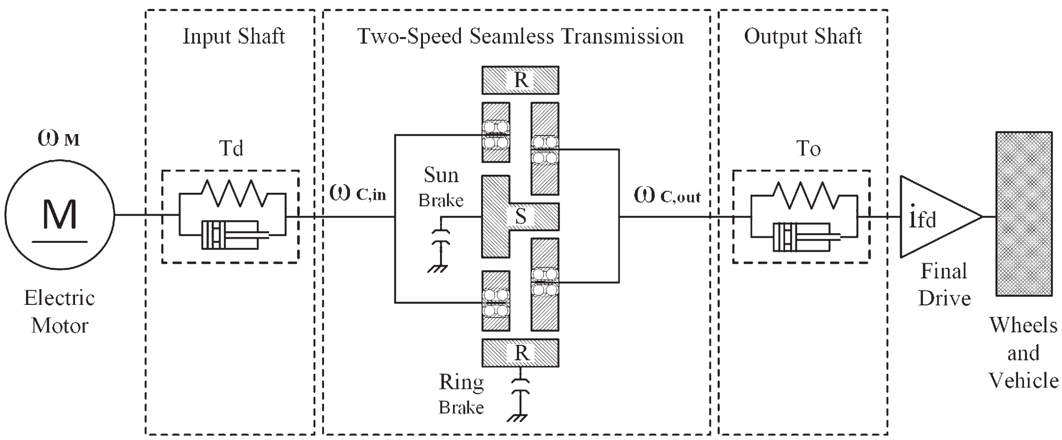

Fig. 1. The driveline of an EV equipped with the proposed two-speed transmission.