

Development of General Motors' eAssist Powertrain

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ABSTRACT

General Motors' (GM) eAssist powertrain builds upon the knowledge and experience gained from GM's first generation 36Volt Belt-Alternator-Starter (BAS) system introduced on the Saturn VUE Green Line in 2006. Extensive architectural trade studies were conducted to define the eAssist system. The resulting architecture delivers approximately three times the peak electric boost and regenerative braking capability of 36V BAS. Key elements include a water-cooled induction motor/generator (MG), an accessory drive with a coupled dual tensioner system, air cooled power electronics integrated with a 115V lithium-ion battery pack, a direct-injection 2.4 liter 4-cylinder gasoline engine, and a modified 6-speed automatic transmission. The torque-based control system of the eAssist powertrain was designed to be fully integrated with GM's corporate common electrical and controls architectures, enabling the potential for broad application across GM's global product portfolio.

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INTRODUCTION

The eAssist is a key part of GM's overall strategy for powertrain electrification, which includes a wide range of propulsion architectures from light hybrid systems like eAssist all the way to fully electric and fuel cell propulsion system. The role of eAssist in this strategy is to be a low cost, high-value hybrid solution that can be applied to mainstream vehicles around the globe. This type of "light electrification" addresses the need for achieving significant increases in efficiency in the otherwise conventional powertrains that are likely to remain the dominant form of automotive propulsion for many years.

The eAssist shares with the original GM 36V Belt Alternator Starter (BAS) mild hybrid system the basic arrangement of a single MG connected to the engine crankshaft through a belt [1]. However, eAssist was designed to operate at a higher voltage and deliver much higher electric boost and regenerative braking power than 36V BAS. In what follows, the key requirements, architecture selection, component design, system integration, and development lessons of GM's eAssist system will be described and explained.

KEY REQUIREMENTS & ARCHITECTURE

The key requirements for the eAssist system were greater fuel efficiency, increased electric boost, lower hybrid system costs, and compatibility with a wide range of existing powertrains and vehicle platforms. The increased fuel efficiency was defined as an increase relative to the conventional vehicle's fuel economy. This was particularly challenging when considering how conventional vehicle fuel economy had evolved as more advanced fuel economy mechanisms were utilized, including some of those used previously only for hybrid vehicles. The increased electric boost was required to not only improve the vehicle's acceleration performance, but also to provide the opportunity for additional fuel savings. Lower hybrid system costs and compatibility with a wide range of powertrains and vehicle platforms also increased the potential for broad market coverage.

In addition to the key program requirements for the eAssist system, the technical solution was further constrained by the strategy to use a single MG attached directly to the engine. This helped in optimizing the hybrid system for use with a conventional engine/transmission powertrain with minimal changes. These additional constraints supported the goals of lower hybrid system cost and compatibility with a broad range of platform applications.



After the key system requirements were defined, systems engineering tools and methods were utilized to guide the architecture definition. The first area studied was the location and means of coupling the MG to the engine. This evaluation was conducted to ensure that the architecture of the first generation system was still appropriate given the new system requirements. Two physical MG locations were evaluated for coupling; front of block connection through serpentine belt identical to the first generation BAS architecture as shown in [Figure 1](#), and rear face of engine block connected to the flywheel commonly known as Flywheel Alternator Starter (FAS) as shown in [Figure 2](#).

