NASA/TM—2011-217021

A Hybrid Power Management (HPM) Based Vehicle Architecture

Dennis J. Eichenberg
Glenn Research Center, Cleveland, Ohio

July 2011

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Glenn Research Center, Cleveland, Ohio

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Glenn Research Center
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Level of Review: This material has been technically reviewed by technical management.

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A Hybrid Power Management (HPM) Based Vehicle Architecture

Dennis J. Eichenberg
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Summary

Society desires vehicles with reduced fuel consumption and reduced emissions. This presents a challenge and an opportunity for industry and the government. The NASA John H. Glenn Research Center (GRC) has developed a Hybrid Power Management (HPM) based vehicle architecture for space and terrestrial vehicles. GRC's Electrical and Electromagnetics Branch of the Avionics and Electrical Systems Division initiated the HPM Program for the GRC Technology Transfer and Partnership Office. HPM is the innovative integration of diverse, state-of-the-art power devices in an optimal configuration for space and terrestrial applications. The appropriate application and control of the various power devices significantly improves overall system performance and efficiency.

The basic vehicle architecture consists of a primary power source, and possibly other power sources, providing all power to a common energy storage system, which is used to power the drive motors and vehicle accessory systems, as well as provide power as an emergency power system. Each component is independent, permitting it to be optimized for its intended purpose. This flexible vehicle architecture can be applied to all vehicles to considerably improve system efficiency, reliability, safety, security, and performance. This unique vehicle architecture has the potential to alleviate global energy concerns, improve the environment, stimulate the economy, and enable new missions.

Introduction

NASA has a wealth of experience with alternative energy vehicles. This includes electric vehicles, gas turbine powered vehicles, Stirling powered vehicles, and rotary engine powered vehicles.

A battery powered electric vehicle researched by NASA is shown in Figure 1 (Ref. 1). Battery powered electric vehicles have many advantages including the elimination of the need for fossil fuels, and no emissions. Battery life has historically been a severe hindrance for electric vehicles. Range is limited by batteries. Batteries must be replaced after a few hundred charge/discharge cycles. Battery performance is severely affected by cold temperatures. Proper battery charging requires sophisticated electronics. Battery disposal poses a severe environmental concern.

NASA's Lunar Roving Vehicle (LRV) shown in Figure 2 was a battery powered electric vehicle that used primary, non-rechargeable silver-zinc potassium hydroxide batteries for the Apollo program (Ref. 2). The LRV was used successfully on Apollo 15, Apollo 16, and Apollo 17.

A gas turbine vehicle researched by NASA is shown in Figure 3 and Figure 4 (Ref. 3). In this vehicle a gas turbine replaced the conventional internal combustion engine. Gas turbines have many advantages including improved efficiency, significant parts reduction, reduced emissions, high power density, operation from a wide variety of fuels, elimination of a water cooling system, reduced maintenance, and long life. Drawbacks of gas turbines include poor throttling ability, and poor economy when throttled.

Figure 1.—A battery powered electric vehicle researched by NASA in the 1970's.

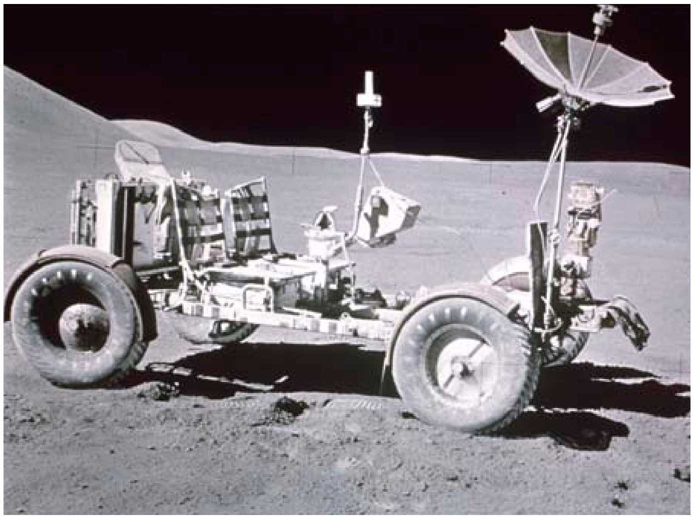

Figure 2.—NASA's Lunar Roving Vehicle was a battery powered electric vehicle used successfully on the Moon in the 1970's.

Figure 3.—A gas turbine vehicle researched by NASA.

