

Developing Mode Shift Strategies for a Two-Mode Hybrid Powertrain with Fixed Gears

Kukhyun Ahn

University of Michigan, Ann Arbor

Suk Won Cha

Seoul National University

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ABSTRACT

Two-mode hybrid architectures with three planetary gear sets and four clutches will bring both flexibility and complexity to energy management of powertrains. In order to take full advantage of the increased degrees of freedom, highly delicate operation strategies are needed. We develop transmission efficiency models for power-split modes, and present a mode shift strategy assuming no battery power. When battery load leveling is additionally considered, the respective optimal operation set for each mode can be obtained and compared to yield a mode shift algorithm for general hybrid operation situations. The investigation of the strategies shows how frequently each mode is used, and verifies the effectiveness of fixed gear operations. We check the validity of the strategies by applying the algorithm to dynamic optimization and by predicting how it works during an actual driving simulation.

INTRODUCTION

Hybrid electric vehicles (HEVs) with single-mode power-split powertrains have dominated the HEV markets since 1997. They were a great success and several top automakers considered or adopted this type of architecture. However, the poor highway mileage and the high cost for electric motors were indicated as the demerits of this type of vehicle. To overcome these drawbacks, a few automakers such as GM and Renault developed two-mode power-split architectures and applied them to transit buses and full-size SUVs.

To review the prior research briefly, the transmission efficiency of the two-mode electrically variable transmission (EVT) has been analyzed, and the optimal engine operation has been discussed [1]. The speed, torque and mechanical power of each component were analyzed assuming constant velocity cruising and full load acceleration [1-5]. The parametric design found the optimal values of planetary gear ratios and component sizes [1]. These pieces of research concluded that the

adaptive use of two different power-split modes provides multiple mechanical points and reduces energy conversion loss throughout the whole speed ratio range. This turned out also to be helpful in reducing electric machine sizes, which will greatly lower the manufacturing costs.

Regarding the system, many questions still need more investigation. Some of them are about the effectiveness of adding a planetary gear set and clutches and when to use the fixed gear operations. In this paper, we develop operation strategies for a two-mode hybrid powertrain with fixed gear (FG) operations. The optimal trade-off and multi-objective optimization will be used to find the most economical mode. The analysis of the optimal mode selection can provide clues to some of the questions.

DESCRIPTION OF THE POWERTRAIN

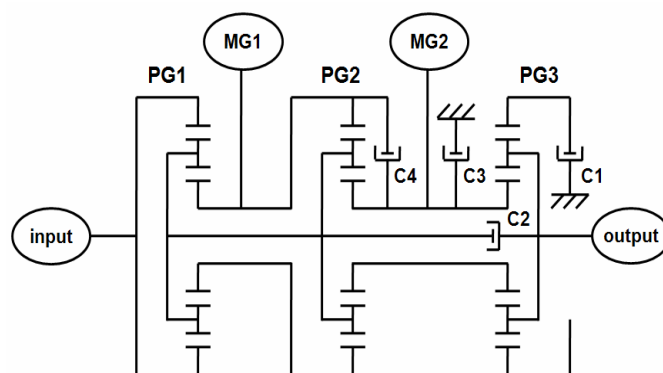


Figure 1: Schematic of the two-mode hybrid powertrain

Figure 1 is a schematic of the two-mode hybrid powertrain which was developed by GM [5]. It has three planetary gear sets and four wet clutches. Engaging or disengaging the four clutches, it realizes six different operation modes including two EVT modes and four FG modes. When either C1 or C2 is engaged and the other three clutches are disengaged, the powertrain has two

degrees of freedom and is operated in EVT1 or EVT2 mode, respectively. The clutch operations for the four fixed gear modes give the powertrain one degree of freedom. The detailed clutch operations are summarized in Table 1 [5].