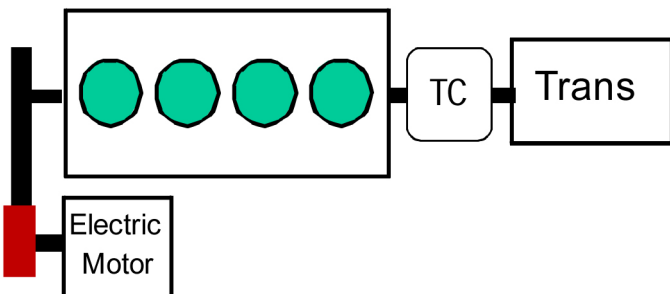


Figure 1. Belt Alternator Starter (BAS) Architecture

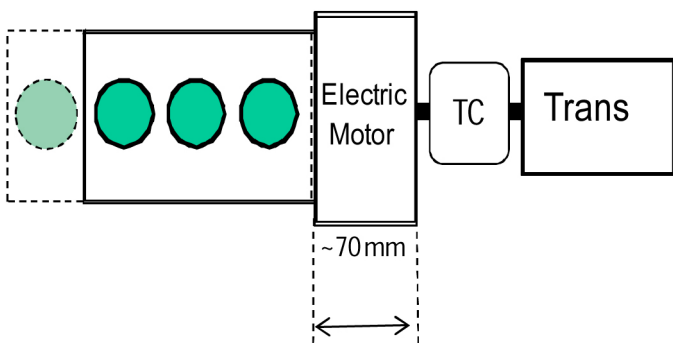


Figure 2. Flywheel Alternator Starter (FAS) Architecture

The FAS and BAS MG units were first sized to meet the system requirements with the predominant sizing factor being the torque required to achieve pleasing engine stops and starts. Given the requirement to utilize existing powertrains the ability to reduce engine start torque by exploring lower engine displacement was not an option. Therefore, the diameter became the primary constraint for the FAS arrangement. Given a fixed diameter it was determined that the minimum active stator axial length was approximately 70 mm and that it would require the use of permanent magnets (PM) for the FAS arrangement to meet the engine starting torque requirement. Minimizing the axial length was critical for a transverse engine arrangement as this impacts the powertrain packaging between the vehicle's main underhood structural elements. The BAS architecture allows more flexibility in motor length and diameter because it is

packaged off the engine axis and can use the belt pulley ratio to achieve the required crankshaft torque. This allowed various motor diameter/length combinations to be considered for BAS as well as various motor types (PM, induction machine (IM), etc.). Once the MG unit dimensions were defined, a packaging assessment for the two architectures could be completed.

The packaging assessment for the two architectures showed that a BAS configuration has several advantages for applications with existing powertrains. The cross-car width of a transverse engine application is essentially unaffected by BAS, whereas the FAS arrangement increases width significantly. Also, the motor sizing flexibility for BAS affords other packaging flexibility and mass savings for the electric machine. Furthermore, the BAS architecture does not require a PM machine to meet the packaging requirements, which results in the opportunity for cost savings.

Another critical evaluation criterion was the potential fuel economy of the different architectures and MG units. As stated previously both systems were sized to provide equivalent stop and start capability, but other fuel economy factors such as regenerative braking capability, system efficiency, and drag losses, varied. A detailed fuel economy study was performed using GM simulation tools to evaluate the options. The results indicated that the FAS architecture with a PM machine yields very similar fuel economy to the BAS architecture with an IM machine when applied to the same vehicles, engines and transmissions. Although the FAS PM machine had higher electrical efficiency and more regenerative energy capture, its back electro-magnetic field (EMF) drag losses during times when the electric machine is not being used are higher than those of an IM. Furthermore, a system with moderate energy storage capacity, conventional brake system, and no engine downsizing or other special modes results in a significant amount of time when the electric machine is not in either motoring or generating mode. Thus, the increased EMF drag losses with the FAS PM architecture offset the increased electrical efficiency and regenerative braking energy captured. Therefore, the FAS and BAS architectures deliver very similar fuel economy in the vehicle studied.

With the conclusion that the fuel economy gains of the two architectures were very similar, it became apparent that the packaging, mass, and cost advantages of the BAS architecture with an IM machine made this the best choice for the eAssist system. To achieve a globally common eAssist system across various vehicle platforms it was necessary to understand the amount of regenerative braking energy needed to be captured with respect to various customer drive cycles. [Figure 3](#) outlines the cumulative regenerative braking energy assuming that the electrical battery charge power is limited at various levels. It is clear from [Figure 3](#) that some drive cycles, such as Japan10-15 and FTP Highway could capture a majority, if not all, the regenerative braking energy available at charge power levels less than 6 kW, which is how the 36V BAS system operated. However, to maximize fuel economy

on a global basis it was necessary to increase the regenerative braking capability and thus set the charge power capability of the eAssist system to 15kW as shown in Figure 3. Even higher charge power levels could be achieved but would require a fully blended electro-hydraulic brake system to meet customer drive-quality requirements.

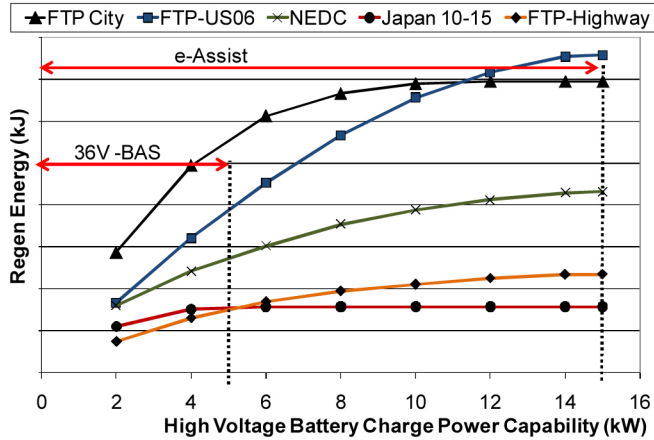


Figure 3. Regenerative Braking Energy Captured versus High Voltage Battery Charge Power

