

Conceptual Design and Evaluation of a Hybrid Transmission with Power-Split, Series, and Two Parallel Configurations

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ABSTRACT

A hybrid transmission may be in any combination of a power-split, series or parallel configuration. This study is aimed to develop a hybrid transmission with six possible configurations: power-split, series, two parallel configurations, and two EV configurations. The Function Power Graph (FPG) methodology was applied in this study. After creating and merging FPGs, a possible solution consisting of only one planetary gearset, one ICE, one MG1, one MG2, two rotating clutches, and one brake clutch was synthesized to satisfy all configuration requirements. This transmission was based on power-split configuration which can switch to other configurations. The parallel configuration I extracted more power from MG1 and ICE during lower speed driving in order to utilize the two sufficiently, and respond to the increased desire for horsepower in the market. Additionally, parallel configuration II was set up so that ICE can directly propel the vehicle during freeway cruising. Compared with power-split configuration, MG1 does not need to keep operating in parallel configuration II, which gives an additional opportunity to develop an energy management strategy. Moreover, both MG1 and MG2 could propel the vehicle in the two-motor EV configuration, thus costly electric machinery and power electronics were utilized more thoroughly. In conclusion, a design process of a multi-configuration hybrid transmission was proposed and the result was evaluated. This study provides some alternative hybrid concepts for further research.

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INTRODUCTION

Motivation and Purpose

Hybrid electric vehicles (HEVs) provide opportunities to economize fuel consumption and improve dynamic performance. However, in hybrid cars, more than one power unit (PU) is used, such as motor-generators (MGs) or an internal combustion engine (ICE). To connect between these PUs, an investigation with respect to hybrid transmissions is required [1, 2].

The hybrid transmissions available on the market may be in any combination of power-split, series or parallel configurations. The transmission in Toyota Hybrid System (THS) [3] can be categorized as a transmission with power-split configuration, and there are some sophisticated multi-configuration transmissions like GM Voltec GEN 2 that can switch between one parallel configuration and two power-split configurations [4]. In this study, a multi-configuration hybrid transmission based on power-split configuration was developed. The power-split architecture in THS, due to the characteristics of planetary gearset (PG), MG1 normally acted as a generator extracting mechanical power from the transmission. Thus, the power output capability is lower than the summation of maximum horsepower of ICE, MG1, and MG2. With regards to performance, the negative power of MG1 is unfavorable.

In contrast, the power output capability in parallel hybrid is simply the summation of power from ICE and all MGs, therefore, a parallel configuration was included as an additional configuration in this study to utilize ICE and all MGs more sufficiently during large power output.

During highway cruising, MG1 must keep operating to maintain power-split operation. In this study, another parallel configuration with relatively lower reduction ratio was included for cruising. It is similar to ICE direct drive in Honda Accord Hybrid Model Year (MY) 2014 (i-MMD), so that MG1 can be idle to avoid power conversion loss between mechanical and electrical power [4, 5, 6, 7, 8, 9, 10].

In power-split, the torque relationship between sun, carrier, and ring gear in PG is under constraint. To provide the ability for ICE to generate electricity efficiently while preserving a way to start the ICE smoothly in diverse scenarios, the series configuration was included as an additional configuration in this study.

In power-split, PG has two degrees of freedom (DOF). When ICE is off, MG1 also loses its ability of torque output. Hence, there is only MG2 available in pure EV. To utilize all MGs in EV mode (such as Toyota Prius Prime and Chevrolet Volt MY2016), the two-motor configuration was also included. When more power is needed, MG1 should also be allowed to propel the vehicle.

Accordingly, to take the benefit of all the configurations, this study aimed to develop a hybrid transmission with one-motor EV, two-motor EV, power-split, series, and two parallel configurations.

Limitation and Procedure of This Study

This study should design a transmission mechanism that not only allows an HEV to have as good of fuel economy as regular power-split HEV does, but also permits the driver to switch to another mode in order to extract more power from power units without any fuel economy requirement in this mode. The method is limited to adding extra clutches and routes on power-split to construct the five other configurations mentioned above, forming a relatively complex transmission. The power units (ICE and MGs) are not the subjects to modify, and thus, limited the range of this study.

