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EVALUATION OF THE 2007 TOYOTA CAMRY HYBRID SYNERGY DRIVE SYSTEM

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ACRONYMS AND ABBREVIATIONS

A/C	air conditioning
ac	alternating current
ANL	Argonne National Laboratory
AWG	America wire gauge
CAN	controller area network
CT	current transformer
DAQ	data acquisition system
dc	direct current
DF	dissipation factor
DOE	U.S. Department of Energy
ECU	electronic control unit
ECVT	electronically controlled continuously variable transmission
emf	electromotive force (measured in volts)
EMI	electromagnetic interference
ESR	equivalent series resistance
EV	electric vehicle
FCVT	FreedomCAR and Vehicle Technologies
HEV	hybrid electric vehicle
HV	high voltage
IC	integrated circuit
ICE	internal combustion engine
ID	inner diameter
IGBT	insulated-gate bipolar transistor
IPM	intelligent power module
LV	low voltage
MG	motor-generator
NdFeB	neodymium iron boron
Nm	Newton meter
NTRC	National Transportation Research Center
OD	outer diameter
ORNL	Oak Ridge National Laboratory
PC	personal computer
PCU	power control unit
PEEMRC	Power Electronics and Electric Machinery Research Center
PI	proportional-integral
PM	permanent magnet
PMSM	permanent magnet synchronous motor
rms	root mean square
rpm	revolutions per minute
Si	silicon
TC	thermocouple
THS	Toyota Hybrid System

1. INTRODUCTION

The U.S. Department of Energy (DOE) and American automotive manufacturers General Motors, Ford, and DaimlerChrysler began a five-year, cost-shared partnership in 1993. Currently, hybrid electric vehicle (HEV) research and development is conducted by DOE through its FreedomCAR and Vehicle Technologies (FCVT) program. The mission of the FCVT program is to develop more energy efficient and environmentally friendly highway transportation technologies. Program activities include research, development, demonstration, testing, technology validation, and technology transfer. These activities are aimed at developing technologies that can be domestically produced in a clean and cost-competitive manner.

Under the FCVT program, support is provided through a three-phase approach [1] which is intended to:

- Identify overall propulsion and vehicle-related needs by analyzing programmatic goals and reviewing industry's recommendations and requirements, then develop the appropriate technical targets for systems, subsystems, and component research and development activities;
- Develop and validate individual subsystems and components, including electric motors, emission control devices, battery systems, power electronics, accessories, and devices to reduce parasitic losses; and
- Determine how well the components and subassemblies work together in a vehicle environment or as a complete propulsion system and whether the efficiency and performance targets at the vehicle level have been achieved.

The research performed in this area will help remove technical and cost barriers to enable technology for use in such advanced vehicles as hybrid electric, plug-in hybrid electric, electric, and fuel-cell-powered vehicles.

The Oak Ridge National Laboratory's (ORNL) Power Electronics and Electric Machinery Research Center (PEEMRC) performed benchmark assessments and subsystem testing of the 2004 Toyota Prius in 2004–2005. This work has been fully reported in two reports [2,3]. In 2006, the PEEMRC performed similar work on the hybrid version of the 2005 Honda Accord [4]. This report presents the results of benchmark testing of the 2007 Toyota Camry electric drive subsystems.

Subsystem-level testing was conducted by the PEEMRC at ORNL, which is a broad-based research center for power electronics and electric machinery (motor) development. Located in the national user facility known as the National Transportation Research Center (NTRC), the PEEMRC has more than 9000 square feet of space for developing and building the next generation prototypes of power electronics and electric machine technologies.

