

Frequency Domain Power Distribution Strategy for Series Hybrid Electric Vehicles

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ABSTRACT

Electrification and hybridization have great potential for improving fuel economy and reducing visual signature or soot emissions in military vehicles. Specific challenges related to military applications include severe duty cycles, large and uncertain energy flows through the system and high thermal loads. A novel supervisory control strategy is proposed to simultaneously mitigate severe engine transients and to reduce high electric current in the battery without oversizing the battery. The described objectives are accomplished by splitting the propulsion power demand through filtering in the frequency domain. The engine covers only low frequency power demand profile while the battery covers high frequency components. In the proposed strategy, the separation filter is systematically designed to identify different frequency components with the consideration of fuel consumption, aggressive engine transients, and battery electric loads. The proposed strategy is implemented into the series HEV simulation framework to assess its effectiveness under various driving cycles. The results show that the proposed power distribution strategy dramatically reduces battery current peaks and aggressive engine transients while maintaining the fuel economy to a competitive level. Longer battery life under the proposed strategy compared to the baseline thermostatic SOC control is explicitly evaluated through cumulative fatigue/damage analysis. The proposed strategy provides more flexibility in HEV design/optimization and enables battery downsizing, due to the extended battery safety margin and the reduced severity of engine transients.

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INTRODUCTION

High oil prices and strict emissions regulation in the transportation sector are the driving forces for automotive manufacturers to develop fuel-efficient and clean vehicles. Vehicle hybridization, one of the promising technologies for improved fuel economy and tailpipe emissions, has been extensively studied and successfully deployed on passenger vehicles. In the case of heavy-duty military vehicles, driving patterns and maneuvers are significantly different from those of passenger vehicles. Thus, the objectives of vehicle hybridization include logistics and tactical issues as well as fuel economy improvement. Interactions in the system and component duty cycles are characterized by very high energy flows. Recently, most studies on hybridization of heavy-duty and military vehicles were focused on fuel economy improvement [1, 2]. Hydraulic systems have been dominantly applied to propel heavy weight due to high specific power and competitive efficiency of pump/motors and the accumulators [3,4,5,6]. However, the low energy capacity of the storage is one of the drawbacks of the hybrid hydraulic system, and a desire to electrify accessories and allow on-

board power generation provides an additional impetus for developing an HEV concept.

Vehicle electrification is an attractive option for military vehicle hybridization due to its capability of silent operation and potential for on-board power generation. Electrification broadens the availability of electronic devices on-board. In addition, a series HEV configuration with hub motors provides unprecedented freedom in the design of the hull for blast protection. The improved technologies for high traction electric motor and high specific power Lithium ion (Li-ion) battery are enablers of the electrification of military vehicles capable of satisfying severe performance targets. The design and modeling of High Mobility Multipurpose Wheeled Vehicle (HMMWV) with series hybrid electric configuration were studied in [7, 8]. However, constraints related to dynamic responses of power sources or battery health issues were not included. In particular, frequent and high current operations in a heavy vehicle reduce the Li-ion battery life span, and hence battery power requires careful management [9]. There is a risk of Li-ion battery fire or explosion due to thermal runaway when operating in extreme conditions such

as high temperature and overcharging/discharging [10]. Hence, avoiding these undesirable operations is directly connected to mission completeness and survivability, and requires novel approaches to HEV supervisory control development.

Many supervisory control strategies for series hybrid vehicles have been proposed in the literature [6, 11,12,13,14,15,16,17,18]. The primary task of supervisory control strategy is to determine the power flows between the engine and the battery to minimize cost function such as fuel consumption. In case of a series architecture the focus is on operation of the power generation sub-system and charge sustaining strategy. The rule-based strategies, such as the Thermostatic SOC control analyzed by Hochgraf et al. [12] are simple and suitable for real-time applications [12, 13]. Optimized strategies developed with dynamic programming algorithm were developed for series hydraulic hybrids and demonstrated very significant benefits [14]. In the context of series HEV for a passenger car, Konev et al. [16] considered SOC regulation based on the power-split approach for modulation of spark-ignition engine power and smoothing of transients. However, survey of literature and a recent study of the HEV power management using a detailed electro-chemistry based battery model indicate extreme battery loads in HEV military applications [25]. Therefore, battery lifespan or battery health has to be included in the supervisory controller development, and we extend the idea of the power distribution in frequency domain to take account of fast and slow dynamics and protect the battery. More specifically, the frequency domain power distribution (FDPD) strategy manages power flow by splitting power demand into low and high frequency components through a signal processing and achieves: 1) reduced battery electric loads, 2) smooth engine transient; and 3) reduced fuel consumption. In this paper, a low-pass filter is used because of filtering performance in spite of simplicity. A low-pass filter is systematically designed to optimize the performance of the FDPD strategy. Alleviated engine transients will reduce soot emissions and correspondingly narrow ranges of battery current and voltage responses will prolong the battery life. The battery life is assessed explicitly through cumulative damage prediction method along with counting algorithm under realistic driving conditions [19,20,21].

