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Probabilistic analysis of energy exchange processes for automotive hybrid powertrain

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ABSTRACT

In this paper a statistical method for establishing the minimum energy reservoir needed for a hybrid-electric vehicle (HEV) is proposed. This method is based on real world data and investigates the statistical properties of the charge and discharge events for a variety of driving profiles. The distribution of the magnitude of discharge and charge events was found to be exponentially distributed. Using an exponential distribution assumption, the probability distribution for the energy stored in the battery was calculated. This distribution is a function of only two parameters, the average discharge energy (μ_d), and the ratio of the average discharge energy to the average charge energy(ζ). These parameters are functions of the drive profiles of interest and the power-level of the HEV power supply. Based on this, a strategy HEV battery capacity and the power-level of the primary power supply was proposed. This strategy is of particular importance for fuel cell based HEVs because the cost of the fuel cell stack directly scales with the power level.

1. Introduction

The traditional engineering design approach is to design a system that meets requirements derived from a set of worst case scenarios. In design of hybrid vehicles there is an additional complexity added by determination of the degree of hybridization required (power ratio between primary source and energy reservoir) [1,2]. Such designs most often follow a "90-10 rule"—90% of the requirements can be met by a design that requires 10% of the resources, satisfying the last 10% of the requirements then uses the remaining 90% of the resources. Building in these performance reserves, while necessary in most cases, adds cost into the systems. Therefore, in setting system requirements it warrants asking *"How likely is this limiting requirement occurs? How much can we save if we accept a small probability of violating this requirement?"* This is an approach commonly used in robust design.

In this paper we present a robust design methodology that encompasses statistical aspects of the system requirements for battery sizing in automotive hybrid powertrains. Although not all automotive requirements can be compromised, some performance attributes do offer a potential of large savings with minor compromises in performance. The method described here relates to sizing of an energy reservoir which is depleted through a random process and cannot be filled above a certain level. It will be demonstrated through an example of sizing hybrid powertrains (ICE[1] or fuel cell [3–8]) for automotive applications.

2. Problem statement, definitions and assumptions

For this analysis a simplified hybrid powertrain is assumed [7,9,10], shown in Fig. 1, that consists of a primary power source (internal combustion engine shown in Fig. 1(a)[10] or fuel cell shown in Fig. 1(b)[8]), an energy storage device (most likely a hybrid battery [11]) and a drivetrain (such as described in Ref. [12]). The power needed by the drivetrain to propel the vehicle is either generated by the primary source, or comes from the energy storage device, or some combination of those two. Several studies explored this energy flow as optimization process with goal of improved efficiency and fuel economy [13–15], while others focused on improvements in efficiency and fuel economy of the primary power source operation [16,17]. Unlike the optimization presented in [18] no battery chemistry nor demographic driver data were considered here. The question that we wish to answer is: *Given a distribution of driving scenarios, as the power required as a function of time, what must be the capacity of the battery to meet a specified fraction of the demand?* Furthermore, we can ask *how the capacity must change with the changes in the power rating of the primary power source?*

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[1] ICE: Internal Combustion Engine.

