

Methodology for Assessment of Alternative Hybrid Electric Vehicle Powertrain System Architectures

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ABSTRACT

Hybrid electric vehicle (HEV) systems offer significant improvements in vehicle fuel economy and reductions in vehicle generated greenhouse gas emissions. The widely accepted power-split HEV system configuration couples together an internal combustion engine with two electric machines (a motor and a generator) through a planetary gear set. This paper describes a methodology for analysis and optimization of alternative HEV power-split configurations defined by alternative connections between power sources and transaxle. The alternative configurations are identified by a matrix of kinematic equations for connected power sources. Based on the universal kinematic matrix, a generic method for automatically formulating dynamic models is developed. Screening and optimization of alternative configurations involves verification of a set of design requirements which reflect: vehicle continuous operation, e.g. grade test; and vehicle dynamic operation such as acceleration and drivability. Only the former are considered in this paper. The method automatically defines a design parameter space for each configuration which eventually would allow configuration evaluation and optimization, e.g. sizing of power sources or optimization of transaxle gear ratios.

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INTRODUCTION

The power-split hybrid electric vehicle propulsion system (Figure 1) uses a planetary gear set (PGS) as a device to split the engine power into two power delivery paths to the wheels, one mechanical path via a set of gears (see gears N_3 , N_2 , N_4 , N_5 in Figure 1), and an electrical path via a generator which transfers electrical power to a traction motor. The mechanical power generated by the electrical traction motor is then transmitted to the wheels via another set of gears (N_1 , N_2 , N_4 and N_5 in Figure 1) that are meshed to the final drive unit and wheels. This configuration allows for pure mechanical, combined mechanical-electrical and pure electrical propulsion.

The power-split system shown in Figure 1 is implemented in Toyota and Ford HEV vehicles. In this configuration, the engine is connected to the PGS carrier, an electric machine referred to as the generator is connected to the PGS sun gear, and the PGS ring gear and second electric machine (referred to as the motor) are connected to the wheels. In this paper we present a methodology that allows assessment of all possible connections of the PGS to the three power source devices, namely, the engine, the motor and the generator. Figure 2 shows all possible connections in a single PGS HEV system.

Each alternative is called a "configuration" or "architecture" in this paper.

This analysis is motivated by the need to understand how alternative configurations impact electric machine speed, torque and power operating requirements and to identify configurations that offer inherent advantages over others relative to vehicle level performance requirements. The approach allows cascade of vehicle requirements to the engine and the two electric machines. The requirement cascade is based on a rigorous mathematical derivation of the equations that describe the kinematics and dynamics of the powertrain. Using the kinematic and dynamic formulations, selected vehicle performance requirements are translated into torque, speed and power requirements for the electric machines. Sensitivity to gear ratios is also captured allowing further optimization of the HEV propulsion system.

The use of clutches has been excluded in this analysis. It is also assumed that one of the electric machines, referred to as the motor, is always connected to the wheels in order to enable full regenerative braking and full electric drive capabilities.

