Mechanism and Machine Theory 114 (2017) 125–140

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

Research paper

Analysis and coordinated control of mode transition and shifting for a full hybrid electric vehicle based on dual clutch transmissions

Zhenzhen Lei[a,b], Dongye Sun[a], Yonggang Liu[a,*], Datong Qin[a], Yi Zhang[c], Yang Yang[a], Liang Chen[a]

[a] State Key Laboratory of Mechanical Transmissions & School of Automotive Engineering, Chongqing University, 400044, China
[b] School of Mechanical and Power Engineering, Chongqing University of Science & Technology, 401331, China
[c] Department of Mechanical Engineering, University of Michigan-Dearborn, Dearborn, MI 48128, USA

ARTICLE INFO

Article history:
Received 6 October 2016
Revised 21 March 2017
Accepted 3 April 2017

Keywords:
Hybrid electric vehicle
Dual clutch transmissions
Mode transition
Shifting
Control strategy

ABSTRACT

A Full Hybrid Electric Vehicle (FHEV) has been proposed with a single motor based on Dual Clutch Transmissions (DCT), which can take the advantage of the distinctive HEV structure and advantages of DCT. The dynamic model of hybrid system has been established taking the characteristics of engine, ISG motor and clutches into consideration. The working modes of the FHEV have been designed based on the optimal system efficiency and the shift schedule for the best economy has also been proposed. As a result, the integrated working mode and shift schedule of the FHEV has been achieved. Due to the mode transition and shifting of the FHEV maybe happen at the same time, the coordinated control strategy has been proposed to implement the mode transition and shifting simultaneously, which can solve the conflict between mode transition and DCT shifting. Simulation model of coordinated control of mode transition and shifting has been established based on Matlab/Simulink platform. The simulation results indicate that the control strategy proposed in this paper is effective to solve the conflict between mode transition and DCT shifting. Furthermore, comparing with mode transition and shifting sequentially, the duration of mode transition and shifting are greatly shortened and the repeated operation of power sources and actuators are also avoided. It also shows that the coordinated control strategy can take advantage of the FHEV equipped with DCT.

1. Introduction

A Full Hybrid Electric Vehicle (FHEV) has multiple power sources which can improve the fuel economy, and it can be operated at different working modes under different driving conditions, such as electric driving mode, engine driving mode and hybrid driving mode. Many researches are focused on the analysis of control strategy and smoothness during the FHEV mode transitions [1–3]. Dual Clutch Transmissions (DCT) has advantages of simple structure, high efficiency and power shift without power interruption, which contributes to an excellent vehicle performance in terms of both dynamics and fuel consumption. The modeling, simulation and experimental analysis of shifting process for dual clutch transmissions have also

* Corresponding author.
E-mail address: andylyg@umich.edu (Y. Liu).

http://dx.doi.org/10.1016/j.mechmachtheory.2017.04.001
0094-114X/

been conducted by many other researchers [4,5]. The FHEV system equipped with DCT proposed in this paper combines the advantages of the FHEV and DCT. Due to its advantages, it has attracted extensive interests in the automotive industry in recent years. Therefore, this paper discusses how to take full advantages of the hybrid power system and DCT system, especially on ensuring an excellent riding comfort for vehicles in the processes of both mode transition and shifting.

During the HEV mode transition, a noticeable impact or torque fluctuation in the hybrid powertrain system happens frequently due to discontinuity of the dynamics and the characteristics of the powertrain system, which will result in the unexpected impact of the powertrain and passenger discomfort [6,7]. Therefore, it is very important for a FHEV control to ensure smooth vehicle operation during the mode transition. Many research projects have focused on the analysis of torque fluctuation and control strategy during the HEV mode transitions. A four-phase transition control strategy from electric driving mode to hybrid driving mode has been presented using disturbance observers, which estimated and compensated for disturbances to improve control accuracy, tracking performance, and drivability [8]. The engine starting control of a parallel-series hybrid electric vehicle has been proposed for transition smoothness and fuel economy improvement [9]. A strategy of coordinated torque control in the process of starting engine during running was presented in literature [10]. The FHEV bus control system with a model reference control law has been proposed to coordinate the motor torque, engine torque, and clutch torque during mode transitions [11]. At the same time, the clutch torque response should also be taken into consideration because of the extremely short engine starting time and the clutch hysteretic characteristics [12]. The development of a control system for engine start using a starting clutch in a parallel hybrid electric vehicle has been described and validated by both simulation and hardware-in-the-loop test result [13].