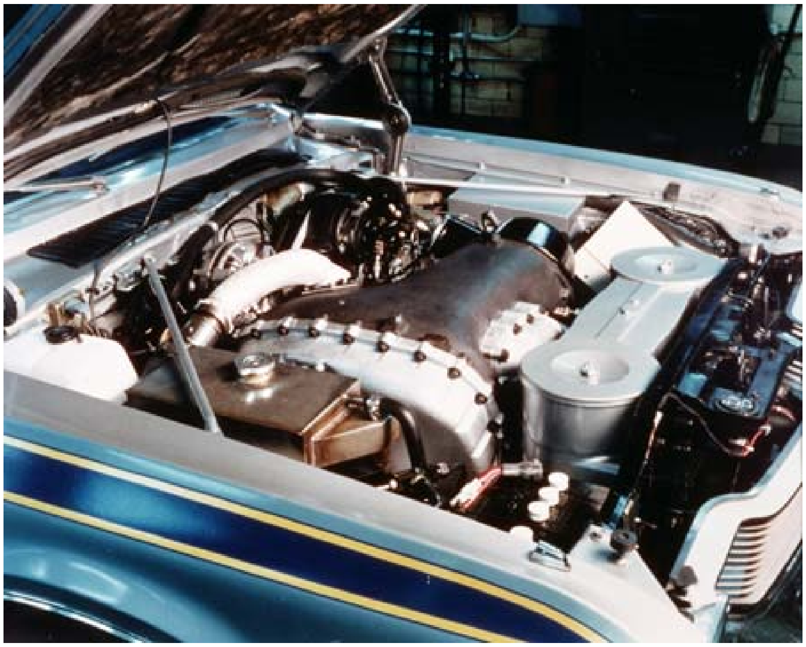

Figure 4.—A gas turbine engine replaced the internal combustion engine in the gas turbine vehicle.

Figure 5.—A Stirling powered vehicle researched by NASA in the 1970's.

Stirling powered vehicles, as shown in Figure 5, were studied by NASA in the 1970's (Ref. 4). A Stirling engine, as shown in Figure 6, replaced the internal combustion engine. Stirling engines provide higher efficiency, lower emissions, operation from a wide variety of fuels, have reduced maintenance, and have long life. Stirling powered vehicles require a warm up time and do not throttle very well.

Rotary, or Wankel, engines, as shown in Figure 7, were studied for vehicle use by NASA in the 1970's (Ref. 5). Advantages of rotary engines include high power density and smooth operation. Disadvantages include complex sealing issues and poor fuel economy.

Figure 6.—A Stirling engine researched by NASA in the 1970’s.

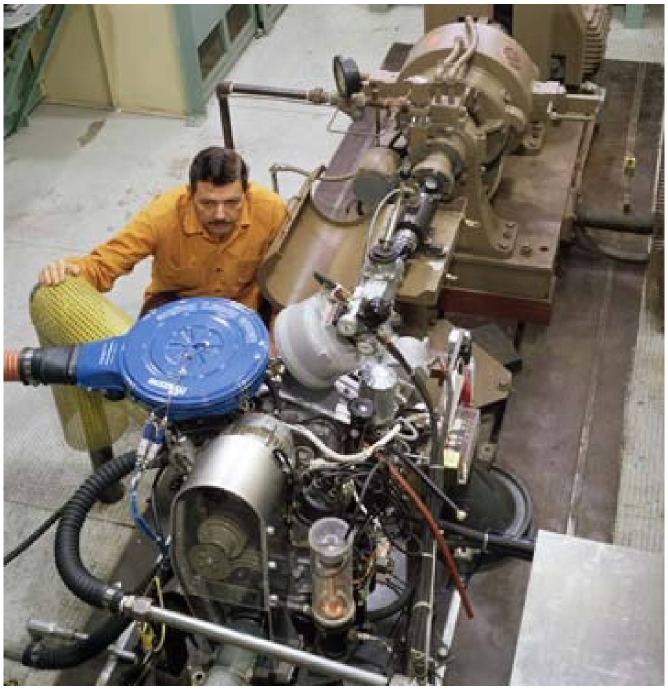

Figure 7.—A rotary engine researched by NASA in the 1970’s.

In the 1990’s NASA GRC developed a hybrid electric transit bus (HETB), as shown in Figure 8 (Ref. 6). This is a 37,000-lb gross weight, 40-ft transit bus which incorporates HPM. The vehicle has many unique features. A natural gas powered internal combustion engine drives an electric generator to charge a bank of ultracapacitors, shown in Figure 9, which delivers power to a variable speed electric motor that drives the rear axle, as well as to the accessories. Ultracapacitors are ideal for this application in that they can repeatedly handle the extremely high charge and discharge currents associated with a heavy hybrid vehicle. The bus uses regenerative braking to improve fuel efficiency. This technology recovers much of the kinetic energy of the vehicle during deceleration. This replenishes the energy storage system each braking cycle and extends the life of the mechanical brakes. The HETB met the Department of Transportation (DOT) White Book acceleration specifications. Fuel economy for a modified Commercial Business District Cycle was 21 percent greater with regenerative braking than without. Ultracapacitors proved to provide significantly better braking performance than batteries. The hybrid configuration provides extended range, improved fuel economy, lower emissions, and higher performance. Disadvantages include greater complexity.

Figure 8.—The NASA Hybrid Electric Transit Bus (HETB).

Figure 9.—The bank of ultracapacitors installed in the NASA Hybrid Electric Transit Bus (HETB).

In the 2000's NASA GRC developed an HPM based fuel cell powered utility vehicle as shown in Figure 10. This is an electric vehicle powered by a proton exchange membrane (PEM) fuel cell, as shown in Figure 11. A bank of ultracapacitors, shown in Figure 12, provides energy storage for the vehicle. The utility vehicle was successfully utilized as an HPM test bed (Refs. 7, 8, and 9). A baseline test was completed with the utility vehicle in its standard commercial configuration with lead acid batteries. It was then tested with power provided only by ultracapacitors, and then tested with fuel cells installed. The fuel cell powered vehicle utilizes two PEM fuel cells, with ultracapacitor energy storage, and metal hydride hydrogen storage. The ultracapacitors act as a buffer to provide the transient power required for the vehicle without damaging the delicate fuel cell membrane. The metal hydride hydrogen storage system stores the hydrogen in a safe controlled manner.

