

Experimental Assessments of Parallel Hybrid Medium-Duty Truck

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ABSTRACT

Fuel consumption reduction on medium-duty tactical truck has and continues to be a significant initiative for the U.S. Army. The Crankshaft-Integrated-Starter-Generator (C-ISG) is one of the parallel hybrid propulsions to improve the fuel economy. The C-ISG configuration is attractive because one electric machine can be used to propel the vehicle, to start the engine, and to be function as a generator. The C-ISG has been implemented in one M1083A1 5-ton tactical cargo truck. This paper presents the experimental assessments of the C-ISG hybrid truck characteristics. The experimental assessments include all electric range for on- and off-road mission cycles and fuel consumption for the high voltage battery charging. Stationary tests related to the charging profile of the battery pack and the silent watch time duration is also conducted.

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INTRODUCTION

The U.S. Government owns and maintains a large fleet of ground vehicles covering a wide spectrum of mission profiles. The cost to supply each vehicle with fuel during peacetime is staggering and becomes more so under war zone conditions. The fuel represents more than half of the logistics tonnage of the Department of Defense (DoD), and more than 70% of the tonnage required to put the U.S. Army into position for battle [1]. The DoD estimates that 40,000 Army personnel involved in either the distribution or movement of energy [2]. Not to mention only two out of the top ten battlefield fuel consumers in the U.S. Army are combat vehicles and the other eight carry fuel and supplies. Over half of the fuel transported to the battlefield is consumed by support vehicles, not vehicles engaged in frontline combat [3]. The impact of the vehicle fuel economy in military applications is amplified due to the fact that much of the present logistics support is devoted to moving fuel [4]. It is critical to reduce fuel consumption of those vehicles that play an important role in the U.S. Army tactical vehicle fleet.

While hybrid technology has advanced radically over the past decade, the focus has been on integration in passenger cars and light-duty trucks. However, recent fuel cost increases have shifted some of this attention to the medium- and heavy-duty truck market. Hybrid vehicles use dual energy sources propulsion system in which energy is used more efficiently than in conventional powertrains. A standard propulsion system has four primary components: (1) The internal combustion engine

(ICE) to supply power for the other vehicle systems; (2) The transmission to control the speed ratio and the level of torque multiplication between the engine and the final drive; (3) The final drive and drive axle assembly to multiply transmission output torque and transfer power to the wheel assembly; (4) The tire and wheel assembly that transfers power from the axle assembly to the ground. To electrifying a vehicle propulsion system, electric machines must be connected somewhere in the power flow. Based on the ratio of electric power to total power of a vehicle, the degree of powertrain hybridization is typically classified into two levels: mild and full (strong) hybrids. The strong hybrid systems enables fuel economy improvements by: (1) Allowing the ICE to be turned off when idling or during periods of low power output - two highly inefficient stages of typical ICE operation; (2) Recapturing waste energy through regenerative braking which can be stored for later use; (3) Providing electric-only driving; (4) Supplying assist during varying power demand.

The Crankshaft-Integrated-Starter-Generator (C-ISG) system replaces the conventional starter motor and alternator with a larger electric machine located between the engine flywheel and transmission. A C-ISG system typically utilizes conventional transmissions with significant packaging changes to accommodate the increased envelope of the electric machine [5, 6]. The electric machine in the C-ISG system may be packaged around torque converter (using a ring type motor) such as [7], or between the engine and the transmission where the torque converter is removed, such as Honda IMA system

[8,9,10]. The C-ISG systems can be changed from mild to strong hybridization by adding starter clutch and increasing the power rating of the electric machine and the corresponding battery capacity, such as [11, 12]. The strong C-ISG configuration is attractive because one electric machine can be used to propel the vehicle, to start the engine, and to be function as generator. Figure 1 shows a layout of typical strong C-ISG hybrid powertrain. An electric machine is connected to the transmission input shaft and takes advantage of the torque multiplication of the transmission. The engine is connected to the drivetrain via a starting clutch. The vehicle may be launched with the motor only where the starting clutch is disengaged and the engine may be turned off or left idling. If the engine participates in the launch, the starting clutch will slip until the transmission input shaft is synchronized with the engine speed. During deceleration, the electric machine regenerates braking energy to the battery. The engine may be disconnected from the transmission for maximum regeneration or it may be left connected for ease of control.