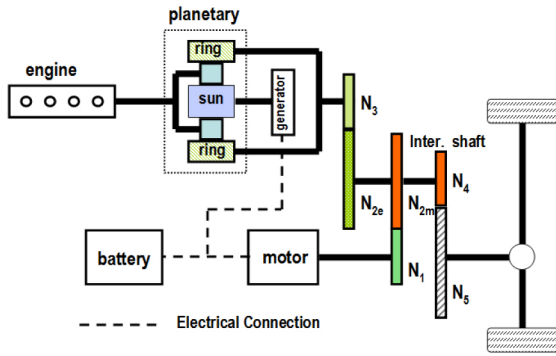


Figure 1. HEV vehicle power-split configuration

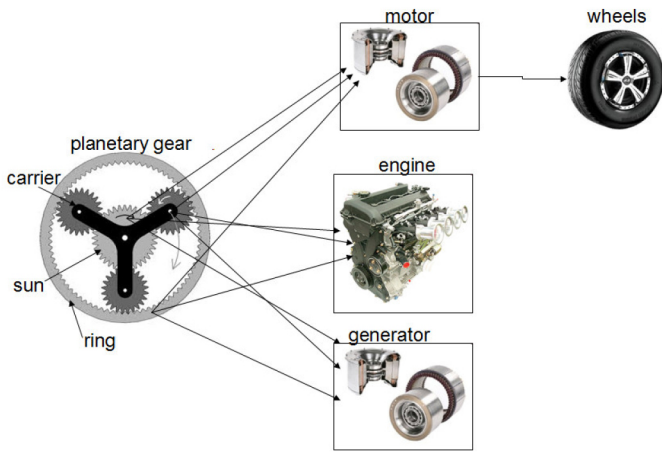


Figure 2. Connectivity alternatives between the planetary gear set and the power source devices, i.e., engine, motor and generator.

Previous frameworks have been proposed and applied to the analysis of alternative power-split hybrid configurations, but with distinct differences to the present work. In [1], a generic dynamic model formulation is derived for common hybrid powertrain configurations by enabling or disabling the presence of electric machines and by enabling or disabling a second planetary gear set or power-split device. The electric machine connection to the power-split device is fixed, with the engine connected to the PGS ring and the PGS carrier connected to the wheels. The paper also presents a chain of optimization tools for hybrid vehicle energy management based on dynamic models and offline and online optimization schemes.

In [2], a model-based analysis and control optimization of power-split HEV systems is addressed. A universal framework is presented for modeling power-split systems covering all possible connections between gear nodes and power sources. Based on this approach, a methodology that automatically generates dynamic models was developed which also enabled the screening of feasible configurations.

There are numerous other publications [3,4,5,6,7,8,9,10,11,12,13] devoted to the different aspects of modeling, analysis, design and control optimization of the

power-split HEV propulsion systems shown in Figure 1. The approach described in the current paper is unique in its look at potential configurations relative to vehicle operating requirements. The focus is on the analysis of power-split configurations for a single planetary gear set. It is based on an analytical formulation of the kinematic and dynamic equations for all possible combinations of engine and electric machine connections. A permutation study of all possible configurations is used to down-select feasible arrangements. These feasible arrangements are analyzed with respect to given vehicle performance requirements.

A unique aspect of this work is that the electric machines (motor and generator) are treated as black box devices without pre-defined characteristics. Vehicle performance requirements are used to define the operating requirements for the electric machines for all feasible architectures. This approach enables design optimization of components and power-split gear ratios for a given configuration and set of vehicle level requirements. The 2010 MY Ford Fusion HEV architecture (Figure 1) is used as a baseline for comparison.

The body of this paper is divided into two main parts. In the first part we derive a set of kinematic and dynamic equations that describe all possible configurations of the power-split planetary gear set connected to two electric machines and an engine. In the second part, we formulate an approach for using vehicle requirements to define electric machine operating envelopes by performing kinematic and dynamic analysis based on system models.

KINEMATIC EQUATIONS

The kinematic relation between speeds in the planetary gear set (PGS) is described by equation (1.1) [14]:

$$\omega_r = (1 + \rho)\omega_c - \rho\omega_s \quad (1.1)$$

Where $\rho = \frac{R_s}{R_r}$ is the ratio ρ between the sun radius R_s and the ring radius R_r .

Equation (1.1) can be rewritten in one of the forms:

$$\omega_r = G_{rc}\omega_c + G_{rs}\omega_s, \text{ where } G_{rc} = (1 + \rho) \text{ and } G_{rs} = -\rho \quad (1.2a)$$

$$\omega_s = G_{sc}\omega_c + G_{sr}\omega_r, \text{ where } G_{sc} = \frac{1 + \rho}{\rho} \text{ and } G_{sr} = \frac{1}{G_{rs}} \quad (1.2b)$$

$$\omega_c = G_{cr}\omega_r + G_{cs}\omega_s, \text{ where } G_{cr} = \frac{1}{G_{rc}} \text{ and } G_{cs} = \frac{1}{G_{sc}} \quad (1.2c)$$