The 2007 Toyota Camry hybrid is equipped with the Hybrid Synergy Drive system which includes an internal combustion engine (ICE), an electric motor, and a generator. These components are integrated with a power splitting planetary gear which provides various power flow configurations for different modes of operation. The electric motor assists the ICE in providing mechanical drive power for the vehicle and also acts as a generator to recharge the battery during regenerative braking. According to published specifications, Toyota claims the motor can deliver a peak power output of 105 kW (143 hp) at 4500 revolutions per minute (rpm). Toyota has not published a rated torque (or power) versus speed graph for the Camry electric motor and no specifications have been published for the generator. The hybrid version of the Camry features a 2.4-liter 4-cylinder, 16-valve engine, which has a specified peak power output of 110 kW (147 hp) at 6000 rpm [5].

The Camry electric drive system has several features in common with the Toyota Prius system as they both use the Toyota Hybrid System (THS) II. Both make use of the electric motor to provide all of the traction power during acceleration from a stop. This continues until the engine is needed for any of several reasons (more torque, low battery state of charge, high battery temperature, etc.) Both vehicles have a dedicated generator, which is used to route power from the ICE to the electric motor. Both use a clutch-less, electronically controlled continuously variable transmission (ECVT) which uses a planetary gear to manage power flow from the ICE and motor to the differential gear unit. The planetary gear configuration of the ECVT provides the opportunity to operate the ICE throughout a more efficient torque-speed range, depending on the torques and speeds of the generator and electric motor.

Unlike the Toyota Camry and Prius, which are both considered to be full hybrids, the Honda Accord hybrid with its smaller motor is considered to be a “mild hybrid” since the motor never propels the vehicle without engine power. In operation, the 2005 Accord hybrid exhibits enhanced performance compared to the conventionally powered Accord, but little or no gain in fuel economy.

In order to fully benchmark the HEV technology used in the 2007 Camry, a design characterization study was conducted to evaluate the vehicle’s hybrid electric drive subsystem. A flow diagram which portrays the baseline benchmarking approach is shown in Fig. 1.1. The characterization study included (1) a design review, (2) a packaging and fabrication assessment, (3) bench-top electrical tests, (4) back-electromotive force (emf) and locked rotor tests, (5) performance and efficiency tests on the motor and inverter, (6) efficiency tests on the bi-directional boost converter, and (7) continuous duration tests of the drive motor and inverter. The design and packaging review includes comparisons to the 2004 Toyota Prius, which was evaluated during previous years. Results from the performance and efficiency tests were used to map electrical and thermal data for motor/inverter operation over the full range of speeds and shaft loads that the motor is capable of producing. The results of the design and packaging assessments are presented in Section 2 and the performance and efficiency tests results are presented in Section 3.

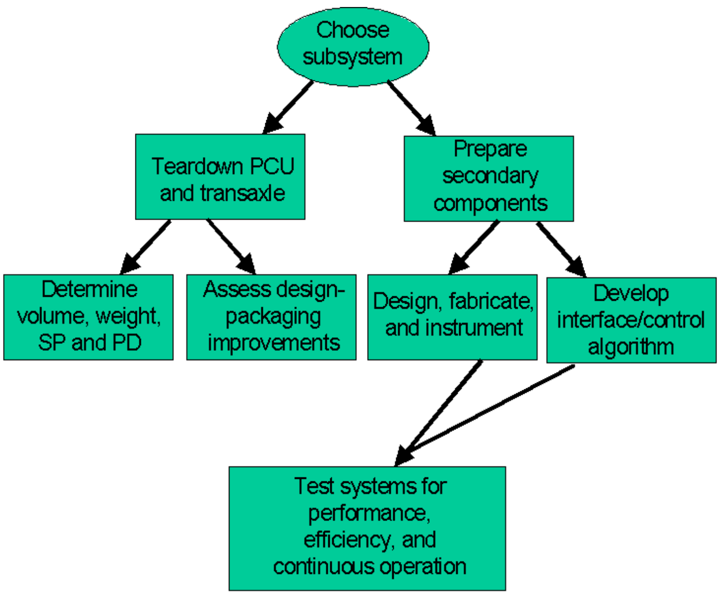

Fig. 1.1. Flow diagram of baseline benchmarking approach.