Figure 10.—A fuel cell powered utility vehicle equipped with ultracapacitors.

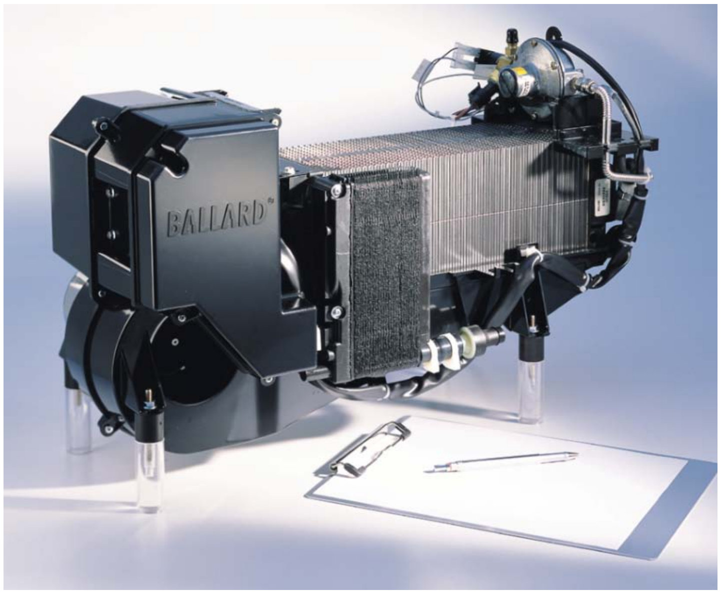

Figure 11.—A proton exchange membrane (PEM) fuel cell powers the utility vehicle.

Figure 12.—A bank of series connected ultracapacitors for the utility vehicle.

Photovoltaic Power Systems

In addition to vehicles, HPM has been successfully applied to photovoltaic power systems (Refs. 10, 11, and 12). Ultracapacitors complement photovoltaic arrays extremely well. The long cycle life and excellent low temperature characteristics of the ultracapacitors complement the characteristics of the photovoltaic arrays, resulting in a higher performance power system.

A stand alone photovoltaic system was developed at NASA GRC, as shown in Figure 13 that incorporates photovoltaic panels, ultracapacitors and a sine wave inverter. The photovoltaic panels are mounted on a passive tracking system to improve system efficiency. The ultracapacitors provide short term energy storage. Tests results indicated a significant performance improvement with the addition of ultracapacitors to the system.

A grid-tied photovoltaic system was also developed at NASA GRC, as shown in Figure 14. The grid-tied system has been an efficient, reliable source of ac power to the GRC utility system.

The HPM based vehicle architecture discussed here is developed from the experience derived from the previous vehicle and power systems.

Objectives

The objective of the HPM based vehicle architecture is to improve vehicle system efficiency, reliability, safety, security, and performance. The flexibility of the vehicle architecture provides opportunities for a very wide range of applications, including space and terrestrial missions.

This effort makes a significant contribution to addressing the national and state interests to reduce fuel consumption and reduce emissions. In addition, this is an excellent opportunity to capitalize on, and transfer technology from the aerospace and military industries to a commercial venture.

Figure 13.—An ultracapacitor backed photovoltaic power system at GRC.

Figure 14.—A grid-tied photovoltaic system installed at GRC.

Discussion

Hybrid Power Management

Peak power requirements of most vehicles are many multiples of their steady state value. This requires a power source large enough to handle the peak power requirement. An excessively large power source reduces system efficiency. The severe nature of transient loads reduces vehicle life and reliability. HPM can significantly improve vehicle efficiency, life, reliability, and performance (Ref. 13).

The unique aspects of HPM are indicated clearly in the HPM system diagram shown in Figure 15. The central feature is the energy storage system, in which an ultracapacitor is an ideal candidate, due to its long cycle life, high reliability, high efficiency, high power density, and excellent low temperature performance. All generated power is sent to the energy storage system, and all loads derive their power from the energy storage system. The system readily accommodates multiple power sources and multiple loads. A hybrid power management controller maintains optimal control over each of the components of the entire system.

Greater understanding of HPM can be achieved through a comparison to the human physiology as indicated in the HPM human analogy diagram shown in Figure 16. The central feature is the energy storage system, which is the stomach in the human case. All generated power is sent to the energy storage system, and all loads (muscles) derive their power from the energy storage system. There can be multiple power sources, each optimized for a particular operating condition. There can be multiple loads as required, each connected to the energy storage system. The brain serves as the hybrid power management controller to maintain optimal control over each of the components of the entire system.

