

Development of Two-Mode Hybrid Powertrain with Enhanced EV Capability

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ABSTRACT

The two-mode hybrid system has several advantages over a one-mode EVT system: greater ability to transmit power mechanically and minimize electrical recirculation power, maximize fuel economy improvement and best meet demanding vehicle requirements. Extending the two-mode hybrid electric vehicle (HEV) to two-mode plug-in hybrid electric vehicle (PHEV) is significant not only to make the internal combustion engine (ICE)-based vehicle cleaner and more efficient in the near term, but also to provide a potential path to battery electric vehicles in the future. For PHEV, the enhanced electric drive capability is of vital importance to achieve best efficiency and best electric only performance.

This paper describes the development of a prototype two-mode hybrid powertrain with enhanced EV capability (2MH4EV). The prototype drive unit includes an additional input brake to the existing General Motors FWD 2-mode HEV system. This enables two new electric-only modes in addition to the existing EVT modes and fixed gears. These two electric-only modes have the capability to cover the entire FTP urban cycle with a properly sized high voltage battery. Hardware design, systems and controls development are described in detail in this paper. Vehicle implementation, testing, and real world assessment of the enhanced electric-only propulsion, mode transition and drivability will also be presented.

INTRODUCTION

General Motors has developed a two-mode hybrid transmission for transverse front wheel drive vehicles [1]. Its electrically-variable transmission architecture incorporates a pair of electric motors, two planetary gear sets and a system of clutches to deliver two continuously-variable speed-ratio

ranges or “modes”, and is similar to the GM 2Mode Hybrid™ for full-size rear wheel drive trucks [2]. In addition to the two variable modes, four clutches in the two-mode hybrid transmission provide four forward fixed gear ratios. The two-mode hybrid powertrain and corresponding hybrid vehicle system deliver up to 50% improvement in EPA unadjusted composite fuel economy.

A vehicle equipped with an EVT transmission can be driven by the electric motor with the engine at zero speed (electric drive). In an input-split (also known as series-parallel) architecture, one motor may propel the vehicle while the other has to be used to maintain the engine at zero speed in order to avoid engine frictional and pumping losses. However, this single-motor electric propulsion has limited electric launch and acceleration capability and is not optimal for efficiency and heat rejection to cover the entire FTP cycle electrically.

By grounding the engine with an input-brake clutch at the transmission input node, both motors can be used to propel the vehicle electrically. This way, vehicle propulsion load can be shared with two motors in either of the two EVT modes. However, in order to take full advantage of the two-mode hybrid system to achieve best system efficiency, mode transition and engine start-stop control need to be developed for the new electric-only modes involved with the input-brake clutch. Due to the complexity of controlling the input brake during mode transition and engine start/stop events, a proof-of-concept development of the 2MH4EV powertrain was undertaken to demonstrate charge-depletion operation and achieve quick and seamless transitions between two new electrical modes, as well as engine start-stop control between the electric modes and the hybrid modes.

This paper starts with an overview of the two-mode hybrid operating principles, and then discusses the addition of the input-brake clutch to enhance the electric drive capability. Mode transition control is the major challenge of this hybrid powertrain and therefore this paper will center around the dynamic analysis, control algorithm development and vehicle calibration of the two-mode electric only transition as well as its associated driveline dynamic control method. The scale and complexity of the control system development of the 2MH4EV required use of model-based development processes, from the first evaluation of system dynamics, controllability and strategy definition, to real-time control strategy design and validation on the hardware-in-the-loop (HIL) test bench, and finally to vehicle integration, calibration and testing. This development process largely improved development quality and decreased development time, and will be detailed throughout this paper.

OVERVIEW OF 2-MODE HYBRID POWERTRAIN

The centerpiece of the two-mode FWD hybrid system is an EVT (electrically variable transmission), which uses a pair of electric motors to choose a wide range of ratios through the transmission. A vehicle equipped with an EVT transmission can be driven by the electric motor with the engine at zero speed (electrical drive), or the engine can be spinning while connected to the output with the vehicle at zero speed (engine on launch), or anywhere in between. The schematic of the two-mode FWD hybrid transmission is shown in [Fig. 1](#), with the input, output and electric motors connected to two planetary gear sets. There are four hydraulically-applied wet-plate range clutches to allow automatic shifting among two continuously variable modes and four fixed gears. A detailed description of the mechanical design, schematic and cross section drawings, operating principles and hydraulic clutch operation can be found in the literature [1].