This paper is organized as follows: First, the simulation framework for a series HEV is presented. Then, the FDPD strategy is described. A low pass filter is designed for frequency decomposition along with analysis of components responses under real-world driving conditions. Next, an approach to estimate battery damage is explained in detail. Vehicle simulation results show the effectiveness of the proposed strategy, and this paper ends with summary and conclusions.

SERIES HEV SIMULATION MODEL

A series HEV model is constructed to predict vehicle behavior under real-world driving condition with a good balance of computational time and prediction accuracy. The specification of the series HEV which is studied in this paper is summarized in Table 1. It is based on the publically available data for the Mine resistant Ambush Protected All-Terrain Vehicle. The model consists of an engine, a generator, motors, a battery, a power bus, and a supervisory controller as illustrated in Fig. 1. The engine drives the generator for converting mechanical power into electrical power. The electrical power is used for operating electric motors or for charging the battery. Electrical power flows among the generator, the battery and electric motors are managed by the supervisory controller through the power bus.

Table 1. Heavy-duty Series-HEV Specification: Hybridized M-ATV

Component	Specification
Vehicle	Hybridized Mine Resistant Ambush Protected All Terrain Vehicle (M-ATV)
Weight	13,740 kg
Payload	1,814 kg (4000 lbs)
Frontal area	5.72 m ² (Width/Height: 2.49/2.70 m)
Engine	I6 Turbo-diesel engine: 330 kW
Generator	Permanent Magnet: 330 kW
Battery	Li-ion 5.0 kWh
Motors	Permanent Magnet: 4*300 kW

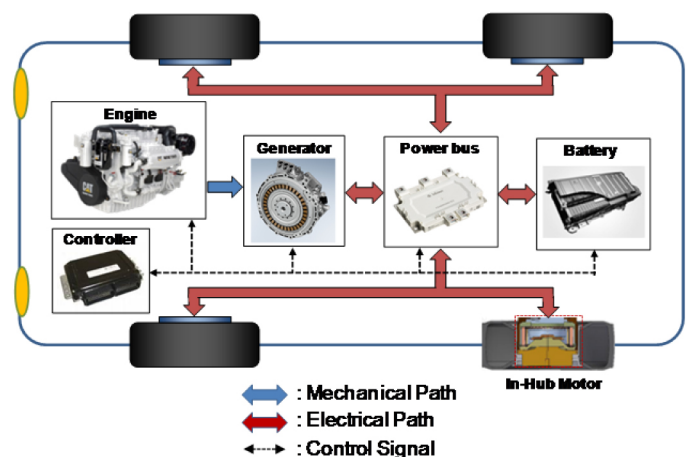


Figure 1. Series hybrid configuration

Figure 2 shows a series HEV simulation framework configured in Matlab/Simulink with a forward-looking scheme. This framework is employed to develop a supervisory control strategy and to assess fuel economy improvement and behavior of powertrain components under realistic driving conditions. The driver generates a control signal such as acceleration or braking pedal position to follow

desired driving cycle, and this control signal is interpreted as vehicle propulsion or braking power demand. The supervisory controller appropriately assigns power demands to the engine and the battery for operating motors.