To illustrate the merits of increased regenerative braking energy capture for eAssist over 36V BAS, two separate drive cycle examples showing velocity, engine speed, and high voltage battery power appear in Figures 4 and 5. A key assumption was that both the 36V-BAS and eAssist systems were applied to the same engine and transmission, but not the same final drive ratio. Due to the greater eAssist electric boost, a lower numerical final drive ratio (FDR) of 2.64 was feasible compared to 3.23 in the 36V BAS, while still maintaining performance. Figure 4 shows a snapshot of cycles 5, 6 and 7 of the 18 cycle Federal Test Procedure (FTP) city cycle for which three key points are outlined. First, since the engine output power is constant and the FDR numerically lower the eAssist system enables a lower engine speed relative to 36V-BAS which results in lower engine friction during regenerative braking events. Second, the regenerative power capability of the eAssist system is three times that of the 36V-BAS system, which increases the amount of electrical energy captured. Third, the extra regenerative braking energy captured was used to provide energy to run accessory loads during situations such as idle stop, engine restart, Deceleration Fuel Cut Off, acceleration and cruise modes. As can be seen in Figure 4 the additional regenerative braking energy resulted in no fuel-on charging of the high voltage battery. In other words, for the eAssist case all of the electrical energy needs of the vehicle are met by energy captured through regenerative braking.

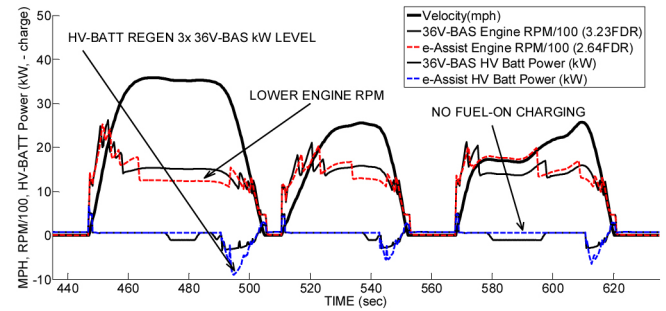


Figure 4. FTP City drive cycle zoomed

Similarly, Figure 5 shows the same signals previously stated but applied during a high speed portion of the FTP US06 drive cycle. Again for the eAssist system, engine speed was lower and regenerative braking energy capture higher relative to the 36V BAS system. However, during high speed operation with the transmission in top gear (6th gear), the reserve power available from the engine is reduced due to the lower numerical final drive ratio (2.64 versus 3.23 in 36V BAS). By the negative high voltage battery power in Figure 5 the eAssist system provides additional boost power in parallel with the engine to eliminate a 5-6 downshift and maintain top gear. This extra eAssist boost power enabled the transmission gear shift points to be optimized for lower fuel consumption in all driving conditions.

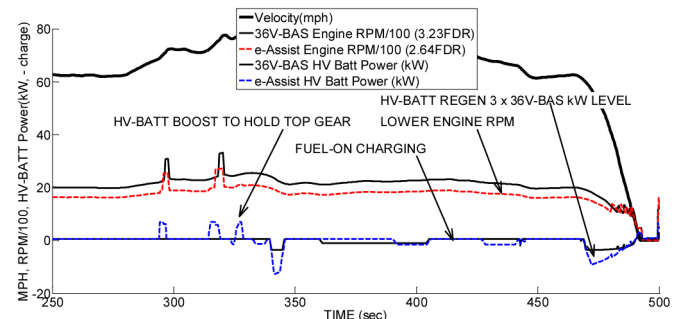


Figure 5. US06 drive cycle high speed portion zoomed

Once the determination of energy and power capacity was completed, the system voltage was defined by the requirements of long battery life, minimizing power electronics cost, and smallest cross sectional area for all cables.

With the fundamental characteristics of the system determined, that being the power, energy, voltage level and MG coupling to the engine, the arrangement and architecture of the remaining hybrid system components were developed, starting with the location for the batteries. One of the critical requirements to ensure battery performance and durability included temperature control near 30 degrees Celsius. These requirements made it logical that a convenient location for the batteries would be in or near the passenger compartment. However, the size of the hybrid battery

reduced from the first generation system due to the advantages of Li-Ion battery technology, prohibited locating the batteries in or even under the passenger compartment in many vehicle platforms. The best option was determined to be a flat, rectangular arrangement directly behind the rear seat. This location had the advantage of being able to utilize conditioned passenger compartment air for temperature control. The flat arrangement provided the option for packaging behind the rear seat or under a flat load floor for various vehicle applications while still maintaining the option for pass-through rear seats in sedan applications.