In addition, in order to analyze the hybrid transmission generated, 0–100km/hr, the number of rotating clutches, the number of brake clutches, and the number of one-way clutches (OWCs) were selected as the metrics in this study. 0–100km/hr reflects the accelerating performance, and the number of clutches reflects the complexity of different hybrid transmissions, and with these, different transmissions with identical power units can be evaluated.

With Function Power Graph methodology, the synthesis procedure was proposed and then a hybrid transmission was generated. Compared with power-split-only transmission, this hybrid transmission contained two additionally rotating clutches with one brake clutch which satisfied all configurations required. The power output capability was also evaluated.

This study is organized as follows:

1. Introduction
2. Function Power Graph Methodology
3. Design Requirements
4. Synthesis
5. Discussion & Analysis
6. Conclusion

FUNCTION POWER GRAPH METHODOLOGY

The Function Power Graph (FPG) methodology was applied to conduct this study. FPG is a powerful tool for powertrain design; it was developed by Mechanism and Machine Theory (MMT) Research Laboratory at National Taiwan University [11, 12]. Its composition and rules are briefly explained as follows:

One of the main purposes of FPG is to standardize the expression of system units and make the system structure, or connecting relation between each unit, clearer. This allows the system structure to be easier to read, and the comparison between different systems becomes more intuitive. In this section, the standard unit symbols used in FPG are introduced, and the process of drawing or transferring a current schematic diagram into the FPG is demonstrated.

System Units of FPG

The common system units seen in this study were collected and classified into five categories: (1) power unit; (2) transmission unit; (3) clutch/brake unit; (4) multiple-degree-of-freedom unit; and (5) connection unit. Their standard symbols used in FPG are arranged in [Table 1](#), [2](#), [3](#), [4](#), [5](#).

Power units are denoted as a rectangle in the FPG, [Table 1](#). The power input unit (IN) shown in [Table 1](#), refers to the sources that generate the power flow into the transmission system. It can be an ICE, MG (motor-generator) [13], a power input shaft, or other power devices. The power output unit (OUT) refers to the destination of the power flow, which can be a power output shaft of a transmission system. However, there may be no strict distinction between power input and power output units, since they are both terminals of the power flow, meaning it can be indiscriminate in regards to which way power flows. For example, when the power flows into the engine—referring to an engine braking operation—the engine becomes a power output unit of a transmission in this scenario. The electric machine becomes an input unit in the motor mode and becomes an output unit in the generator mode. The state of input or output should be decided by the operation of the unit according to the applied scenario.

Table 1. FPG symbols—power units

Unit	Symbol	Description
P		General symbol of a power unit
IN		General symbol of a power input unit
ICE		Internal combustion engine
MG		Motor-generator (Electric machine)
OUT		General symbol of a power output unit
W		Wheel

The function of the transmission unit is to generate a speed ratio which can change the speed and torque of the power flow to the desired speed of the vehicle. The symbols of transmission units are denoted as a pentagon in FPG and arranged in [Table 2](#). All the transmission units have two poles to connect to the other system units.

A 1-DOF gear pair or gear train is denoted as a ‘G’ in an irregular pentagon. This unit has a fixed speed ratio and does not have the gear-shifting ability. Gear ‘G’ only contribute a constant speed ratio to the system. In some cases, they can be eliminated to simplify the FPG.

Clutch units are used to control the connection between different system units. A brake clutch or brake unit is used to connect the units to the ground to reduce the speed of the element. Their symbols in FPG are shown in [Table 3](#). The symbol of a clutch unit is similar to the switch symbol in an electric circuit diagram.

Table 2. FPG symbols—transmission units

Unit	Symbol	Description
T		General symbol of a transmission
AT		Automatic transmission
DCT		Dual-clutch transmission
G		Gear pair or gear train

The one-way clutch (OWC) is used in the GM Voltec GEN 2 and Toyota Prius Prime. It is located at ICE output shaft and only allows rotation in one direction. If the shaft tends to rotate backward, the OWC will be triggered and stop the shaft; note that when it is triggered, it acts like a brake and reduces DOF of the transmission system by one.

Table 3. FPG symbols—clutch units

Unit	Symbol	Description
C		Clutch (Rotating clutch)
OWC		One-way clutch
B		Brake (Brake clutch)

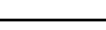
Multiple-degrees-of-freedom (MDOF) mechanisms are often seen in transmissions. The planetary gearset may be the most common MDOF, which is a two-degrees of freedom (DOF) device. The corresponding symbol of a planetary gearset is noted in Table 4, it is a triangle where each corner is denoted with letter s, c, and r—indicating sun gear, carrier, and ring gear respectively. There are some other MDOF devices such as Ravigneaux gearset and differential gearset, but these were not used in this study.