2. HYBRID ELECTRIC DRIVE SYSTEM DESIGN AND PACKAGING

The hybrid Camry includes significant advancements in HEV technology since the electric drive system features higher peak power and more extensive continuous operation capabilities, yet the size and weight of the system has decreased when compared to that of the Prius. This is primarily due to the care taken in packaging the inverter/converter system and the design of a higher-speed, higher voltage permanent magnet synchronous motor (PMSM). The Camry HEV subsystem design and packaging will be assessed and summarized in this section.

Table 2.1 presents an overview of several general HEV design features and published specifications and indicates similarities and differences between the Camry and Prius vehicles. The primary drive PMSM is referred to as MG2 and the generator is referred to as MG1. Although both PMSMs can function as a motor or a generator, MG2 is commonly referred to as "motor" and MG1 is commonly referred to as "generator." Both MG1 and MG2 are powered by separate three-phase inverters which share the same direct current (dc)-link. The battery voltage is boosted by a bi-directional boost converter which feeds the dc-link. This configuration facilitates the use of multiple power flow modes wherein the ICE, MG1, and/or MG2 may supply energy to the battery pack, the battery pack may supply MG1/MG2 alone, or the ICE and battery pack can simultaneously power the vehicle.

Table 2.1. Comparison of hybrid Camry and the Prius design features and published specifications

Design Feature	Hybrid Camry	2004 Prius
Motor peak power rating	105 kW @ 4500 rpm (disputed to be 70kW)	50 kW @ 1200–1540 rpm
Motor peak torque rating	270 Newton meter (Nm) (667 after speed reduction gear)	400 Nm
Top rotational speed	14,000 rpm (5,670 rpm after speed reduction)	6,000 rpm
Separate generator used?	Yes (although the motor also serves as a generator during regenerative braking)	Same as Camry
Generator specifications	Not published	33 kW
Source of power to MG2	Battery and/or ICE via generator	Same as Camry
PMSM rotor design	Interior permanent magnets (PMs) with "V" configuration at each pole with a reinforcement web in the laminations (middle of the V) to enable high-speed operation	Interior PMs with "V" configuration at each pole (no reinforcement)
Motor winding configuration	Parallel	Series
Number of rotor poles	8	Same as Camry
Boost converter output voltage	250–650 Vdc output	200–500 Vdc output
Boost converter power rating	30 kW	20 kW
PMSM cooling	Oil circulation with water/glycol heat exchanger	Same as Camry
Inverter/converter cooling	Water/glycol loop	Same as Camry
Hybrid transaxle	Planetary gears used for speed reduction and power split	A single planetary gear used for power split
Fan-cooled high-voltage (HV) Ni-MH battery	244.8 V, 6.5 Ah, 30 kW	201.6 V, 6.5 Ah, 20 kW

Design and packaging assessments are presented in Subsections 2.1 and 2.2 beginning with the power control unit (PCU) and concluding with the transaxle. Studies on the PCU include subjects such as general design and packaging, power electronic devices, and multifaceted capacitor assessments. Assessment topics associated with the transaxle are general design and packaging, PMSM design, and magnet hysteresis measurements. These assessments provide useful feedback regarding technological developments and other characteristics needed to determine packaging complexity and fabrication costs.

2.1 PCU

The general locations of the Camry inverters and the bi-directional boost converter assembly are shown in Fig. 2.1. The figure makes evident the fact that the motor and generator inverters, dc-link capacitor, and half of the cold plate comprise about 65% of the total volume. The buck/boost converter and half the cold plate comprise the remaining 35%. The size and proportions of the PCU are similar to that of a conventional 12 Vdc car battery.