Table 1: Clutch operations for EVT and FG modes

	C1	C2	C3	C4
EVT1	on			
EVT2		on		
FG1	on			on
FG2	on	on		
FG3		on		on
FG4		on	on	

The following discussion is based on a quasi-static scenario neglecting transient motions of powertrain components. Some modifications may be needed to consider transient responses of the powertrain before we apply the findings to actual systems. However, the findings here will provide a basis for further modifications and developments.

For each mode, torques and speeds of MG1 and MG2 are expressed with torques and speeds of input and output shafts. The steady-state equations of motion are summarized below.

EVT1:

$$T_1 = -\frac{1-ab}{1+b}T_i \quad (1)$$

$$T_2 = -(1+a)\frac{b}{1+b}T_i + \frac{c}{1+c}T_o$$

$$\omega_1 = \frac{1+b}{1-ab}\omega_i - b\frac{1+a}{1-ab}\frac{1+c}{c}\omega_o \quad (2)$$

$$\omega_2 = \frac{1+c}{c}\omega_o$$

EVT2:

$$T_1 = -\frac{1-ab}{1+b}T_i + \frac{1}{1+b}T_o \quad (3)$$

$$T_2 = -(1+a)\frac{b}{1+b}T_i + \frac{b}{1+b}T_o$$

$$\omega_1 = -\frac{1}{a}\omega_i + \frac{1+a}{a}\omega_o \quad (4)$$

$$\omega_2 = \frac{1}{ab}\omega_i - \frac{1-ab}{ab}\omega_o$$

FG1:

$$T_1 + T_2 = -T_i + \frac{c}{1+c}T_o \quad (5)$$

$$\omega_1 = \omega_2 = \omega_i = \frac{1+c}{c}\omega_o \quad (6)$$

FG2:

$$(c-b)T_1 + (1+c)T_2 = -(ab+c)T_i + cT_o \quad (7)$$

$$\omega_1 = \frac{c-b}{c}\omega_o$$

$$\omega_2 = \frac{1+c}{c}\omega_o \quad (8)$$

$$\omega_i = \frac{ab+c}{c}\omega_o$$

FG3:

$$T_1 + T_2 = -T_i + T_o \quad (9)$$

$$\omega_1 = \omega_2 = \omega_i = \omega_o \quad (10)$$

FG4:

$$T_1 = -\frac{1-ab}{1+b}T_i + \frac{1}{1+b}T_o \quad (11)$$

$$\omega_1 = (1+b)\omega_o$$

$$\omega_2 = 0 \quad (12)$$

$$\omega_i = (1-ab)\omega_o$$

a, b, c : planetary gear ratios of PG1, PG2 and PG3

T, ω : torque and speed of each component

$i, o, 1, 2$: subscripts for input, output, MG1 and MG2

TRANSMISSION EFFICIENCY OF EVT OPERATION

The transmission efficiency of the power-split hybrid powertrain can be expressed as a function of input speed, input torque and speed ratio [1,6]. Assuming no battery power, the power conversion loss is calculated in equation (13) and the power transmission efficiency is obtained in equations (14) and (15). Equation (14) is for EVT1 mode which is an input-split mode and equation (15) is for EVT2 mode which is a compound-split mode.

$$\frac{\omega_1 T_1}{\eta_1} + \frac{\omega_2 T_2}{\eta_2} = 0 \quad (13)$$

$$\eta_{e1} = \frac{1}{\rho} \left\{ \frac{\eta_2}{\eta_1} (\rho - \rho_{e1}) + \rho_{e1} \right\} \quad (14)$$

$$\eta_{e2} = \frac{1}{\rho} \frac{\rho_{e21}(\rho - \rho_{e22})\eta_2 / \eta_1 - \rho_{e22}(\rho - \rho_{e21})}{(\rho - \rho_{e22})\eta_2 / \eta_1 - (\rho - \rho_{e21})} \quad (15)$$