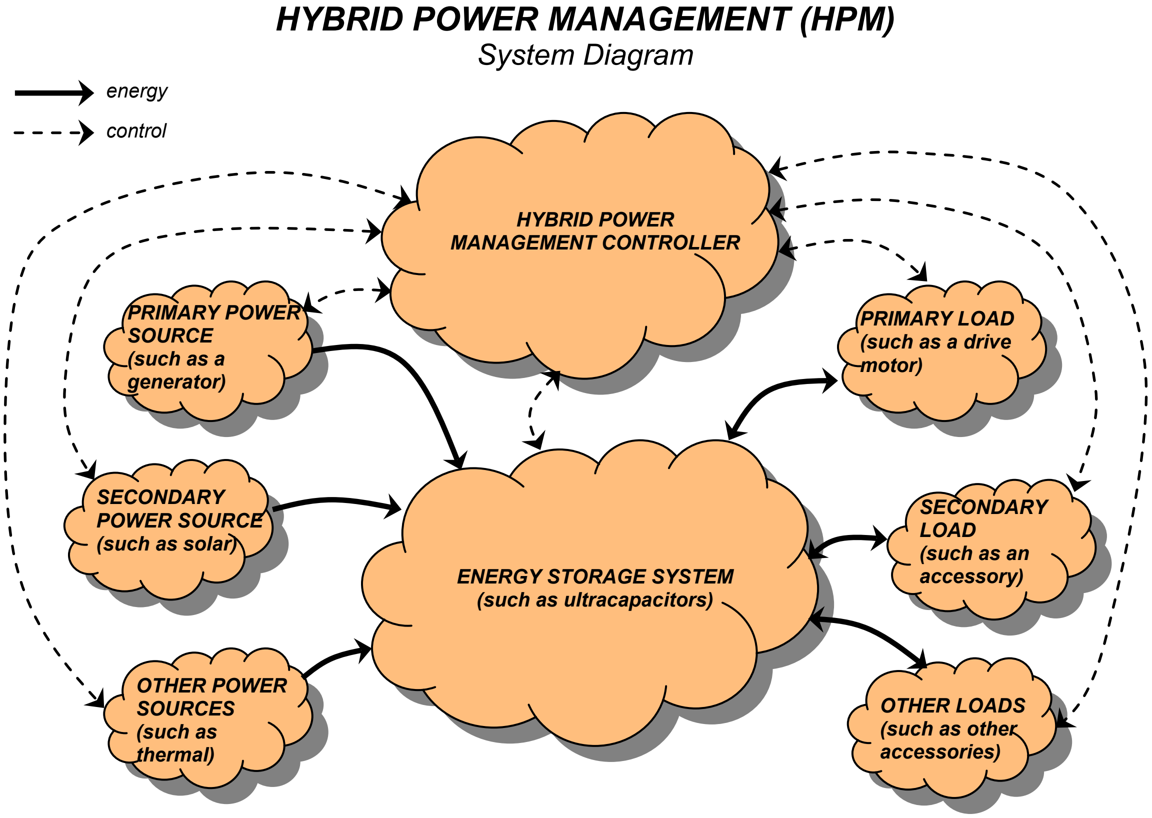

Figure 15.—A system diagram of Hybrid Power Management (HPM).

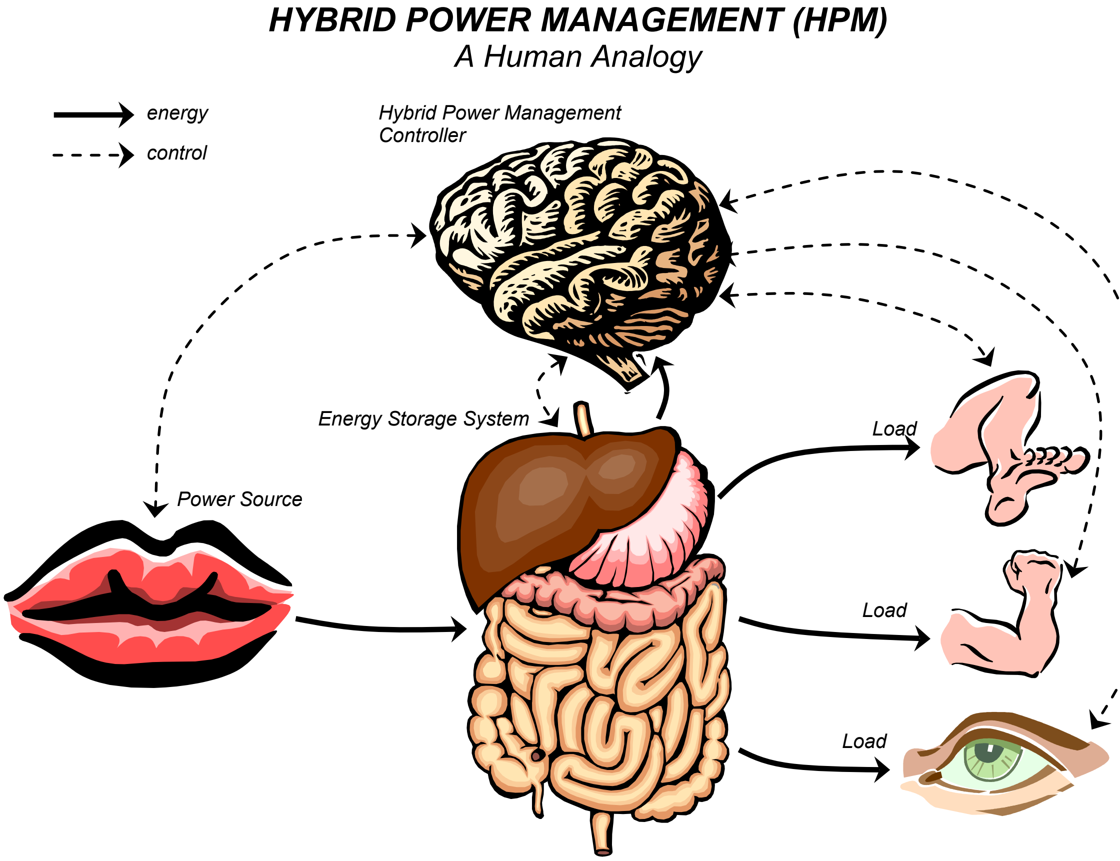

Figure 16.—A human analogy of Hybrid Power Management (HPM).

