

Modern Hybrid Systems for Critical Needs

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ABSTRACT

For 70 years Yardney has been a leader in specialty battery and energy systems for military, space, avionics, weapon systems and undersea vehicles. In addition to battery systems, Yardney also delivers hybrid systems for ground, space, undersea and avionic applications. The beauty of hybrid systems, combining energy sources such as batteries, capacitors, fuel cells and solar, is that they can be used to optimize energy and power density, and with proper design, the systems can also lead to longevity of components and an overall cost savings. For ground applications, utilization of hybrid systems can assist in conservation of fuel by making vehicle applications more efficient. For space applications, satisfying pulses can be improved by a capacitor and battery hybrid energy storage system. To optimize aircraft performance and decrease operating costs, avionics are beginning to move towards more electric aircrafts (MEA). This embraces the concept of utilizing electrical power for driving aircraft subsystems currently powered by mechanical means. An important part of this concept is the development and demonstration of a hybrid (battery-capacitor) system of appropriate size and mass that can be shown to stabilize the bus, enhance reliability, fault-tolerance, and power density. For these needs, Yardney has developed models, delivered systems and continues working on new applications.

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INTRODUCTION

For hybrid energy systems consisting of such constituents as fuel cells, batteries, capacitors and solar, fuel cells can provide the most energy of these on a large scale, however, at a smaller scale they come at a cost due to their inefficiencies and bulk. Where batteries can be used as a source of peak load balancing with a fuel cell, a battery can also be coupled with a capacitor, the latter of which now will be used to balance peak loads. Hybrid systems optimization requires balancing based on the energy storage envelope volume, mass, load and application needs.

Ground applications are focused on enhancing fuel economy, or minimizing fuel consumption for power take-off applications. Fuel for the military can come at a premium in dangerous

locations. For instance, according to a story in NDIA Magazine [1], a gallon of fuel costs the Defense Logistical Agency \$2.82 per gallon. Once shipped to a forward-deployed location during peacetime it escalates to \$13 per gallon. The fuel continues getting more expensive based on the area and risk involved for delivery. To reach hostile areas the price can reach \$600 per gallon for "in theatre" delivery. This indicates that every gallon of fuel saved can have profound cost savings for the military, and the recovery cost of hybridizing vehicles for fuel conservation can be quickly met. The hybrid system can include batteries, capacitors, and if adequate exposure to the sun is available, solar is ideal to provide power directly and to charge the on-board energy storage system. Solar can allow the vehicle to remain an electrical hub without running its internal combustion engine.

Yardney has explored utilizing a battery/fuel cell hybrid system for submersible vehicles. In such hybrid systems, a high power, Lithium-ion battery (LiB) could provide backup power, start-up power, and burst power. Limiting the peak load on the fuel cell saves significant mass by allowing it to be designed for peak size and efficiency. The secondary LiB can act as the power source, while the latent but substantial energy from the fuel cell recharges it to sustain an overall most efficient system. A drawback about this approach is that the platform must have a rather large total energy need in order to overcome the inactive weight of the fuel cell.

For space applications, a battery can often be considered an integral part in the lifetime of the craft that it powers. Considering the cost of transporting the vehicle to the location where it will perform its duty is massive compared to the cost of the battery, a hybrid system that lengthens the lifetime of the battery is a major asset. Pulses on a battery to drive things like ion engines can have deleterious effects on the battery, whereas a capacitor has much greater capabilities for pulses, but lacks the energy storage capability of batteries. Therefore synergy is realized by pairing the capacitor with a battery in a space vehicle.

Development of a hybrid power system is seen as a critical enabler for the more electric aircraft (MEA) to unlock significant improvements in terms of aircraft weight, fuel consumption, total life cycle costs, maintainability and aircraft reliability.

What will be discussed herein is Yardney's approach at designing hybrid systems for advanced performance. Examples and data related to tests we have performed on components and systems will be provided.

HYBRID SYSTEMS FOR VARIOUS APPLICATIONS

Various types of hybrid systems will be discussed including solar and battery systems for ground vehicles, space systems that Yardney has addressed with batteries paired with capacitors, a theoretical approach at pairing batteries with fuel cells for undersea applications, and a hybrid system for

avionics that pairs a battery with a Li-ion capacitor for improving energy performance and resilience to temperature extremes.

Ground Applications

The military has various applications requiring power in the field, which can benefit from optimizing fuel consumption for cost savings. Small vehicles, large trucks and trailers can all benefit. It suffices to say "all" applications that run on fossil fuel can benefit from a hybrid system.

Table 1 shows the solar energy generation and fuel savings possible atop a 20 Foot ISO Container at various world locations. Using the solar power generated to replace power from a large diesel engine gen set, annual fuel savings alone can range from over \$500 in Dusseldorf, Germany to over \$1,100 in Dakar, Senegal for one ISO Container assuming \$4/gallon diesel fuel cost. If we assume the power is used at a forward-deployed location during peacetime, those savings are estimated to be between \$1,700-3,700 per year assuming \$13/gallon diesel fuel cost. These savings don't include maintenance or logistical cost savings associated with solar power generation. Solar installed on military vehicles, like a Humvee M1165A1, which has 48 sq. ft. of roof space, can result in similar savings if they replace power from smaller diesel engine gen sets (e.g., 5 kW), which are less efficient than large gen sets. On an actual test vehicle for the Maine Department of Transportation, a Ford F-350 with an eNow solar-powered system has demonstrated annual fuel savings equal to about \$3,500 with gasoline at \$4 per gallon.

eNow designs and sells proprietary renewable solar power systems for the transportation sector, and is currently focused on the commercial trucking industry because of its size. Applications range from 50-watt (W) battery charging systems, to multi-kW auxiliary power units (APUs). These products are designed to reduce fuel and maintenance costs, save energy, and reduce emissions. eNow's solar photovoltaic (PV) panels are mounted on top of a vehicle's roof to capture sunlight and convert it to direct current (DC) electricity. The DC electricity goes to a solar charge controller, which maximizes the power output of the PV panels and then sends the power to an auxiliary energy storage system or load.