Many researchers have focused on the shifting quality for dual clutch transmissions. A detailed model is presented for the quantitative analysis of DCT kinematics and dynamics [14]. A method for combined speed and torque control is proposed for vehicle powertrains with dual clutch transmissions [15]. A controller based on the relevant actuator dynamics and the clutch slip dynamics is designed for fast and smooth clutch engagement of a powertrain equipped with a dual-clutch transmission [16]. The model-based torque coordinating control strategy has been produced to effectively improve the shift quality of DCT under various shifting conditions with strong robustness [17]. A gearshift control strategy for dual wet clutch transmission has been developed and integrated with engine control to achieve synchronization during the transfer of engine torque from clutch-to-clutch through clutch slip control [18,19]. In a previous paper, the authors proposed the shift control strategy for DCT and validated the simulation based on prototype vehicle testing [20].

The above mentioned literatures have researched on the riding comfort of FHEV during mode transition and DCT shifting, respectively. These research findings provide valuable technical references for the modeling, simulation, and control of FHEV and DCT. However, due to the mode transition and shifting of the FHEV equipped with DCT maybe happen at the same time under some driving conditions, this conflict can traditionally be solved through setting the priority level between mode transitions and DCT shifting. In this paper, in order to take advantage of the FHEV system equipped with DCT, the coordinated control strategy has been proposed to implement the mode transition and shifting simultaneously, which cannot be seen in present literatures.

Apart from the powertrain configuration and the control of mode transition and shifting, another issue that affects the FHEVs' performance is the EMS (Energy Management Strategy) of the hybrid system. The EMS plays an important role on FHEVs, in terms of vehicle performance in fuel consumption, emission and durability of power sources. There are various control methods used in the energy management system of the FHEV. The knowledge-based energy management strategy has been designed based on static system efficiency to achieve highest system efficiency for available driving modes in a recent paper [21]. The methods of controlling mean power and peak power according to the load current have been presented to improve the efficiency and lifecycle of the main power supply system [22]. Specially, the engine ON/OFF strategy has been put forward for fuel reduction, and can be also easily implemented in online controllers [23]. Furthermore, the battery aging should be considered for EMS in terms of shallow-depth charge/discharge cycles [24] and a cycle life model has been developed, which is able to predict the battery cycleability accurately [25]. These literatures will provide valuable reference for the EMS design of the FHEV.

In this paper, firstly, the dynamic model of hybrid system has been established taking the characteristics of engine, ISG motor and clutches into consideration. Secondly, the whole working mode of the FHEV has been analyzed based on the optimal system efficiency and the shift schedule for the best economy has also been proposed. The integrated working mode and shift schedule of the FHEV has been achieved, which indicates the mode transition and shifting of the FHEV maybe happen at the same time. At last, the coordinated control strategy has been proposed to implement the mode transition and shifting simultaneously. The coordinated control for engine, motor, main clutch and dual clutches have been analyzed during the process of mode transition and DCT shifting. The simulation results indicate that the control strategy proposed in this paper is effective to solve the conflict between mode transition and DCT shifting.

2. Development of FHEV powertrain model

The structure of FHEV with an Integrated Starter/Generator (ISG) motor based on DCT is shown in Fig. 1. The main parts of the hybrid powertrain system include an engine, a main clutch, an ISG motor, batteries and DCT. There are two power sources which are the engine and the motor. The function of the main clutch is to engage or disengage the engine from the powertrain of the FHEV. Therefore, this FHEV system can realize all the working modes by reasonably controlling the