Table 4. FPG symbol—multiple-degrees-of-freedom unit

Unit	Symbol	Description
PG		Planetary gearset

The connection line is used to link system units to establish the structure of the powertrain. When three or more connection lines join together, a coupling point is used to denote the intersection. The symbols of a connection line and a coupling point are shown in Table 5.

Table 5. FPG symbols—connection units

Unit	Symbol	Description
Connection line		Connected to units or couplers
Coupler (Coupling point)		Coupled to three or more connection lines

Hybrid Transmissions in FPG

Current hybrid transmissions can be transferred into FPG. In FPG, hybrid transmissions become more intuitive and concise. A typical power-split hybrid transmission (input-split) such as Toyota THS and Ford HF35 was transferred into FPG (Figure 1) [3, 14, 15]. In this FPG, the triangle of PG (planetary gearset) expressed the famous 2-DOF relationship between ICE, MG1, and MG2.

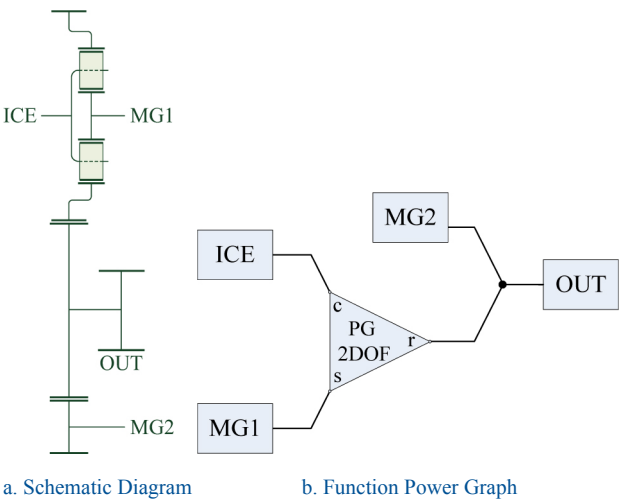


Figure 1. A power-split hybrid transmission.

In regular THS, a vehicle in pure electric mode (EV mode) can only utilize one motor (MG2), since MG1 cannot contribute any power when ICE is off (free rotating). This is not ideal given that production costs of electric machines and power electronics are currently still high. However, Toyota Prius Prime has a power-split transmission with ICE OWC: There is an OWC located at ICE output shaft (Figure 2 (a)) [16, 17, 18]. When an increase in power is required in EV mode: the MG1 will be on, the ICE shaft will tend to rotate backward, and the OWC will be triggered (ICE shaft will be locked). The PG will lose one DOF, so that all motors are able to propel the car in pure electric mode, and the FPG in this situation is equivalent to Figure 2 (b). All MGs can be utilized in EV mode; which was also one of the focuses of this study.

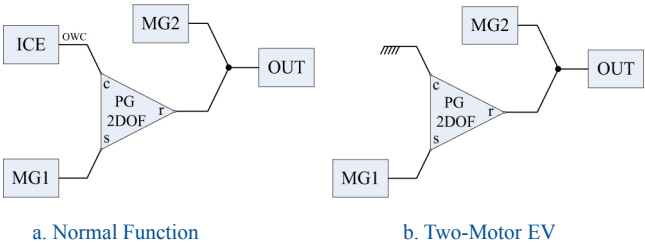


Figure 2. Power-split hybrid transmission with ICE OWC (a) Normal Function (b) Two-Motor EV

Compared to single-PG GM Voltec GEN 1 [7], GEN 2 is a dual-PG hybrid transmission [4] (Figure 3 and Table 6). This is a sophisticated hybrid transmission that can be switched between one parallel configuration, two power-split configurations and two EV configurations, FPG standardized the expression of system units and make the system structure, or connecting relation between each unit, clearer.