The next step in the architecture definition required placement of the power electronics. The engine compartment would be a convenient location for the power electronics because this would be near the MG. However, vehicle engine compartments with existing powertrains offered little opportunity for adding content underhood even though power electronics have evolved and sizes decreased. Because packaging the power electronics underhood on some applications would have meant relocating existing underhood components and to maintain broad application coverage with minimal change, alternative locations for packaging the power electronics were considered. These locations needed to comprehend the cooling requirements for the power electronics. The power level and associated heat rejection given the duty cycle of the application suggested that air cooling might be an appropriate cooling method. Studies were performed to understand if the battery cooling airflow could also efficiently cool the power electronics. When this was confirmed, it became apparent that locating the power electronics in the rear of the vehicle with the batteries was efficient for packaging, system cost, and performance. A flat rectangular profile was prescribed for the power electronics to maintain the packaging advantages mentioned previously for the batteries. This arrangement was also well suited for air cooling because it enabled a direct heat transfer path from the critical power electronic components to a simple plate-fin heat exchanger.

Defining a controls architecture which was compatible with GM's corporate common architecture was critical for meeting the requirement of broad application coverage. Options that were studied considered different locations for microprocessors, various numbers of processors, serial data bus requirements, and various locations for software code. Each control function was analyzed to determine its performance with the various options. Consideration was given for factors such as communication latency, microprocessor throughput, compatibility with software code utilized by other GM and non-GM applications. At the completion of this study, it was determined that the best solution was two microprocessors located in the new Power Electronics controller with one's primary purpose being hybrid system supervisory control and the second being used primarily for the MG controls. The hybrid supervisory controls were designed to act in concert with the existing engine and transmission controls.

POWER PACK

The high voltage eAssist Power Pack Subsystem (PP) provided the capability to control, monitor, store, and distribute electrical energy in support of vehicle functionality. The Battery Power Inverter Module (BPIM), Accessory Power Module (APM), Energy Storage System (ESS), High and Low Voltage Distribution, Air Cooling Ductwork, and Battery Disconnect components were packaged in one unit. Integrating the components in this manner optimizes package space, simplifies power distribution interfaces and reduced the number of parts dedicated to thermal management by enabling cooling of the ESS and power electronics in series. In addition, the powerpack was designed to utilize the structure of its major sub-components (ESS and BPIM) to provide structural integrity to the end item assembly. For example, the ESS brackets and powerpack tray share vehicle mounting points. This integration strategy served to stiffen the tray, improving structural vibration performance of the powerpack assembly.

The PP also provided the following functions:

- Converted 3-phase alternating current (AC) from the electric motor to direct current (DC)
- Inverted DC electrical energy into 3-phase AC current for motor control
- Converted DC from high voltage bus to 12V electrical vehicle loads
- Isolated high voltage to the energy storage devices
- Communicated with primary vehicle controller
- Provided cooling for the ESS, BPIM and APM