There are two continuously variable modes for the two-mode EVT transmission. The first continuously variable mode (EVT1 or M1) covers the higher speed ratio range with clutch-brake CB12R applied, while the second continuously variable mode (EVT2 or M2) covers the lower ratio range with clutch C234 applied. The system has a total of four fixed gears (FG1, FG2, FG3 and FG4) that are achieved by locking two range clutches simultaneously. The second gear FG2 is located at the ratio of the synchronous transition point between EVT1 and EVT2, with both CB12R and C234 applied. Synchronous mode transition can be smooth in this two-mode EVT, because the shifting clutches can be pre-synchronized in speeds by using the electric motors. Taking EVT1 to EVT2 mode transition as an example, the electric motor/generator A (MGA) first controls the engine speed to vary through the transmission ratio in EVT1 range until the C234 clutch is synchronized with zero slip speed. This is called the “speed phase”. Next is the “torque phase”, which is

simply a torque transfer from the off-going clutch CB12 to the on-coming clutch C234, while maintaining both clutches synchronized. Finally the transmission reaches the EVT2 mode at the particular speed ratio where the grounding clutch for EVT1, CB12, has zero slip speed. There is only one ratio that satisfies the synchronous condition between EVT1 and EVT2, which is ratio of the second fixed gear (FG2).

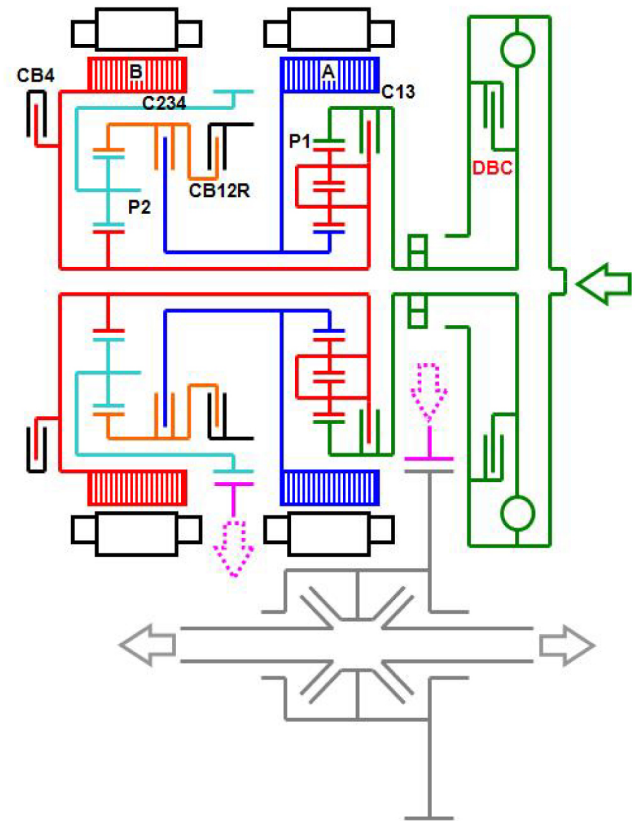


Figure 1. Schematic of Two-mode FWD Hybrid Transmission

OVERVIEW OF TWO-MODE HYBRID POWERTRAIN WITH ENHANCED ELECTRIC DRIVE CAPABILITY

A vehicle equipped with the EVT transmission can be driven by electric motors with the engine speed at zero, which is called the “electric vehicle” (EV) mode. With the two-mode hybrid powertrain as described in the previous section, there are potentially two EV modes: EVT1 with zero engine speed and EVT2 with zero engine speed. Due to system constraints only the EVT1 electric mode is available at lower vehicle speeds. This low speed electric only mode is called “EV0”. [Figure 2](#) illustrates the existing and desired operating modes of the two-mode based plug-in hybrid system. EV0 has only limited speed range and acceleration capability with current design of ratio and component size.

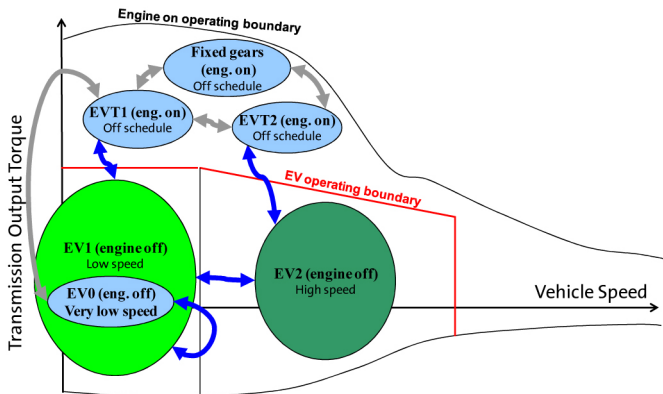


Figure 2. Plug-in Hybrid operating modes

The 2MH4EV architecture is based on the current FWD two-mode hybrid system with an additional input-brake clutch CB5 as shown in Fig.3, for significantly improved electric propulsion capability. The damper by-pass clutch (DBC) in Fig. 1 is removed and its hydraulic control circuit is reused for controlling CB5. There are two new electric-only modes: EV1 and EV2:

