

Powerpack Optimal Design Methodology with Embedded Configuration Benchmarking

Andrej Ivanco
Clemson-ICAR

Kan Zhou and Heath Hofmann
University of Michigan

Zoran S. Filipi
Clemson-ICAR

ABSTRACT

Design of military vehicle needs to meet often conflicting requirements such as high mobility, excellent fuel efficiency and survivability, with acceptable cost. In order to reduce the development cost, time and associated risk, as many of the design questions as possible need to be addressed with advanced simulation tools. This paper describes a methodology to design a fuel efficient powerpack unit for a series hybrid electric military vehicle, with emphasis on the e-machine design. The proposed methodology builds on previously published Finite element based analysis to capture basic design features of the generator with three variables, and couples it with a model reduction technique to rapidly re-design the generator with desired fidelity. The generator is mated to an off the shelf engine to form a powerpack, which is subsequently evaluated over a representative military drive cycles. An iterative procedure is developed, in which the optimization of the supervisory controller is embedded into the design optimization framework. Therefore, for every combination of design parameters the Dynamic Programming routine develops a benchmark control for minimum fuel consumption. This ensures realistic numbers for every function call, and convergence on a true optimum. Results can then guide the development of the new generator for a selected production engine and SHEV configuration.

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INTRODUCTION

Mobility, fuel efficiency, survivability and affordability are the primary objectives for military vehicle design. In this context the modeling and simulation approach is essential for developing a feasible and cost effective solution for new military. Many options can be screened, and viable designs can be fully developed and evaluated prior to building an expensive prototype. This paper demonstrates and validates a methodology for designing efficient powertrains. In particular, we develop a powerpack design for a series hybrid electric military vehicle (SHEV). The methodology is used to find the optimum engine-generator configuration providing the lowest fuel consumption, while ensuring safe operation and meeting the performance requirements of aggressive military drive cycles. Due to limited production volumes of military vehicles, and excessive cost of developing a completely new Heavy Duty (HD) diesel engine, an off-the-shelf commercial engine is typically selected as the starting point. However, it is unlikely that an electric machine from standard production line will be a perfect match for a selected diesel engine. Furthermore, tailoring of the performance characteristics of emachines is commonly done through relatively small modifications of the base design. Profitability is possible with much lower

production volumes than in case of the HD diesel engine. Therefore, a viable strategy for maximizing the fuel economy while keeping the cost in check is to optimize the design of the generator coupled to an off-the-shelf engine based on the vehicle system requirements. The outcome will be used as input in negotiations with a supplier specializing in electric machines.

The powerpack (engine coupled to a generator) is the primary energy source for SHEV vehicle propulsion. It provides the necessary electrical energy to balance the battery state of charge and power the auxiliaries. The powerpack is mechanically decoupled from the wheels; therefore electricity generation can be controlled independently from the vehicle power demand. The battery pack acts as an energy buffer to store or release the excess of available or demanded energy. This provides an additional degree of freedom in orchestrating the powertrain operation.

Due to this complexity of the powertrain, finding the best design requires application of an optimization algorithm. Relying on engineering intuition is not sufficient given the number of parameters and complex interdependencies in the system. Several design

optimization techniques have been previously applied. In [1] the Particle swarm optimization was used to find the pareto set characterizing tradeoff between the degree of powertrain hybridization and the cost of the powertrain. The computational effectiveness was proven feasible, but the objective function did not include acceleration performance. In [2] the vehicle performance was included into multiobjective optimization using the Genetic Algorithm (GA). Optimization runs were setup on a distributed system for faster computations, and the authors were able to produce the Pareto front of the vehicle dynamic performance and fuel consumption. In order to further increase the computational speed, the convex optimizations method can be used [3]. This approach promises more than tenfold improvements, but problem convexity is a necessary precondition. The design optimization problem becomes even more challenging when a range of customer drive cycles are considered [4].

Finally, an additional degree of complexity is introduced through the interdependence of SHEV system design and supervisory control. The performance of any given hardware depends on the control strategy, and the strategy may need to be adjusted in case of a significant hardware change.