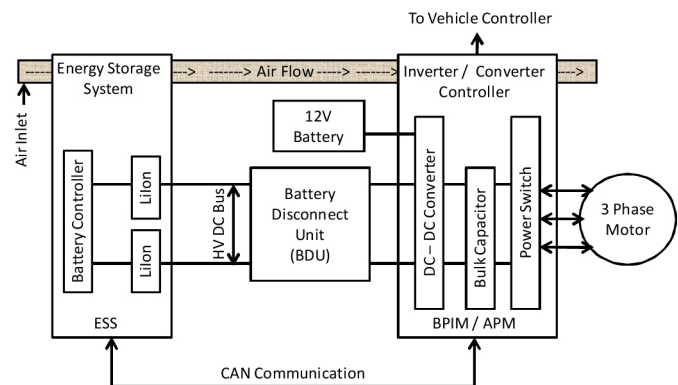


Figure 6. Power Pack Block Diagram

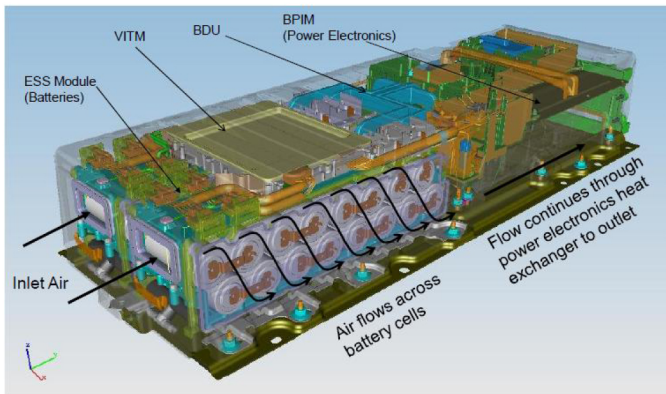


Figure 7. Power Pack Assembly

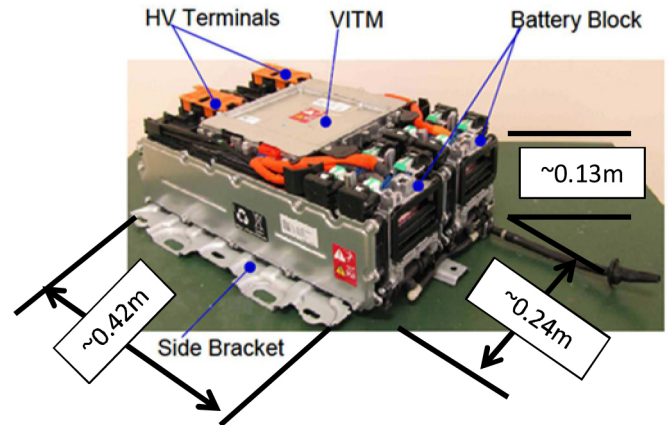


Figure 9. eAssist Battery Pack

ENERGY STORAGE SYSTEM (ESS)

The eAssist system includes an efficiently designed high power lithium ion battery pack (ESS) that, when compared to the 36V-BAS system, provides more than three times the nominal voltage while significantly reducing mass. The design utilizes 32 air-cooled cylindrical cells connected in series to provide up to 18 kW discharge power. The ESS includes an integrated controller called the Voltage Current Temperature Module (VITM) that monitors and reports pack and cell voltage, current, and cell temperatures to the battery control processor. The battery was custom designed for the eAssist application. Seven temperature sensors are strategically located within the ESS to monitor cell and air inlet temperatures.

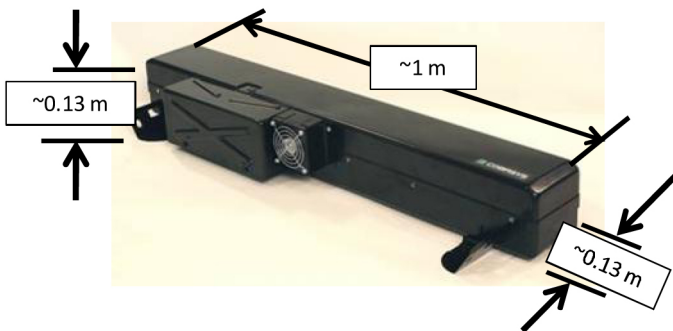


Figure 8. 36V BAS Battery Pack

System Characteristics	36V BAS	eAssist
Chemistry	Nickel Metal	Lithium Ion
Capacity	8.5 Ah	4.4 Ah
Nominal Voltage	36 V	115 V
Cell Count	60 cells (3 parallel sets of 2 modules in series, 10 cells in series per module)	32 cells (2 modules in series with 16 cells per module)
Useable Energy	105 Wh	175 Wh
Discharge Power	12 kW	18 kW
Charge Power	10 kW	15 kW
Mass	25 kg	14 kg
Volume	17 liters	13 liters

Figure 10. Energy Storage Comparison

BATTERY STATE ESTIMATOR (BSE)

In order to optimize use of the ESS, GM engineers developed a model-based battery state estimator (BSE) algorithm that reports estimated state of charge (SOC), state of health (SOH) and available power to the powertrain control system. Due to the change in chemistry from 36V-BAS (NiMH) to eAssist (Lithium-ion), it was necessary to evolve the BSE algorithm. The BSE enabled the control system to optimally utilize the ESS to provide maximum fuel economy and drive quality without violation of key ESS operating parameters. The BSE utilized an equivalent circuit model and employed a recursive least squares regression of model parameters to estimate SOC. By analyzing a sufficiently varying current and voltage signal over time, the BSE continuously adapts. The advantage of an adaptive model is that it accounts for all influences on battery behavior including temperature, age, and pack-to-pack variation.