General HPM Vehicle Architecture

The general HPM vehicle architecture discussed here consists of electric motors for traction drive and regenerative braking, powered by multiple primary power sources, with an energy storage system, and all electric accessories, controlled by an HPM power management controller. This general architecture is shown in Figure 17.

The evolution of power electronics technology has offered the possibility of revolutionary drive trains for vehicles. Electric motors using efficient solid state power devices offer infinitely variable power and speed control. Several of the motors currently being offered by industry have very high power densities and can be controlled to also act as generators. When coupled with onboard energy storage systems, such as batteries, flywheels, or ultracapacitors, this drive train offers several advantages including:

- Improved fuel economy
- Reduced emissions
- Lower noise levels
- Elimination of multiple-gear transmissions
- Elimination of fluid coupling losses
- Near constant speed and load to the primary power source
- Recovery of energy during braking
- Reduced drive train and brake maintenance
- Flexible vehicle configuration for improved vehicle design

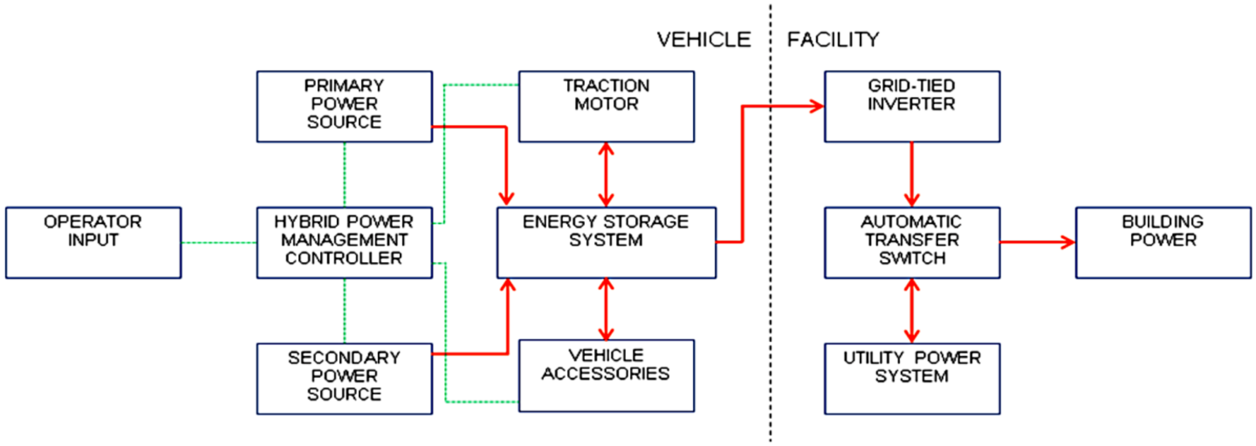

Figure 17.—General HPM vehicle architecture.

Electrical power trains with energy storage uncouple the short-term power requirements of the vehicle from the load seen by the primary power source. Thus the primary power source in such a power train can operate at its highest efficiency design point. In addition, the size of the primary power source can be reduced significantly in some vehicles and drive cycles to the long-term average value of power. Energy storage provides the short term power supplement needed during acceleration and for going up a grade. This reduced power source size, higher efficiency, and constant speed yields significantly improved emissions, fuel economy, and life for the primary power source.

The energy storage system is necessary to provide a smooth power requirement to the primary power source and as a place to absorb the regenerative braking energy. Regenerative braking significantly improves vehicle efficiency, and braking performance, providing consistent braking over time. Regenerative braking can be used to perform complete stops under most driving conditions, which significantly extends mechanical brake life, thus improving safety and reliability, and reducing maintenance costs.

The individually powered electric accessories (such as air conditioning, power steering, and power brakes) eliminate the parasitic loads of the accessories as they are only operated when required. This improves economy and life. This configuration also allows the accessories to be located in the optimum location in the vehicle, rather than a central location.

The HPM vehicle architecture also provides an auxiliary power system for facility power. This is used as an emergency backup power system in the event of a utility power system failure. It can also be used to supplement the utility power system.

The energy storage system allows the vehicle to readily accommodate multiple power sources. Multiple power sources can improve vehicle efficiency, and allows accessories, such as the air conditioning, to be operated when the primary power source is not operating. The additional power sources can also be used for the auxiliary power system.

The HPM power management controller provides control over the entire vehicle power system to maintain optimum efficiency and safety.

Gas Turbine Based HPM Vehicle Architecture

Based upon presently available technology, the gas turbine based HPM vehicle architecture being discussed consists of four or more electric wheel motors for traction drive and regenerative braking, powered by one or more gas turbine generators, along with a photovoltaic power system, and all electric accessories, controlled by a hybrid power management controller. This configuration is shown in Figure 18.