Therefore, pursuing an optimization of a complex HEV system necessitates a balance of the following: (i) predictive, and yet computationally efficient, component models, (ii) optimization framework capable of handling a complex system and considering the interdependence of design and control variables, and (iii) definition of constraints that ensures real-world applicability of results. Based on these premises, we propose a design optimization framework with an embedded loop for optimizing the supervisory control during every evaluation of the cost function. A physics-based electric generator model is incorporated in the SHEV simulation, real-world duty cycle is used to evaluate fuel economy, and every candidate design is checked for feasibility before assessing convergence.

Genetic algorithm is utilized for optimizing generator design parameters. The generator design modifications are based on the Finite Element Analysis (FEA) model. Therefore, a physics based efficiency map is constructed for every new combination of the (i) number of turns, (ii) dimensional scale and (iii) number of poles. Subsequent benchmarking of the configuration is pursued by an embedded Dynamic Programming (DP) [5]. The fuel consumption number for a given configuration is determined over a complete driving cycle and reported back to the GA. Applying the DP determines the best way to operate a given powerpack configuration while maintaining charge sustaining behavior, thus ensuring a fair comparison of different designs. In other words, for every perturbation of the powerpack design a benchmark is achieved by optimizing the control strategy as well. The overall design objective is to minimize the fuel consumption.

The paper starts with the description of the SHEV powertrain configuration. The physics based FAE modeling approach for the generator design is outlined next. The core part of the paper presents the design framework optimization methodology, with embedded controller benchmarking. The paper concludes with result and discussion of the powerpack design outcomes.

VEHICLE MODEL

Vehicle Configuration

The vehicle configuration used in this study is a Series Hybrid Electric Vehicle (SHEV), Figure 1. This architecture offers several advantages. As there is no driveshaft between the powerpack and individual wheels, it offers flexibility in vehicle hull design. All four in-wheel motors can be operated independently which offers an unprecedented maneuverability. There is also a larger battery pack enabling vehicle silent operation. In addition, the electrical power generated on-board can be used for auxiliaries or exported when the vehicle is parked. All of the considered notional vehicle parameters are summarized in Table 1.

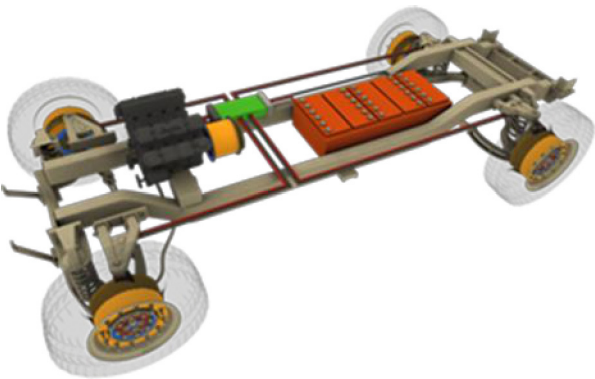


Figure 1. SHEV configuration

Table 1. Notional vehicle parameters

Vehicle weight	14 ton
In wheel motor power	4x128 kW [9]
Powerpack output	~250 kW electrical
Battery pack	9 kWh

The general advantage of the SHEV configuration is that the powerpack’s power output can be operated independently from the power demand on wheels. This offers twofold benefits. The powerpack can be completely shut down during the low power demand. Also, the powerpack does not need to be designed for maximum load, since the battery pack can provide additional power during instantaneous peak requests. Finally, the engine and generator in the powerpack can be operated along its best combined efficiency line.

Vehicle Simulation Environment

The goal of this paper is to demonstrate the optimized design methodology based on application of the Genetic Algorithm and an embedded control optimization algorithm. The powerpack design is optimized to minimize the fuel consumption while fulfilling the power demands of the aggressive drive cycle. For this case study, the engine design is fixed, and the generator design is modified using a physics based FEA simulation and a model reduction technique [6, 7]. This enables a fast execution of the design iterations while keeping a very good model fidelity. A fast-executable, backward facing [8] longitudinal vehicle model is used to evaluate the vehicle fuel consumption over the military drive cycle. The baseline engine efficiency map (Figure 2) represents a 2.5 kW, 10L V8 diesel engine