- EV1: electric only mode-1 with engine off and input brake on. The transmission is in the first continuously-variable mode EVT1 with both brake-clutch CB12R and input-brake clutch CB5 applied. With CB5 applied and providing reaction torque at the first planetary gear set, both MGA and MGB can provide positive propulsion or negative regenerative braking torque thus enhancing the electric drive capability.
- EV2: electric only mode-2 with engine off and input brake on. The transmission is in the second continuously-variable mode EVT2 with both rotating-clutch C234 and input-brake clutch CB5 applied. With CB5 applied and providing reaction torque at the first planetary gear set, both MGA and MGB can provide positive propulsion or negative regenerative braking torque thus enhancing the electric drive capability.

Overall, EV1 has a higher output torque capability. It has better efficiency in the lower speed, higher torque region, and will be used as a low speed electric-only mode. Conversely, EV2 has better efficiency in the higher speed, lower torque region, and will be used as a high speed electric-only mode.

The design target for the 2MH4EV transmission is to make it practical to cover the entire EPA FTP urban cycle with electric only operation, without increasing the size or cooling capacity of the motors. Figure 2 illustrates the operating modes and the possible mode transitions of 2MH4EV as a function of output torque and vehicle speed. In addition to the existing engine-on operating modes EVT1, EVT2, and fixed gears FG1, FG2, FG3, and FG4 as well as the low speed electric-only mode EV0, the two new electric-only modes EV1 and EV2 cover the entire low-torque low-speed region assuming a sufficient amount of battery power. Figure 2 also

illustrates the required mode transitions to enable the operation of this multi-mode EVT system, including mode transitions between EV1 and EV2 as well as other engine-on operating modes and fixed gears, engine start operation from EV0 / EV1/ EV2 to EVT1 / EVT2 or engine stop operation from EVT1 / EVT2 to EV0 / EV1/ EV2.

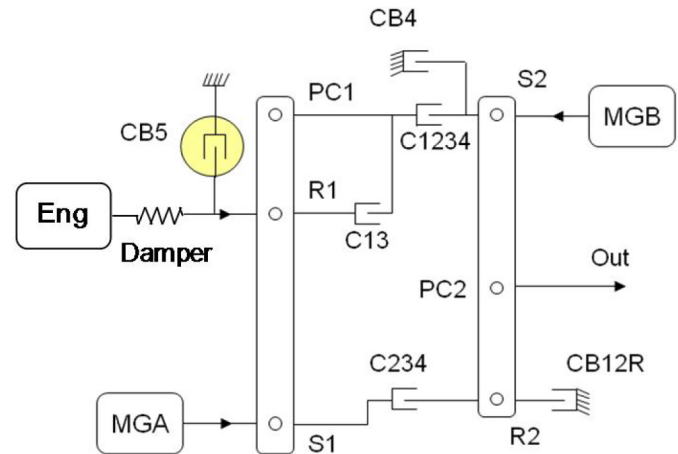


Figure 3. Schematic of 2MH4EV transmission

HARDWARE DESIGN OF 2MH4EV TRANSMISSION

The 2MH4EV prototype hardware is modified from the 2MH FWD hybrid system. The major modifications in hardware design can be summarized as follows:

- Incorporate an engine brake clutch for enhanced plug-in capability
- Meet functional requirements with no increase in package space over 2MH while minimizing cost, mass and risk and maximizing fuel economy/PHEV range

Features of the prototype design include:

- Elimination of the damper bypass clutch used in the 2MH FWD hybrid transmission.
- A hydraulically applied engine node brake clutch downstream of the damper. The hydraulic circuit previously used for the bypass clutch was adapted for actuation of the brake clutch.
- Increase in C234 capacity (added plates, increased auxiliary pump maximum pressure.)
- Reduction in CB12R spin loss.

The resulting cross-section and dry damper assembly are shown in Fig. 4. The powertrain damper has two sets of conflicting requirements it must meet as shown in Fig. 5: First, it must have low hysteresis for excellent isolation during engine-on driving. Secondly, during engine cranking,

it must have high torque capacity with low dynamics. General Motors' 2MH system uses an actively controlled clutch to meet these requirements and provide world-class engine start-stop smoothness. For expediency in the prototype system, the hydraulic circuit used for the damper bypass clutch was re-used to actuate the input brake. For this reason, the dry damper incorporated a tunable hysteresis element, which permitted the selection of the best hysteresis level for both engine cranking and isolation.