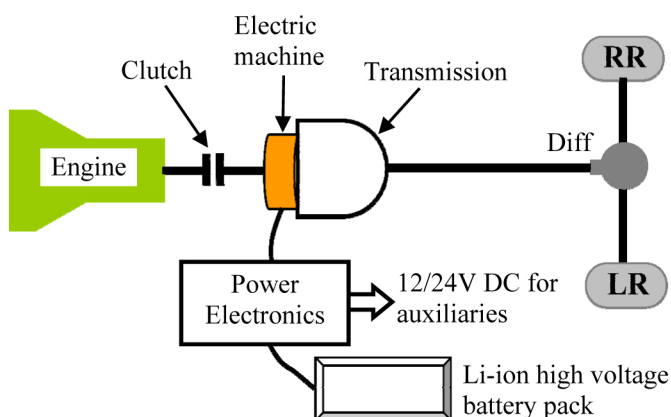
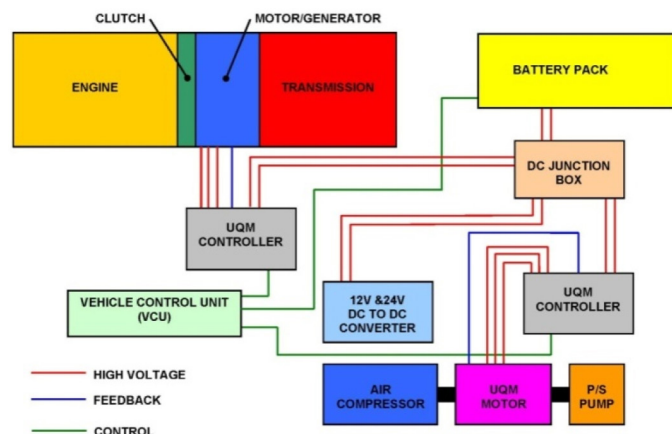


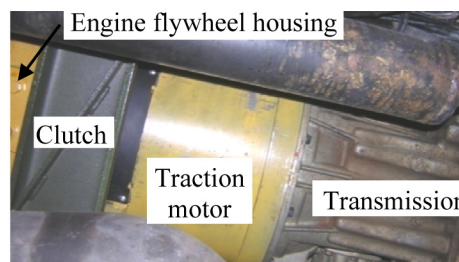
Figure 1. A typical layout of strong C-ISG hybrid powertrain

The C-ISG hybrid powertrain has been implemented in one M1083A1, a 5-ton Family of Medium Tactical Vehicles (FMTV) cargo truck [13]. The prototype-built truck is a parallel hybrid system incorporating a clutch between the engine and the electric drive motor as shown in Fig. 2(a) and 2(b). The drive motor is the UQM SMG-333-77-2 motor/generator (330 Nm peak torque, 125kW peak and 45kW continuous power) as shown in Fig. 3(a) [14]. The clutch allows the engine to be disconnected from the downstream drivetrain to provide electric-only propulsion. This electric-only propulsion is limited by the drive motor power (performance limit) and the energy capacity of the high voltage battery pack (range limit). Figure 3(b) shows the SAFT-HEMV7 Li-ion high voltage battery pack (30Ah capacity, 307V nominal voltage, 138 kW pear power, and 74 kW continuous power at 50% State Of Charge-SOC) [15] and mounted in the bed of the truck. Power electronics devices and low voltage battery compartment is shown in Fig. 3(c). This prototype-built hybrid truck still has the 12/24V low voltage battery pack consisting of four lead-acid batteries in series/parallel connections.

This paper presents the experimental assessments of the C-ISG hybrid truck characteristics that are the operational features of the hybrid. The characteristics assessments include All Electric Range (AER) for on- and off-road mission cycles and fuel consumption for battery charging. Stationary tests related to the charging profile of the high voltage battery pack and the silent watch time duration is also conducted. The experimental tests do not specify performance criteria or threshold values other than give component thresholds because the purposes for the tests are to obtain data to evaluate the hybrid propulsion system operation. Nevertheless, the threshold is determined by the safe operating range of each component, such as the performance of battery pack is controlled by the battery management system.