It is assumed that the traction motor is connected to the wheels with the ratio G_{mw}

$$\omega_m = G_{mw} \omega_w, \quad (1.3)$$

The three power sources (motor, engine and generator) can be connected to the planetary gear in six different ways. The kinematic ratio matrix G_{xp} , for each of the configuration defines the relations between the speeds of the power sources and the planetary gear set as follows

$$\omega_x = G_{xp} \omega_p, \quad x = \{m, e, g\}, \quad p = \{r, c, s\}, \quad \text{with } G_{xp} = \frac{1}{G_{px}} \quad (1.4)$$

where $\{m, e, g\}$ refers to the traction motor, engine and generator, respectively, while $\{r, c, s\}$ refers to the ring, carrier and sun gears, respectively. Equations (1.2) show that G_{xp} values may be negative.

Next, a connectivity matrix L_{xyz} of size (3×3) is introduced to characterize how the power sources are connected to the planetary gear set. The subscript of the connectivity matrix is made of a code of three consecutive letters xyz , selected from the set $\{“M”, “E”, “G”\}$ which denotes “M”=motor + wheels, “E” = engine, and “G” = generator. The first letter in the subscript corresponds to the connection to the PGS ring; the second letter in the subscript corresponds to the connection to the PGS carrier; and the third letter in the subscript corresponds to the PGS sun.

There are six possible configurations which correspond to the six connectivity matrices below

$$\begin{aligned} L_{MEG} &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}; L_{MGE} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}; L_{EMG} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ L_{EGM} &= \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}; L_{GME} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}; L_{GEM} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix}; \end{aligned} \quad (1.5)$$

Note that the power-split configuration of the Toyota Prius and Ford Fusion HEV is defined by the connectivity matrix L_{MEG} .

DYNAMIC MODEL FORMULATION

In this section a generic dynamic model is formulated which describes the operation of all six power-split configurations defined by (1.4)-(1.5). The equations are obtained in analytical form by using Lagrange's formalism [15]:

$$\frac{d}{dt} \frac{\partial K}{\partial \dot{q}} - \frac{\partial K}{\partial q} = Q \quad (2.1)$$

where K is the kinetic energy of the system, q is the vector of generalized coordinates and Q is the vector of generalized forces (torques). The reader is reminded that neither power losses nor electric power are included in the analysis.

We now select the motor and engine speeds as two independent variables in the dynamic equations, i.e.:

$$\dot{q} = [\omega_m, \omega_e]^T \quad (2.2)$$

The kinetic energy is calculated as

$$K = \frac{1}{2} (J_m^* + \frac{J_v}{G_{mw}^2}) \omega_m^2 + \frac{1}{2} J_e^* \omega_e^2 + \frac{1}{2} J_g^* (G_{gm} \omega_m + G_{ge} \omega_e)^2 \quad (2.3)$$

where J_m^* , J_e^* , J_g^* are the effective rotational inertias of the motor, engine and generator, respectively; and $J_v = m_v r_{tire}^2$ is the inertia of the vehicle as a function of the vehicle mass m_v and the tire radius r_{tire} . Computation of the inertia vector $J^* = \{J_m^*, J_e^*, J_g^*\}^T$ is done via the connectivity matrices in (1.5) in the following way

$$J^* = \begin{Bmatrix} J_m^* \\ J_e^* \\ J_g^* \end{Bmatrix} = \begin{Bmatrix} J_m \\ J_e \\ J_g \end{Bmatrix} + L_{xyz} \begin{Bmatrix} \frac{J_r}{G_{xr}^2} \\ \frac{J_c}{G_{yr}^2} \\ \frac{J_s}{G_{zr}^2} \end{Bmatrix} \quad (2.4)$$

where J_m , J_e , J_g are inertias of the motor, engine, and generator, respectively; J_s , J_c , J_r are inertias of the sun, carrier, and ring, respectively; J_m includes the inertia of the traction motor and effective inertia of all gears connecting the motor to the wheels.

The coefficients G_{gm} and G_{ge} are defined by the planetary gear ratios (1.3) and the configuration connectivity matrix (1.5).

Equations (2.1), (2.2) (2.3), (2.4) yield

$$A \dot{a} = Q = T \quad (2.5)$$

The (2×2) effective inertia matrix A equals