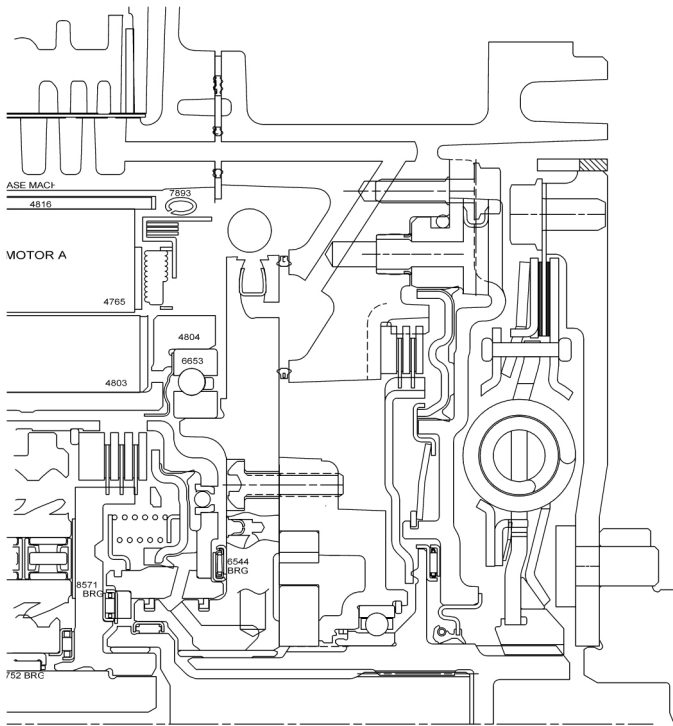


Figure 4. Cross-section of the input-brake clutch housing

Simulated damper hysteresis effects on engine start-stop disturbance and steady-state isolation, Mode 1 and Mode 2

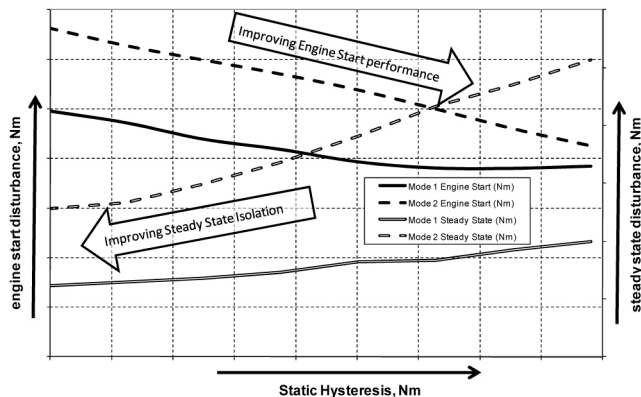


Figure 5. Damper hysteresis effects on engine S/S and steady state isolation

CONTROLS METHODOLOGY AND SIMULATION

The initial investigation of system dynamics, controllability and the design of the control strategy of the 2MH4EV were conducted with a GM proprietary software package called Unified Model (UM) [5]. It helps to define: the operating strategy of the hybrid powertrain, understand the constraints of each operating mode, and provide insights into how the mode transitions affect driveline dynamics. All of these are essential for control algorithm development and software implementation of the hybrid control system.

As shown in Fig. 6, the Hybrid Control module implemented in the Unified Model includes five major functional modules which conceptually represent the same functionalities as the software implementation of the two-mode hybrid real-time controller, the hybrid control processor (HCP):

- Hybrid Range State and Engine Speed optimization
- Engine Torque optimization
- Motor Torque Control
- Shift Execution Control
- Engine Start-stop Control

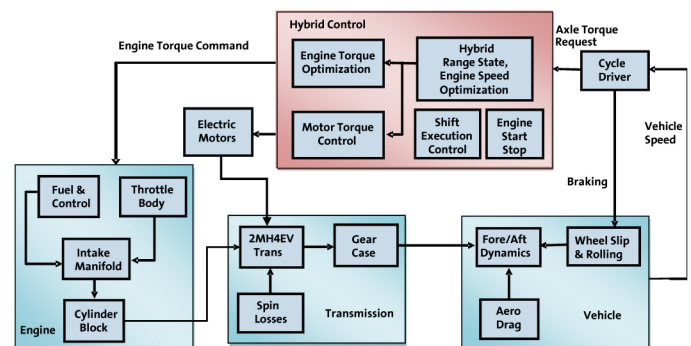


Figure 6. Unified Model top level configuration

Based on current vehicle operating conditions, an instantaneous C-code optimization routine embedded in the Unified Model determines the hybrid range states, engine speed, and optimal torque split between the engine and electrical motors by minimizing the total power loss of the powertrain, while keeping the battery state-of-charge (SOC) balanced. These vehicle operating conditions and parameters include vehicle speed, accelerator pedal input, engine speed, vehicle braking requirement, battery SOC, power and voltage limits, etc.

Detailed dynamic models of the two-mode hybrid transmission including clutches, gear sets and electric motors are developed in the Unified Model to evaluate the system dynamic behavior during hybrid mode transition and engine