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Powertrain dynamics and control of a two speed dual clutch transmission for electric vehicles

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ABSTRACT

The purpose of this paper is to demonstrate the application of torque based powertrain control for multi-speed power shifting capable electric vehicles. To do so simulation and experimental studies of the shift transient behaviour of dual clutch transmission equipped electric vehicle powertrains is undertaken. To that end a series of power-on and power-off shift control strategies are then developed for both up and down gear shifts, taking note of the friction load requirements to maintain positive driving load for power-on shifting. A mathematical model of an electric vehicle powertrain is developed including a DC equivalent circuit model for the electric machine and multi-body dynamic model of the powertrain system is then developed and integrated with a hydraulic clutch control system model. Integral control of the powertrain is then performed through simulations on the develop powertrain system model for each of the four shift cases. These simulation results are then replicated on a full scale powertrain test rig. To evaluate the performance of results shift duration and vehicle jerk are used as metrics to demonstrate that the presented strategies are effective for shift control in electric vehicles. Qualitative comparison of both theoretical and experimental results demonstrates reasonable agreement between simulated and experimental outcomes.

1. Introduction

As the electric vehicle (EV) market continues to grow, new strategies for improving both the dynamic performance and overall economy of the vehicle develop at pace. Several recent studies [1–3] have investigated the application of multi-speed transmissions to electric vehicle platforms. These are viewed as one of the most promising options that meet the needs for both a wider range of torque application and higher energy efficiencies than single speed equivalents. Such investigations have typically focused on the system level perspective to evaluate the energy consumption and performance improvements, but have not included detailed study of the controllability of these platforms during gear shift. The purpose of this paper is to fill that gap in knowledge, evaluating the transient behaviour of multi-speed EVs (MSEV) during gear shift with full scale tests. This includes all forms of shifting: power-on and power-off variants of up and down shifts, with comprehensive experimental verification of results.

Applications for dual clutch transmissions (DCT) have traditionally been orientated around conventional vehicle systems. However, as hybrid and electric vehicle systems have come to the fore DCTs have been viewed as an applicable technology

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to these new energy vehicles. Primarily as multiple speed ratios and power-on shifting capabilities meet requirements for both efficiency and driver comfort [4]. Recent examples of the application of multi-speed transmissions to hybrid and electric vehicle applications include clutchless automated manual transmissions (CLAMT) [5], dual motor multi-speed EV transmissions [6], and two speed planetary transmission [7]. Each configuration has both benefits and limitations. For example, the CLAMT configuration is simple to control and will have high operating efficiencies with fewer viscously coupled components (i.e. open wet clutches). However, torque interrupt is present during gear change events as the motor must be de-energized to facilitate the release of synchroniser mechanisms during gear change. Alternatively, dual motor EV platforms overcome this limitation through toque hole filling with the second motor, but incur additional costs with multiple motors and additional power electronics and control requirements. Dual clutch transmission (DCT) and AT variants of MSEVs overcome this limitation through the use of clutch-to-clutch shift control strategies that have been demonstrated in conventional DCT and AT studies such as [8,9].

Torque based control of automotive powertrains is the predominant control strategy applied in this field owing partly to traditional use in conventional vehicles [8] and convenience for integration with conventional electric motor torque control strategies. A number of studies have been undertaken for conventional [8,9] and electric vehicle applications [10]. An optimal control strategy for a two speed planetary geared transmission was developed in [10], with the control strategy demonstrated with bench top tests. Similar methods have also been extended into applications of Synchroniser mechanism control, such as [11] where online estimation of drag torque is used enhanced mechanism control. Furthermore integration of control strategies with transmission control systems, notably clutch hydraulic systems, is vital for ensuring robust shift control. Such examples include [12] where a linearized model of the complex hydraulic system is used for precise control of clutch-to-clutch gear shifts.

A noteworthy extension of torque based control strategies is refined speed synchronization control during the inertia phase of shifting [13]. This method can be used to improve the performance of gear change, increasing robustness of the shift process. Control strategies have also been further refined through the estimation of transmission output torque. Studies such as [14] have developed observers for real-time estimation of individual clutch torque. Whereas [15] develops a robust observer for stepped ratio EV applications using an H-infinite based strategy, achieving high torque estimation accuracy when verified experimentally. The variations to traditional torque based control strategies are capable of delivering higher quality of shift control through improved torque estimation.

The remainder of this paper is divided as follows. Section 2 summarizes the existing work in studying multi-speed EVs and practicalities of prototype development. Section 3 presents the detailed mathematical modeling of the powertrain system, including electric machine and power electronics model, summary of the clutch hydraulics model, and multi-body vehicle powertrain model. Section 4 details the powertrain control strategy employed, including power-on and power-off techniques for up and down shift strategies. Section 4 presents several measures of shift quality that are utilised in the study for evaluating performance. Section 5 presents the experimental setup. Section 6 presents simulation and experimental results of the study. Finally, conclusions and recommendations are presented in Section 7.

2. Prototype development and evaluation of appropriate gear ratios

Much work has been involved in the study of gear ratio selection for multi-speed EVs, including work in the development of an inverse automated manual transmission (IAMT) [16], where a dynamic programming strategy was applied to select the optimal ratios. A study by Zhou, et al. [17] mapped the driving efficiency over a large number of gear ratios using simulations for the NEDC driving cycle. This demonstrates that there are a large number of ratio combinations that will provide very similar average driving efficiency. However, transmission efficiency was considered to be constant. In Di Nicola et al. [18] it was proposed that the use of multi-speed transmissions can reduce peak motor torque demands, this was supported by work in Roser [19]. Furthermore, the use of multi-speed transmissions, particularly those with wet clutches, introduces additional losses to the powertrain system. This has been studied in Zhou et al. [20] where the dominant losses in this transmission system is in the wet clutches. Experimentally verified results demonstrated that the minimum efficiency of the transmission was approximately 94%.

For the purpose of prototyping of this system a DQ250 dual clutch transmission with hydraulically actuated wet clutches was selected, primarily as the system is robust and the wet clutches are more resilient during testing. The downside to the use of a wet clutch DCT is that there are higher parasitic losses in the hydraulic control system and wet clutch, which is undesirable for EV applications. Using this transmission with parallel lay shafts, gear ratios were restricted to 3.46, 2.08, 1.32, and 0.9 with a final drive of 4.12, and 0.91 and 0.79 with a final drive of 3.04. Based on the result of studies in Zhou et al. [17] and Roser et al. [19] ratios of 2.08 and 1.32 (both multiplied by the final drive ratio of 4.12 to give 8.5696 and 5.4384, respectively) were selected to minimise the step between gear ratios during shifting, whilst maintaining a reasonable ratio spread. This will also have the effect of reducing the losses in the wet clutches as these are dependent on the relative speed in the clutch.