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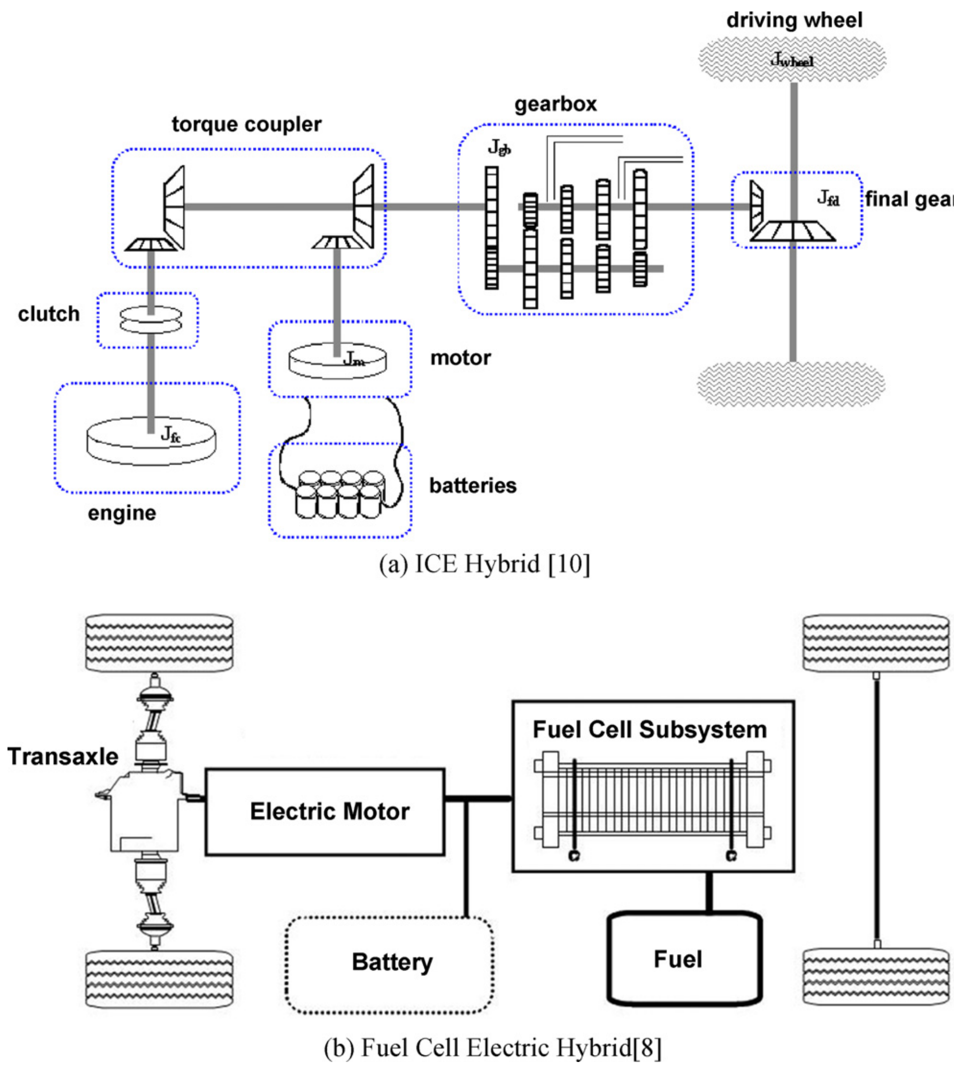

Fig. 1. Simplified hybrid powertrain architecture.

In order to answer these questions, several statistical variables were introduced (graphically explained in Fig. 3):

T_{above}— time above the threshold, $P(t) > P_H$

T_{below}— time below the threshold, $P(t) < P_H$

$$E_{above} = \int_{T_{above}} [P(t) - P_H]\,dt - \text{energy above } P_H$$

$$E_{below} = \int_{T_{below}} P(t)dt - \text{energy below } P_H$$

$$E_{fill} = \int_{T_{below}} [P_H - P(t)]\,dt - \text{energy available to charge}$$

where $P(t)$ is power required at time t, and P_H is the maximum power of the primary power source.

Conventional wisdom dictates that the power rating of the primary source has to be greater than the maximum power required by the vehicle. Questioning this approach the following sizing strategy questions were posed: *How small can the primary power source be made without changing the energy storage capacity required? If the primary source maximum power is P_H, how much energy would the energy storage device need to provide and for how long? Can*

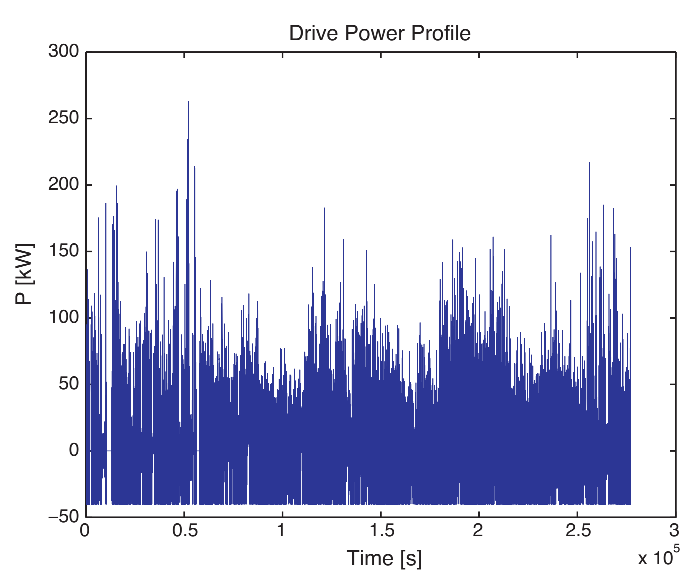

Fig. 2. Overall drive power profile.