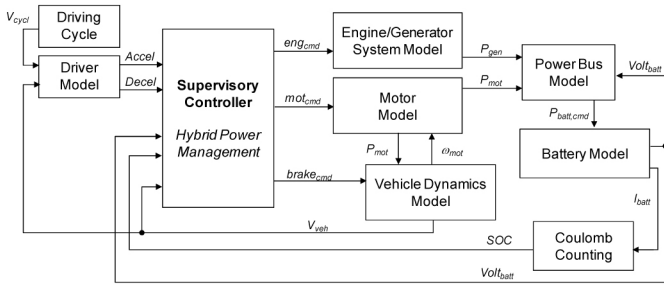


Figure 2. Simulation frame work for the series hybrid electric vehicle

Engine

The engine model in the simulation is a map-based model augmented by a fuel controller sub-model emulating turbocharger lag during transients. The engine torque is expressed as a function of the engine speed ω_{eng} and the fueling rate $\dot{m}$. The engine is assumed to be fully warmed up, and the fueling rate is adjusted with the consideration of turbocharger dynamics [6].

In the series HEV configuration, the engine is mechanically connected to the generator. The speed of the two systems are set to same and calculated from the rotor dynamics with the combined rotational inertia $J_{eng/gen}$:

$$J_{eng/gen} \frac{d\omega_{eng/gen}}{dt} = T_{eng} - T_{gen} , \quad (1)$$

where $\omega_{eng/gen}$ is the speed of engine/generator unit, and T_{eng} and T_{gen} are the engine torque and the generator torque, respectively.

Motor/Generator

The motor and the generator are modeled using quasi-steady state efficiency maps since their dynamics are much faster than vehicle dynamics. The efficiency of the electric machine (EM) η_{EM} is expressed as a function of electrical power P_{elec} (or torque T_{EM}) and speed ω_{EM} :

$$P_{mech} = P_{elec} \cdot \eta_{EM} , \quad (2)$$

and

$$\eta_{EM} = \eta_{EM}(\omega_{EM}, T_{EM}) , \quad (3)$$

or

$$\eta_{EM} = \eta_{EM}(\omega_{EM}, P_{elec}) , \quad (4)$$

where P_{mech} is mechanical power. Maximum output torque of the motor T_{max} is governed between the continuous torque curve and the peak torque curve accounting for the heat index α as follows:

$$T_{max} = T_{cont} \cdot \alpha + T_{peak} \cdot (1 - \alpha) , \quad (5)$$

$$\alpha = -0.3 - \int \frac{0.3}{\tau} \left(\frac{T_{EM}}{T_{cont}} \right) dt , \quad (6)$$

where T_{peak} and T_{cont} are the peak and continuous torque respectively, and these torques are a function of the motor speed. The heat index varies from zero to one and is used to emulate the change in the torque limit based on motor temperature. The time constant, τ , of 180 seconds is selected [22].

Battery

The battery is modeled using an equivalent circuit approach due to its fast computation. The equivalent circuit model can predict the battery state of charge (SOC) accurate enough to be used in developing a model-based supervisory controller. The open circuit voltage V_{oc} and internal resistance during discharging and charging R_{int} are a function of battery SOC. The battery SOC is calculated based on coulomb counting:

$$\dot{SOC} = -\frac{I}{Q} , \quad (7)$$

where I and Q are current and battery capacity respectively. The battery terminal voltage is calculated by subtracting the voltage drop due to the internal resistance from the open circuit voltage. Maximum discharging and charging power limit can be obtained by the following equations.

$$P_{max, dch} = V_{min} \cdot I_{max} = V_{min} \frac{(V_{oc} - V_{min})}{R_{int, dch}} , \quad (8)$$

$$P_{max, chg} = V_{max} \cdot I_{min} = V_{max} \frac{(V_{max} - V_{oc})}{R_{int, chg}} , \quad (9)$$

where I_{min} and I_{max} are the minimum and maximum available current respectively, V_{max} and V_{min} are the manufacturer specified voltage limits, which in this study are 2.7 V and 3.9 V respectively. The battery is assumed to operate around the desired temperature. Positive sign denotes battery discharging for sign convention.