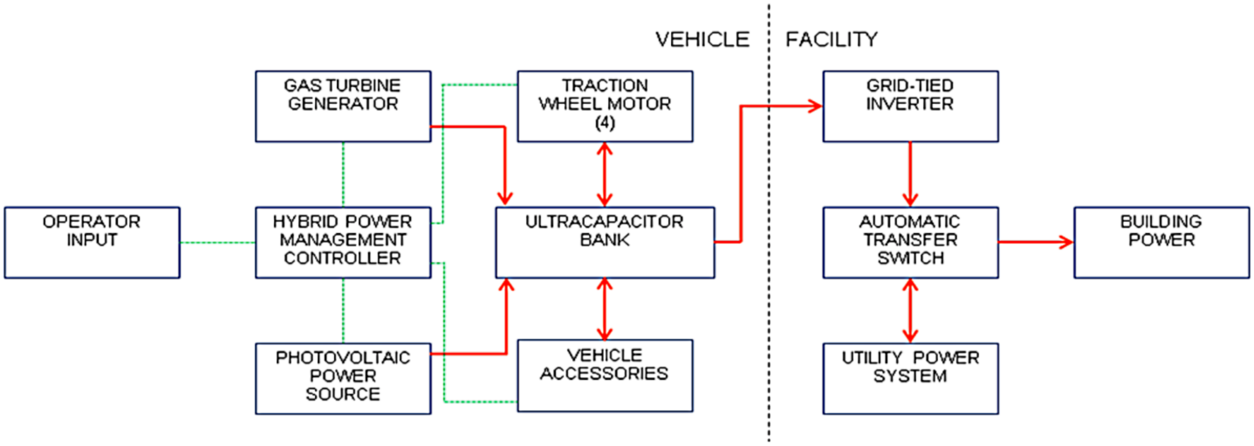

Figure 18.—Gas turbine based HPM vehicle architecture.

This flexible vehicle configuration permits the vehicle layout to be determined by its mission, rather than by its components. The vehicle can be designed for maximum efficiency for its intended application. Parameters such as load carrying capability, maximum acceleration, maximum speed, or maximum traction can be considered.

Traction Motors

Electric wheel motors are optimal for the HPM vehicle architecture. Electric motors produce maximum torque at zero speed, which is ideally suited for vehicle operations. Electric motors provide consistent performance over their life, unlike internal combustion engines whose performance degrades. The motors provide infinitely variable speed control. This eliminates the need for a transmission, which saves weight and cost, and improves efficiency and reliability. Electric wheel motors provide optimal drive and braking characteristics. Any quantities of drive wheels are possible with this technology. This configuration facilitates traction control, anti-skid braking, and yaw control through the dynamic control of the motors. Multiple wheel motors permit the use of tires with decreased aerodynamic drag and rolling resistance. Regenerative braking significantly improves vehicle efficiency, and braking performance, providing consistent braking over time. Regenerative braking can be used to perform complete stops under most driving conditions, which significantly extends mechanical brake life, thus improving safety and reliability, and reducing maintenance costs. Regenerative braking reduces the emission of brake material and heat produced by mechanical brakes. It also significantly reduces the environmental concern from brake disposal. Mechanical brakes must be provided for braking at very low speeds, and as a backup for the regenerative braking in the event of a motor control failure.

Ultracapacitor Energy Storage System

The central feature of HPM is the energy storage system. All generated power is sent to the energy storage system, and all loads derive their power from the energy storage system. An HPM energy storage system must be extremely reliable, have an extensive life, and must have very high efficiency, since all generated power is sent to the energy storage system, and all loads derive their power from the energy storage system. The ultracapacitor is an ideal candidate for an HPM energy storage system. A capacitor is an electrical energy storage device consisting of two or more conducting electrodes separated from one another by an insulating dielectric. An ultracapacitor is an electrochemical energy storage device, which has extremely high volumetric capacitance energy due to high surface area electrodes, and very small electrode separation. Commercially available ultracapacitors provide a reliable, long life, maintenance free, energy storage system, and have many advantages over energy storage systems such as batteries.

- Batteries can only be charged and discharged hundreds of times, and then must be replaced. Ultracapacitors can be charged and discharged over 1 million times. The long cycle life of ultracapacitors greatly improves system reliability, and reduces life-of-system costs.
- Long ultracapacitor life significantly reduces environmental impact, as ultracapacitors will probably never need to be replaced and disposed of in most applications.
- The environmentally safe components of ultracapacitors greatly reduce disposal concerns.
- High ultracapacitor power density provides high power during acceleration, and the ability to absorb high power during regenerative braking. Ultracapacitors are extremely efficient in capturing regenerative braking energy.
- Ultracapacitors are extremely rugged, reliable, and maintenance free.
- Ultracapacitors have excellent low temperature characteristics.
- Ultracapacitors provide consistent performance over time.
- Ultracapacitors promote safety, as they can easily be discharged, and left indefinitely in a safe discharged state.

Gas Turbine Generator

Electric utility power was originally provided by reciprocating engines. Turbine generators were then implemented which provided greater efficiency, improved reliability, and longer life, and became the standard power source. Gas turbine generators are commercially available and are an ideal power source for the HPM vehicle architecture. In spite of the many advantages of the gas turbine over the internal combustion engine, it does not make a good power source to drive the vehicle directly because it does not throttle very well, requiring optimum speed operation to achieve good efficiency. Turbines also have throttle lag. These problems are resolved with a hybrid configuration in which the turbine is configured as an electric generator to power the electric drive motors. The turbine can be operated at the optimum speed in a hybrid configuration. The gas turbine generator offers many advantages over reciprocating engines.