Table 1. Savings based on replacing fuel from a large (200 kW) diesel engine generator with an efficiency of 0.0975 gal/kWh.

World Location	Solar Energy Potential		Fuel Savings Potential		
	Daily Average (kWh/day)	Annual Average (kWh/year)	Annual Gallons (gal/year)	Annual Dollars @ \$4/gal (\$/year)	Annual Dollars @ \$13/gal (\$/year)
Dusseldorf, Germany	3.64	1,329	130	\$518	\$1,684
Seoul, S. Korea	5.00	1,825	178	\$712	\$2,313
Tashkent, Uzbekistan	6.53	2,383	232	\$930	\$3,021
Ft. Hood, TX	6.92	2,526	246	\$985	\$3,201
Rio De Janeiro, Brazil	7.08	2,584	252	\$1,008	\$3,275
Perth, Australia	7.75	2,829	276	\$1,103	\$3,585
Dakar, Senegal	8.03	2,931	286	\$1,143	\$3,715



Yardney and eNow developed a model for a no-idle capacitor/battery lift gate system which kept a constant charge by using solar power. Figure 1 shows a truck generator charging the hybrid unit while driving only. This demonstrates that the battery/ capacitor unit can power the lift gate successfully while extending battery and motor life. This lift gate model could also be leveraged for winch operations.

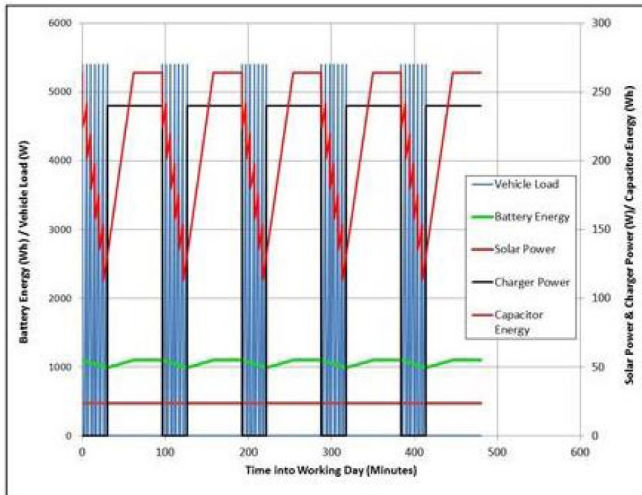


Figure 1. Model of the daily use of a no-idle lift gate running on a hybrid capacitor/battery energy storage unit with solar support.

Space Applications

Several research attempts have been made to understand the performance of ultracapacitors with batteries and fuel cells under specific loads [2,3]. Despite the fact that Li-ion batteries have superior energy density compared to other battery systems, the performance of the Li-ion battery is greatly affected by high current discharges. Li-ion batteries have a high energy density of about 150 Wh/kg, but high energy batteries suffer with a lower power density. This makes batteries attractive for energy support, but batteries are plagued with power fade problems. Ultracapacitors (UCAPs) are not, and as a result the addition of UCAPs in parallel with a battery broadens the utilization of the energy/power storage system [4]. At higher rates of discharge the high power density of UCAPs [5] is more beneficial under pulsed power loads which are frequently encountered in commercial and defense/military communication and mobile systems.

Space missions require battery-based electrical power subsystems that often undergo thousands of charge/discharge cycles and short, high-rate discharge cycles over the length of the mission. This equates to thousands of extra cycles, shortening the useful life of the batteries. Employing UCAPs as a power buffer in the electrical discharge circuit can enable the deployment of payloads and spacecraft bus systems for the high power and short duty cycles without adversely impacting the lifetime of the battery. In recent work, Yardney with Maxwell Technologies successfully demonstrated the efficacy of using

batteries and ultracapacitors in energy applications that require intermittent pulse power. The design involves the use of a DC/DC converter for control of power and energy flow between the battery, ultracapacitors and the load. This work entailed the development of hybrid systems for space applications [6].

A Comparison of Li-ion battery and Ultracapacitors:

- Ultracapacitors are power dense components (>10kW/L)
- Lithium-ion Batteries are energy dense components (~200 Wh/L)
- Ultracapacitors and lithium-ion batteries are complimentary
- Strengths and weakness show advantages to pairing the two.
- Ultracap's reduce power flow stress on the lithium-ion battery
- Improvement of calendar and cycle life
- Reliability and performance at cold temperatures
- Overall safer system

Table 2. Comparison of a Li-ion Energy battery and Ultracapacitors

Attribute	Unit	UCAPs	LiB
Power density	kW/L	10	4
Energy density	Wh/L	6	400
Cold Temperature	°C	<-40	~-20
Hot Temperature	°C	+65	+40
Rate capability	x C	>1800	<40
SOC window	%	100	~50
Efficiency @ 40C	%	→98%	~95%

The NASA Lunar Rover energy cycle includes high current pulses which stress a high energy battery. Based on this, the current battery system is oversized based on the energy requirement to achieve power and maintain the discharge rate below 0.8C for battery life. The new high-energy storage system includes UCAPs, bi-directional DC/DC and a Li-ion battery (LIB), as shown in Figure 2. By introducing UCAPs into the power system, high current pulses accompanying load demands are changed to a steady average current to the battery. The bi-directional converter charges the UCAP from the LIB when the load is light and delivers high current spikes to the load connected to the battery when the load is high.