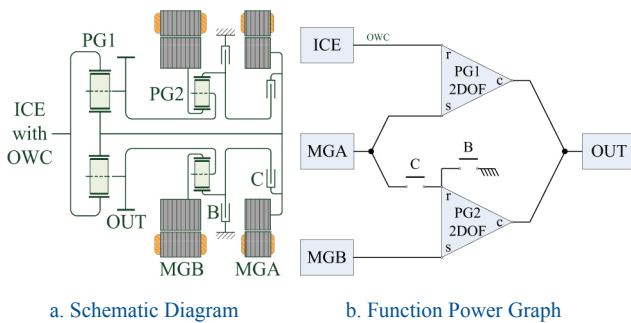


Figure 3. GM Volt GEN 2

Table 6. Clutch States and modes of operation of Volt GEN 2

Clutches Engaged

B	C	OWC	Modes of Operation
•			One-motor EV
•		•	Two-motor EV
•			Low Extended Range (Power-split)
•	•		Fixed Ratio Extended Range (Parallel)
	•		High Extended Range (Power-split)

DESIGN REQUIREMENTS

After reviewing the current hybrid transmissions above, the targets of this study are identified. This study is aimed to develop a hybrid transmission mechanism with the following configurations:

1. One-Motor EV
2. Two-Motor EV
3. Power-Split
4. Series
5. Parallel I
6. Parallel II

These six configurations above are demonstrated with six FPGs in the following sections. The new proposed transmission mechanism should meet each of these FPGs.

One-Motor EV Configuration

This configuration was used at light loads with only MG2 to propel the vehicle. The requirement for this configuration is shown in Figure 4. The box drawn with a dotted line is the transmission mechanism that needs to be determined. In one-motor EV, no element needs to be in the box. Since power-split is one of the requirements needed to be met, power-split is selected as the framework or template. All other configurations are reconfigured based on power-split.

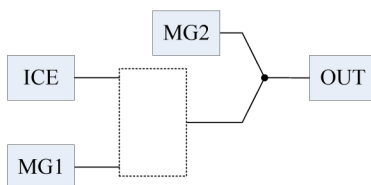


Figure 4. FPG requirement for one-motor EV configuration

Two-Motor EV Configuration

Some HEVs with two MGs such as Toyota Prius 4, Honda Accord Hybrid MY2014, can only utilize one of their two MGs in their pure electric modes, even though the production cost of electric machinery and power electronics is still high. Currently, in pure EV mode, one of the MG's has to be large enough to deal with peak power demand. To utilize all MGs in EV mode (such as Toyota Prius Prime and Chevrolet Volt MY2016), two-motor configuration was included in this study. When more power is needed, MG1 should be allowed to propel the vehicle. This requirement is noted in Figure 5. The blue lines with arrows indicate the power flow paths required to satisfy the configuration. To prevent engine drag, ICE can be disconnected or braked in this EV configuration.

To achieve two-motor EV and other configurations, a different power flow path should be arranged in different configurations. To switch between different configurations, clutches can be used in FPG. However, to limit complexity of the mechanism, the clutches used in creating solutions for each configuration should be no more than two.

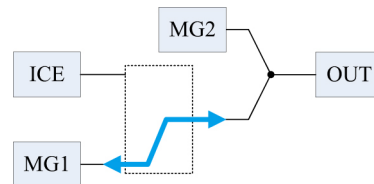


Figure 5. FPG requirement for two-motor EV configuration

Power-Split Configuration

As mentioned before, power-split was selected as the main framework. Regular input-split configuration has been widely used in THS and Ford HF35, and it is also adopted in this study, shown in Figure 6. Power-split allows ICE to work at the desired speed [3, 15], and allows the speed ratio to vary continuously without pulleys or belts required, but MG1 needs to work as a generator or motor to regulate the speed.

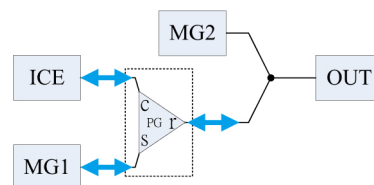


Figure 6. FPG requirement for power-split configuration

Series Configuration

When battery SOC is low, series configuration is an option. Though other configurations, such as power-split and parallel are also possible. In a series configuration, the engine is fully decoupled from the wheels and the engine speed can be controlled independently of vehicle speed. This not only simplifies the control of the engine, but most importantly, allows the engine to operate at specified operating torque and speed to achieve better efficiency [2]. The series configuration was included in this study and shown in Figure 7.