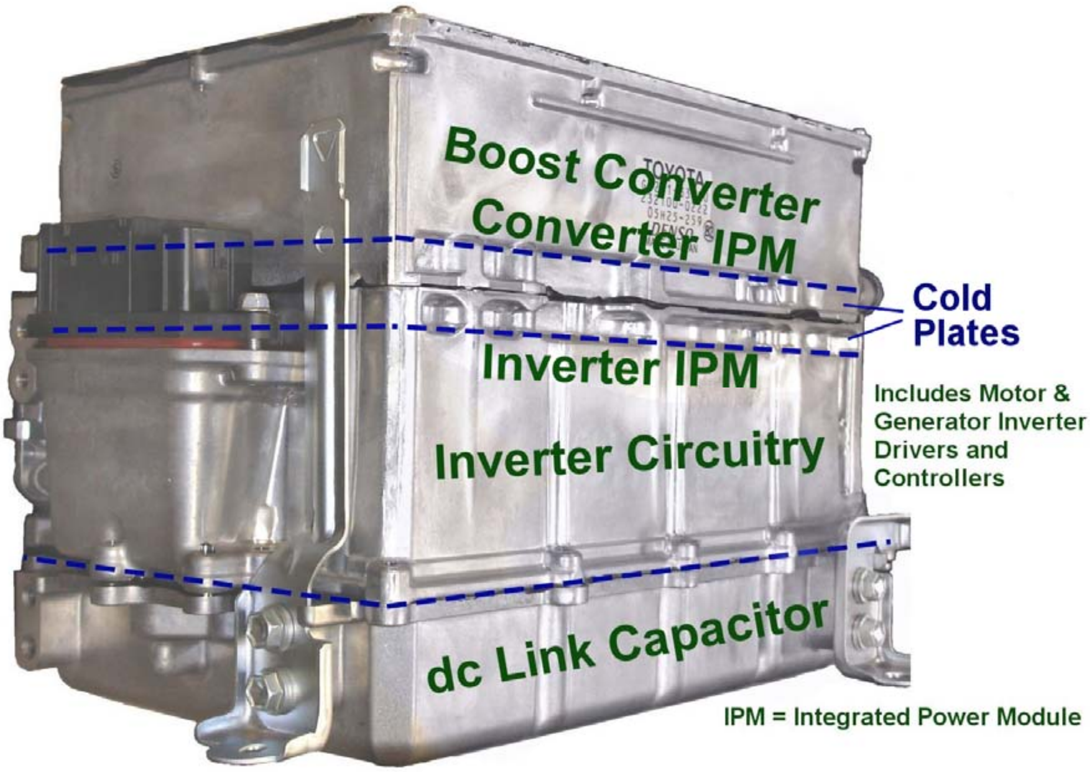

Fig. 2.1. Subsystems of the Camry inverter and converter assembly.

Because the Ni-MH battery is rated at 30 kW, it is assumed that the boost converter will not operate at power levels exceeding 30 kW. Similarly, it is assumed that the motor inverter has a peak power rating that matches the measured power rating of the motor.

The overall circuit diagram of the PCU is shown in Fig. 2.2. A 250 Vdc battery supplies power to the PCU, which is connected to the low voltage (LV) side of the boost converter. A 500 V, 378µF capacitor is connected across the input with a 212 µH inductor between the battery and the boost converter power electronics module. A small 53.8 kΩ resistor, 750 V, 0.9 µF filter capacitor, and 750 V, 2098µF smoothing capacitor is located on the HV side of the boost converter. This HV bus serves as the dc link for both the motor and generator inverter. Table 2.2 provides specification comparisons between the components found in the Prius and Camry PCU. The boosted voltage ranges from 250–650 Vdc depending on driving conditions such as desired acceleration and required regenerative braking and is controlled accordingly by commands from the MG electronic control unit (ECU) and the THS ECU. Detailed capacitor test results are provided in Section 2.1.3.