η : motor/generator efficiency or transmission efficiency

ρ : speed ratio

$\rho_{e1} = (1+a) \frac{b}{1+b} \frac{c}{1+c}$: EVT1 mechanical point

$\rho_{e21} = 1+a$: first EVT2 mechanical point

$\rho_{e22} = 1-ab$: second EVT2 mechanical point

The equations above use the reciprocal of the motor/generator (MG) efficiency if the corresponding electric machine is converting mechanical power into electric power because the power conversion equation is of a general form. Before we start to develop detailed models, we can obtain a simplified transmission efficiency model by inserting constant MG efficiency values into equations (14) and (15). The graph is shown in Figure 2 and the powertrain data used in the calculation including fixed gear ratios are summarized in Table 2. In order to obtain the planetary gear ratios and the final reduction ratio, we used 25 candidate Latin-hypercube design samples to compare the attributes such as city driving mileage, 60 mph cruising mileage and top velocity. Additional optimization works will be conducted and presented in our further research.

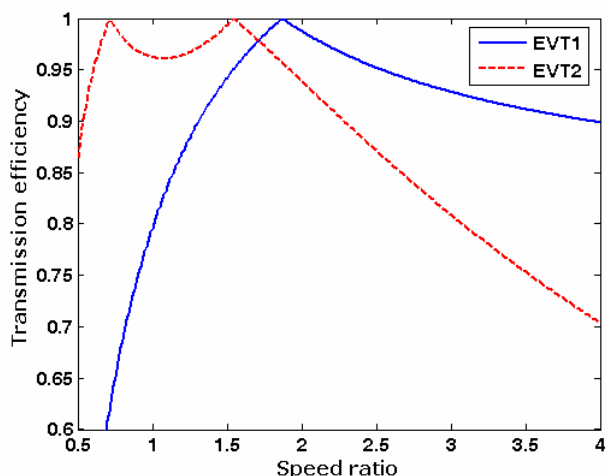


Figure 2: Simplified transmission efficiency curves

The transmission efficiency curves of both EVT modes are highly dependent on the speed ratio. The curves show the three mechanical points: one from the input-split mode and two from the compound-split mode. The input-split and compound-split operations supplement each other constituting an envelope which has a high efficiency value throughout the speed ratio range.

Table 2: Powertrain specification

Engine	63 kW	FG3	1
Battery	40 kW	FG4	0.715
MG1	30 kW	Weight	1749 kgf
MG2	30 kW	Rolling resistance	0.009
PG1	0.543	Drag coefficient	0.3
PG2	0.524	Frontal area	1.746 m ²
PG3	0.397	Tire radius	0.293 m
FG1	3.52	Final drive (FD)	3.632
FG2	1.72	FD efficiency	0.95

Unlike the simplified models, the detailed models require the two MG efficiencies to be calculated with respect to the operational states of electric machines. The electric motor/generator efficiency characteristics required for the calculation are displayed in Figure 3 (the first quadrant). When input speed, input torque and speed ratio are known, the MG1 and MG2 speeds are calculated using equations (2) or (4). By eliminating output torque in equations (1) or (3), MG1 torque is expressed as a first-order polynomial of MG2 torque. Then, MG2 torque becomes the only unknown in equation (13) and can be obtained by solving the equation numerically. This gives all the information needed to calculate equation (14) or (15). The efficiency is visualized in Figures 4 and 5.

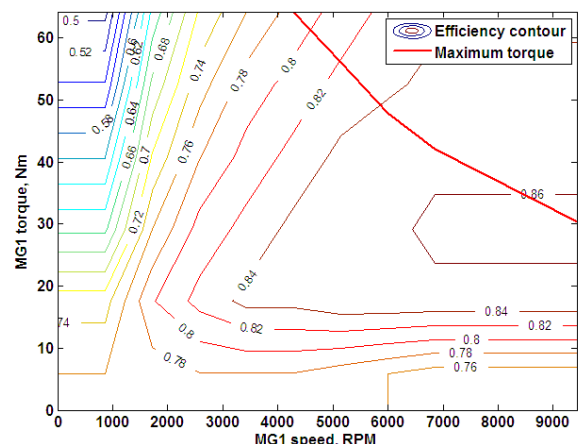


Figure 3: Electric motor efficiency map