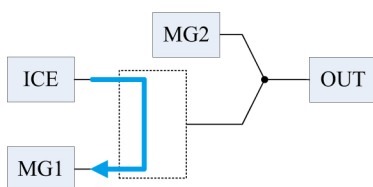


Figure 7. FPG requirement for series configuration

Parallel Configuration I

Parallel configuration I was proposed to provide a direct drive option for exerting all power from ICE and MG1 during low vehicle speed. In power-split configuration, due to the characteristics of planetary gear, torque from ICE and torque from MG1 interact with each other. This configuration was included in this study to provide a simple way, without a complicated control strategy, for a heavy-duty scenario. Denoted by Figure 8, the speed ratio ($\omega_{ICE} / \omega_{OUT}$) should be high to enhance accelerating ability in low vehicle speed.

It is not necessary to switch directly between Parallel Configuration I & II. Using other configurations, such as power-split, as a middle ground can allow for a big difference between the speed ratios of Parallel Configuration I & II.

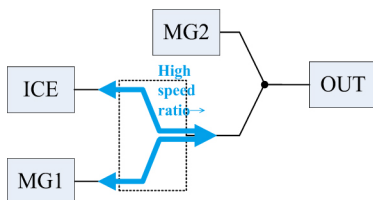


Figure 8. FPG requirement for Parallel Configuration I

Parallel Configuration II

This configuration was proposed to provide a direct drive option for highway cruising. Compared to the power-split and series, the energy conversion loss during electricity generation or power electronics conversion is avoided, and both the GM Voltec GEN 2 and Honda iMMD have adopted this strategy to deliver better fuel economy at cruising speeds [4, 6, 10]. Figure 9 displays this configuration. In this figure, MG2 is available. It could be used for regenerative braking and acceleration. MG1 is not indispensable, but if MG1 is available in a parallel solution, the solution is considered preferable.

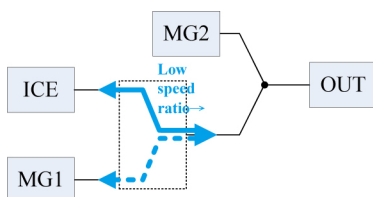


Figure 9. FPG requirement for Parallel Configuration II

This configuration shall be equipped with an extra low speed ratio ($\omega_{ICE} / \omega_{OUT}$) to permit ICE to work in the low speed region. For example, if vehicle speed of 100km/h corresponds to ICE speed of

2000rpm, 34hp is available in this time. Then ICE speed is only 1000rpm at 50km/h, and only 14hp is available. So “Parallel Configuration II” was not suitable for substituting “Parallel Configuration I”

Vehicle Information

A powertrain can be mounted on a vehicle to demonstrate its performance. A hypothetical vehicle was set up to cooperate with the transmission mechanism developed in this study. It mainly refers to the publicly available information about Toyota Prius Prime [3, 16, 17, 18]; the information of this hypothetical vehicle is listed in Table 7 and Figure 10. The ICE used in this study is based on the publicly available information of 2ZR-FXE [19]—the ICE that was used in Prius until 2015—because the publicly available information of the latest partially modified ESTEC 2ZR-FXE engine [20] is still insufficient for simulation. MG1 and MG2 are assumed ideal. MG1 has constant torque before 5491 rpm and constant power after 5491 rpm; MG2 has constant torque before 3105 rpm and constant power after 3105 rpm.

Table 7. Hypothetical vehicle specification

Weight (with driver)		(1510+65) kgw
Wheel base		2700 mm
Weight distribution		60% front : 40% rear
Drivetrain		Front-wheel drive
Cd		0.25
Frontal area		2.07 m ²
Rolling resistance coefficient		0.01
Effective wheel radius		0.302 m
Coefficient of road adhesion μ		0.85
Planetary gear ratio ρ		30T (Sun) / 78T (Ring) = 0.3846
Final drive ratio i_f		3.476
ICE	Type	1.8 L gasoline engine
	Maximum power	73 kW @ 5200 rpm
	Maximum torque	142 Nm @ 4000 rpm
	Maximum speed	5200 rpm
MG1	Maximum power	23 kW
	Maximum torque	40 Nm
	Maximum speed	11000 rpm
MG2	Maximum power	53 kW
	Maximum torque	163 Nm
	Maximum speed	17000 rpm
MG2 reduction ratio i_2		3.117
MG1+MG2 maximum power (Battery discharge limit)		68 kW
Battery capacity		8.8 kWh