a. System control block diagram of C-ISG hybrid powertrain



b. Photo of 5-ton FMTV hybrid truck

Figure 2. Prototype-built C-ISG FMTV hybrid truck

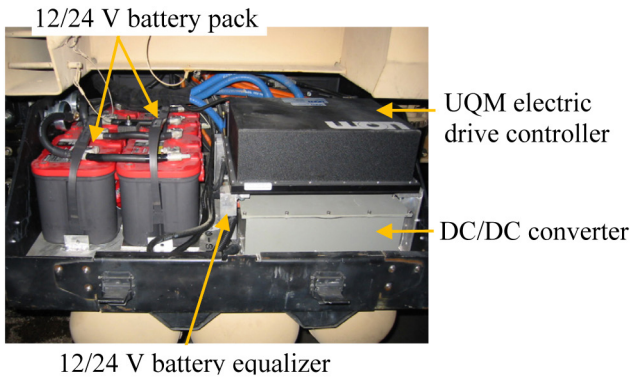


a. UQM 125 kW electric machine

Figure 3. Electric components for propulsion



b. SAFT Li-ion battery pack mounted in the truck bed



c. Electronics and low voltage battery compartment

Figure 3. (cont.) Electric components for propulsion

EXPERIMENTAL ASSESSMENTS SETUP

The purpose of this experimental investigation is to evaluate performance characteristics of the C-ISG hybrid truck. Testing procedures are based upon selected HEV America Baseline Test Sequence [16], SAE [17], and EERE [18] to obtain the required data. When appropriate the vehicle was ballasted to (Gross Vehicle Weight) GVW with weight distribution per standard vehicle loading guidelines. The road testing took place at the Houghton County Airport runway and taxiway in Houghton, Michigan. The static testing was at the GS Engineering [19]. A minimum of three successive test runs are conducted at each prescribed experiment, and measured data is averaged such that the variations in the measure is taken into account for the analyses.

Data Acquisition System

The test truck is equipped with instrumentation and sensors to capture related data during test events. A Dewetron data acquisition system, voltage and current sensors, and a serial Controller Area Network (CAN) connection is used to capture data from both the electrical system and the truck on-board CAN diagnostics. The analog input data acquisition system uses a sample rate of 10 kHz with a peak frequency expected of approximately 2.5 kHz, associated with the motor commutation. This data is recorded to a file using the Root Mean Square (RMS) calculation of data between points. Data post-processing uses spreadsheet to perform calculations and graph pertinent data. In order to provide the best data comparison, absolute values of end results are used to eliminate data convention issues. For instance, current into a battery would be positive convention, while the current out of a

battery would be negative convention. For silent watch testing, data is compared indicating energy consumed by a load and delivered by the battery. Both values are converted into positive convention for comparison. Sampled voltages and currents based on RMS values of the raw sampled data are used in the data acquisition and post-processing. The RMS is calculated internal to the data acquisition system and uses a standard method shown in Equation 1.

$$X_{RMS} = \sqrt{\frac{1}{n} \sum_{first\ sample}^{last\ sample} X(t)^2} \quad (1)$$

where $X(t)$ is the measured sample value and n is the sample size.

Temperature Dependent Battery Charging Profile Testing

The purpose of this test is to determine the silent watch characteristic of the hybrid propulsion system. Silent watch is a role that requires all mission functions be met while keeping acoustic and infrared signature levels to a minimum. For this reason, silent watch often requires the vehicle to operate without use of the main engine and sometimes even auxiliary engines. The mission requirements in the silent watch might include air condition system, observation equipment, fire control systems, and possibly remote weapon systems.

The test is intended to characterize the viability of using the high voltage battery system to power silent watch type loads. Since typical silent watch loads are operating from the low voltage (12/24Vdc) system, a load bank is installed on the 24V bus of the vehicle. The architecture of the vehicle utilized a DC/DC Switch Mode Power Supply (SMPS) to transform the high-voltage DC bus (ISG bus) to a voltage usable by the low voltage vehicle systems (nominal setting at 27.6Vdc). The series of tests are selected to characterize how the battery is discharged or charged. Specifically, the test is intended to quantify total energy sources and time duration utilizable for silent watch, and available for battery charging. Additionally, the test is designed to show the temperature dependence of the energy quantity available or generated. No performance criteria or pass/fail metrics are set. Available weather conditions are utilized for temperature soaking of the vehicle for cold weather operation testing. The test facility climate control system, auxiliary heaters and a tent over the equipment under test are utilized for temperature soaking of the vehicle to simulate hot weather operations. The vehicle is soaked overnight or over the course of the day to achieve a consistent test point temperature. Each charge test is performed twice at each temperature. The charging is performed using only essential vehicle electrical loads with the engine at low idle speed and the transmission in neutral. Due to the vehicle configuration, no adjustment is available to vary the charging rate. By design of the hybrid system manufacturer, the output of the ISG system is limited to 25A output to the high voltage bus, part of which is used to charge the low voltage batteries.