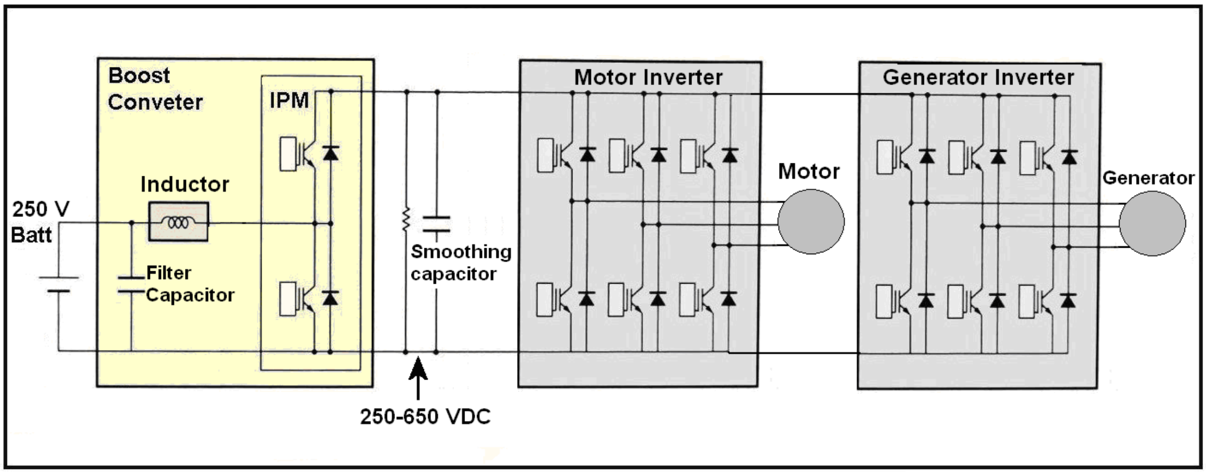

Fig. 2.2. Circuit diagram of PCU.

Table 2.2. Comparison of hybrid Camry and the Prius PCU component specifications

Design Feature	Hybrid Camry	2004 Prius
Boost converter power rating	30 kW	20 kW
Battery voltage	244.8 V	201.6 V
Filter capacitor (LV side)	500 Vdc, 378 μF	600 Vdc, 282 μF
Inductor	212 μH at 1 kHz	373 μH at 1 kHz
Small resistor (HV side)	53.8 kΩ	64.3 kΩ
Small capacitor (HV side)	750 Vdc, 0.9 μF	750 Vdc, 0.1 μF
Smoothing capacitor	750 Vdc, 2098 μF	600 Vdc, 1,130 μF

Figures 2.3 and 2.4 show the converter and inverter compartments, respectively, prior to disassembly. Figure 2.5 shows the general assembly and packaging of the major subcomponents of the Camry inverter and converter. Not shown for the inverter is the dc-link capacitor and its casing which serves as a cover to the inverter assembly. Because the inverter/converter assembly was designed to be integrated into an existing vehicle (the non-hybrid Camry), there was a need to package the unit in a minimal volume, which is evident in the figures provided in this section. The Camry MG ECU is located within the PCU just above the inverter driver board. Communication between the Camry MG ECU and other ECUs is accomplished though controller area network (CAN) digital data transmission. The Prius MG ECU is located outside of the PCU with analog control signals being transmitted over a conductor length of several feet. Together, the MG ECU and THS ECU monitor vehicle conditions and control the PCU components to orchestrate proper system operation.

In the inverter compartment, the controller board includes power regulation electronics, two identical MG microprocessors, a boost-converter microprocessor, two Tamagawa AU2802 integrated circuits (IC) for MG speed/position detection, hardware for CAN communication, MG current measurement, safety interlock devices, and temperature feedback. The driver board includes regulated isolation power supplies, isolated driver electronics, and hardware to prevent faults and overlapping as well as voltage, current, and temperature sensing circuitry for each insulated-gate bipolar transistor (IGBT). More information regarding the power electronics modules for the inverters and converter is provided in Section 2.1.2.