- Higher efficiency
- Higher power density
- Reduced emissions
- Operational on alternative fuels
- Smooth and quiet operation
- High reliability
- Lower maintenance
- Longer life
- Parts count reduced by 80 percent
- Lower manufacturing costs
- Solitary start-up spark plug eliminating a distributor
- Regular oil changes not required as no combustion contaminants enter oil
- No water cooling system and antifreeze required
- Easy low-temperature starting
- No warm-up required
- Instant heat available in the winter

Multiple gas turbines can be used independently as HPM vehicle power sources. The architecture permits one turbine to be used as a power source, and other turbines to be turned on as necessary to meet the specific vehicle power requirement, and then shutdown when not required to limit fuel use and emissions.

As other technologies, such as fuel cells, mature, they may become credible alternatives for the HPM vehicle architecture power source in the future.

Photovoltaic Power System

Modern photovoltaic (PV) panels are readily available, reliable, efficient, and economical with a life expectancy of at least 25 years, and make an ideal secondary power source for the HPM vehicle architecture. The PV panels are semiconductor panels that convert energy from sunlight to DC electrical power. The panels are unbreakable and maintenance free. PV is entirely pollution free during use. PV system production end wastes and emissions are manageable utilizing existing pollution controls. End-of-use recycling technologies are under development to minimize negative environmental effects. PV systems can operate with minimal operator intervention or maintenance after initial setup.

Control System

The hybrid power management controller provides sequencing for system/subsystem startup and shutdown as well as control of the state of discharge of the energy storage system. The state of the energy storage must be optimized to allow for full recovery of energy during braking while also providing adequate vehicle performance. The vehicle must respond to operator accelerator and brake controls as similarly as possible to the response of a conventional vehicle. The choice of the energy storage system and its associated electrical characteristics strongly influences the design of the vehicle control strategy. The ultracapacitor system has several characteristics that are significantly different from those of conventional chemical storage batteries. First the state of charge of capacitors can be determined very precisely from the measured capacitor voltage. This is a significant advantage over chemical batteries in which the relationship between voltage and state of charge is non-linear. Chemical batteries also exhibit hysteresis of their voltage, current, state of charge characteristics. Battery energy storage systems require a much more sophisticated state of charge control system. A second difference between batteries and capacitors is that batteries must be current (and/or cell voltage), limited especially when being charged. This is even more critical as the battery achieves full charge. Near full charge lead acid and many other chemical batteries are unable to accept high currents without damage. To prevent loss of battery life, additional hardware and software is needed which again adds complexity of the charge control system. Ultracapacitors, on the other hand, have very high current capabilities and efficiency, approach their voltage limit more slowly, and do not experience damage while accepting current below full charge. Overall, the use of ultracapacitor energy storage reduces the complexity of the power operation of the vehicle which uses ultracapacitor voltage as feedback to control the power set point, updated continuously, of the engine generator set.

Auxiliary Power System

Society is concerned with the security of the electric utility system. The HPM architecture allows the vehicle to serve as a mobile power generator. A gas turbine is an excellent long life power source, and lends itself to use for this application. The generator can be used to power a home, and multiple vehicles can be used to power hospitals and other critical institutions. This enhances safety and security. The photovoltaic power system is an ideal source for the auxiliary power system during daylight hours. The photovoltaic power system can be used to provide emergency backup power, and can also be used to supplement the utility power system, reducing the burden on the utility. Parked school buses at a school could provide much, and perhaps all, of the power required by the school during the day when the highest level of power is required, significantly lowering fuel use, emissions, and energy costs.

Modern electronics is the enabling technology behind grid-tied power systems, making them safe, reliable, efficient, and economical with a life expectancy of at least 25 years. A grid-tied power system is connected directly to the utility distribution grid. Facility power can be obtained from the utility system as normal. The auxiliary power system is synchronized with the utility system. The auxiliary power system provides power for the facility, and excess power is provided to the utility. For safety, an automatic transfer switch permits the vehicle to provide power to the facility when utility power is unavailable, and automatically switch back to utility power when it does become available.