Vehicle

The longitudinal dynamics of the vehicle is calculated as follows:

$$M_v \frac{dv_{veh}}{dt} = F_{prop} - F_{RR} - F_{WR} - F_{GR} - F_{brake} , \quad (10)$$

where M_v and v_{veh} are the mass and velocity of the vehicle respectively, F_{prop} is the propulsion force, and F_{RR} is the rolling resistance force expressed by

$$F_{RR} = f_r M_v g \cos \theta , \quad (11)$$

where f_r is rolling resistance and θ is the road grade. The wind resistance force is

$$F_{WR} = \frac{1}{2} \rho_{air} C_d A v_{veh}^2 , \quad (12)$$

where ρ_{air} is the air density, C_d is the drag coefficient, and A is frontal area of the vehicle. The grade resistance force, $F_{GR} = M_v g \sin \theta$, is set to zero in the driving cycles in this study.

SUPERVISORY CONTROL STRATEGY

The series HEV configuration, with the engine decoupled from the wheels, can take advantage of the flexibility in controlling engine operation and effective regeneration. However, inherent multiple energy conversions decreases total system efficiency. Furthermore, a battery needs to be operated within the allowable voltage range during very aggressive driving conditions leading to high peak currents. Therefore, a supervisory control design is important for the series HEV development to improve fuel economy while reducing engine emissions and to ensure safe battery operations.

The primary task of supervisory control strategy is determining power flows between the engine and the battery to minimize fuel consumption and emissions. The driver's power demand as well as other constraints should be satisfied. Previous studies of series hybrid electric vehicles employed a heuristic control technique, thermostatic SOC control strategy, since this strategy is advantageous due to the ease of implementation, the effectiveness of SOC regulation, and the improvement of fuel economy [12, 18, 23]. The thermostatic SOC control strategy, considered as a baseline strategy, is a rule-based in that the engine operates to charge the battery or to assist power demand. As it can be seen from Fig. 3, as long as current SOC is higher than the target SOC, the engine provides zero power. The engine starts charging the battery with the predetermined power level when SOC drops to the target SOC. The dead band is implemented to

prevent frequent engine on/off's. When power demand for the vehicle propulsion is higher than the battery discharging power limit, the engine operates in power assisting mode. Table 2 summarizes design parameters such as maximum power, threshold power, maximum power SOC, target SOC, and deadband.

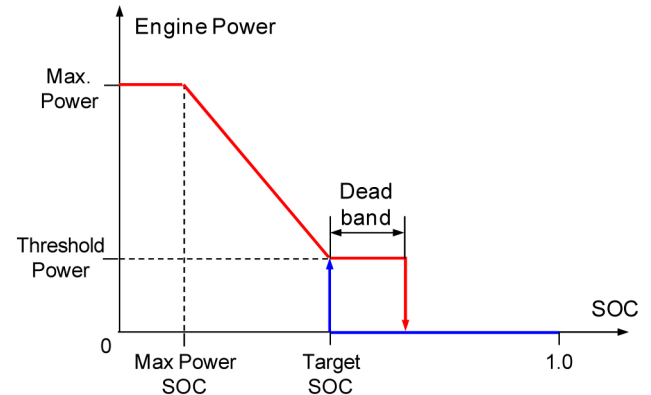


Figure 3. The schematic of the thermostatic SOC control strategy

Table 2. Values of parameters of thermostatic controller

Parameter	Value
Target SOC	0.4
Deadband	0.04
Max. Power SOC	0.05
Max. Power	330 kW
Threshold Power	140 kW

However, the thermostatic SOC strategy has drawbacks due to its operation characteristics. When the SOC low threshold is reached the engine operation changes aggressively from zero power demand to enable battery charging. This behavior is significantly harmful for tailpipe emissions, as shown by Hagena et al. in [23, 24]. Sudden engine ramp up leads to significant spikes of particulate emissions [23]. Furthermore, this strategy prefers using the battery power to the engine/generator power, leading to multiple power conversion. More importantly, It was found that the Lithium-ion concentration at the surface of solid particles at electrodes can be depleted when high peak currents are drawn from the battery under aggressive conditions, possibly leading to battery degradation through over-discharging [25]. Based on lessons from previous works, it is necessary to develop a novel power blending strategy with capability of resolving those drawbacks of the baseline strategy.

FREQUENCY DOMAIN POWER DISTRIBUTION (FDPD) STRATEGY

Separation of power demand in frequency domain provides tailored control inputs to each power source