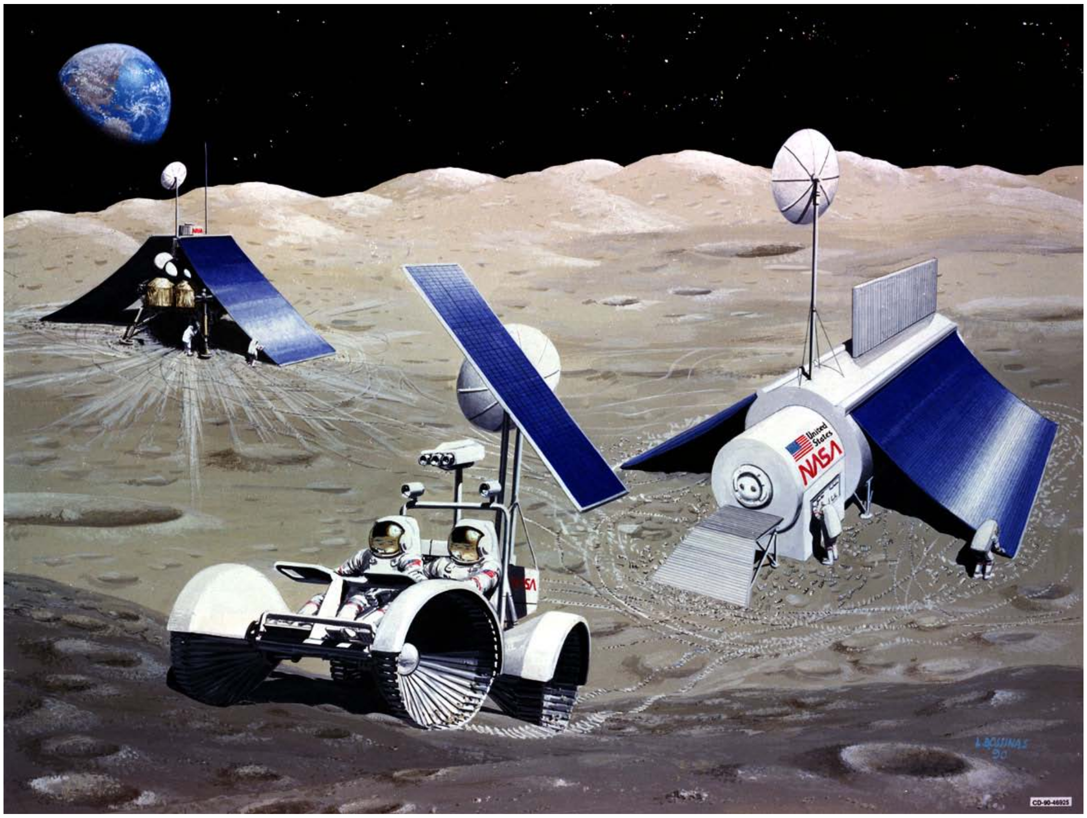

Figure 19.—HPM is being investigated for numerous space exploration applications.

Grid-tied power systems provide many benefits. Operating costs of a PV power system are low compared to conventional power technologies. PV can displace the highest cost electricity during times of peak demand in most climatic regions, and thus reduce grid loading. Net metering is often used, in which independent power producers, such as PV power systems, are connected to the utility grid via the customers' main service panel and meter. When the PV power system is generating more power than required at that location, the excess power is provided to the utility grid. The customer pays the net of the power purchased when the on-site power demand is greater than the on-site power production and the excess power that is returned to the utility grid.

Rovers

The HPM technology developed for the terrestrial applications described is now being applied to the next generation of lunar rovers and other space exploration vehicles (Ref. 14), as depicted in Figure 19. HPM is ideal for space applications where long life, high efficiency, extreme reliability, and excellent low temperature performance is critical. Many of the HPM components, such as fuel cells, photovoltaic panels, and ultracapacitors, are being integrated into optimal configurations for space exploration vehicles.

Concluding Remarks

The Hybrid Power Management (HPM) based vehicle architecture provides a practical solution to reducing fuel consumption and emissions from vehicles, while providing the capability to operate from alternative fuels, and fulfilling a need for an effective backup facility power system.

The key element of HPM is the energy storage system. All generated power is sent to the energy storage system, and all loads derive their power from the energy storage system. This technique can significantly reduce the power requirement of the primary power source, while increasing the vehicle reliability. Ultracapacitors are ideal for HPM based energy storage systems due to their exceptionally long cycle life, high reliability, high efficiency, high power density, and excellent low temperature performance. Multiple power sources and multiple loads are easily incorporated into an HPM based vehicle. A hybrid power management controller maintains optimal control over each of the components of the entire vehicle. This flexible operating system can be applied to all vehicles to considerably improve vehicle efficiency, reliability, safety, security, and performance.

The HPM based vehicle architecture has the potential to provide significant improvements in space and terrestrial based vehicles.

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 01-07-2011	**2. REPORT TYPE** Technical Memorandum	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE A Hybrid Power Management (HPM) Based Vehicle Architecture	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Eichenberg, Dennis, J.	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER WBS 069746.02.03.0485.02
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191	**8. PERFORMING ORGANIZATION REPORT NUMBER** E-17686
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001	**10. SPONSORING/MONITOR'S ACRONYM(S)** NASA
	11. SPONSORING/MONITORING REPORT NUMBER NASA/TM-2011-217021

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category: 44
Available electronically at http://www.sti.nasa.gov
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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Society desires vehicles with reduced fuel consumption and reduced emissions. This presents a challenge and an opportunity for industry and the government. The NASA John H. Glenn Research Center (GRC) has developed a Hybrid Power Management (HPM) based vehicle architecture for space and terrestrial vehicles. GRC's Electrical and Electromagnetics Branch of the Avionics and Electrical Systems Division initiated the HPM Program for the GRC Technology Transfer and Partnership Office. HPM is the innovative integration of diverse, state-of-the-art power devices in an optimal configuration for space and terrestrial applications. The appropriate application and control of the various power devices significantly improves overall system performance and efficiency. The basic vehicle architecture consists of a primary power source, and possibly other power sources, providing all power to a common energy storage system, which is used to power the drive motors and vehicle accessory systems, as well as provide power as an emergency power system. Each component is independent, permitting it to be optimized for its intended purpose. This flexible vehicle architecture can be applied to all vehicles to considerably improve system efficiency, reliability, safety, security, and performance. This unique vehicle architecture has the potential to alleviate global energy concerns, improve the environment, stimulate the economy, and enable new missions.

15. SUBJECT TERMS
Automobiles; Electric automobiles; Energy conversion; Electric power

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** STI Help Desk (email:help@sti.nasa.gov)
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	22	**19b. TELEPHONE NUMBER** *(include area code)* 443-757-5802