

Design Optimization, Development and Manufacturing of General Motors New Battery Electric Vehicle Drive Unit (1ET35)

Shawn Hawkins, Alan Holmes, David Ames, Khwaja Rahman, and Rodney Malone
General Motors Co.

ABSTRACT

The General Motors (GM) 1ET35 drive unit is designed for an optimum combination of efficiency, performance, reliability, and cost as part of the propulsion system for the 2014 Chevrolet Spark Electric Vehicle (EV) [1]. The 1ET35 drive unit is a coaxial transaxle arrangement which includes a permanent-magnet (PM) electric motor and a low loss single-planetary transmission and is the sole source of propulsion for the battery-only electric vehicle (BEV) Spark. The 1ET35 is designed with experience gained from the first modern production BEV, the 1996 GM EV1. This paper describes the design optimization and development of the 1ET35 and its electric motor that will be made in the United States by GM. The high torque density electric motor design is based on high-energy permanent magnets that were originally developed by GM in connection with the EV1 and GM bar-wound stator technology introduced in the 2Mode Hybrid electric transmission, used in the Chevrolet Volt and in GM eAssist systems. The 1ET35 transaxle provides high power density and low system loss over a wide speed range, resulting in a class-leading combination of vehicle performance and vehicle range on a variety of global drive cycles.

CITATION: Hawkins, S., Holmes, A., Ames, D., Rahman, K. et al., "Design Optimization, Development and Manufacturing of General Motors New Battery Electric Vehicle Drive Unit (1ET35)," *SAE Int. J. Alt. Power.* 3(2):2014, doi:10.4271/2014-01-1806.

INTRODUCTION

Government regulations in the United States and other nations effectively demand the production of battery-only electric vehicles (BEVs) whose sole source of propulsion energy is electricity. Today, battery technology is still challenged to supply sufficient energy by itself for vehicles that customers will purchase in the numbers required by the regulations. Although most drivers drive less than 60 km (or 40 miles) on most days, day-to-day variation in driving distance and driving conditions causes drivers to reasonably demand a vehicle that has a much greater nominal range. For an electric vehicle (EV) classification where the extended-range powertrain of the Chevrolet Volt (which operates as an EV until battery energy is low) is excluded, range is subject to the limits of practical battery technology and acceptable battery cost.

Today, the most expensive part of a typical BEV is the battery itself. The fundamental cost of the battery, that is the cost of the cells themselves, may exceed the cost of the entire remainder of the propulsion system. Part of the cost of the BEV battery is due to the requirement for output power, but the primary cost driver is from the requirement for enough output energy. The battery must deliver enough energy to provide sufficient range to make customers feel comfortable in everyday driving. For such range, an optimized propulsion system for a BEV must also include an electric motor that is

efficient over a wide range of driving conditions and an efficient mechanical connection from the motor to the wheels. This combination makes the best use of power and energy from the battery, so as to minimize the power and energy requirement on the battery while delivering appealing vehicle performance and range.

At the same time, this combination of electric motor and mechanical connection to the wheels, known together as the drive unit (DU), must also be lightweight and compact, in keeping with the need for an efficient vehicle. The drive unit must also be exceptionally quiet, as compared with the powertrain of a conventional automobile, to deliver one of the special benefits of the BEV, relatively peaceful driving. Furthermore, this particular drive unit must meet the commercial customer driving demands by being robust to different driving conditions, including hill climbing, merging, freeway driving and hot and cold temperature extremes.

GM used experience with the drive unit from GM EV1, the first modern production BEV, in the design of the 1ET35 for the Spark EV. The original concept vehicle for the EV1, the GM Impact, was one of the first vehicle demonstrations of neodymium-iron-boron permanent magnet (PM) motors, but in the early 1990s, the production of high-energy magnets was relatively immature. For production, the EV1 design used a relatively conventional squirrel-cage induction motor. Both

induction and PM type of electric motors were included in an optimization study of the 1ET35 as part of an optimum propulsion system for the Spark EV.

An induction motor uses current induced in the rotor cage to produce the rotor magnetic field, which also produces some resistance losses which would not be present if the rotor field were instead produced by high-energy magnets. Therefore, the optimization of a drive unit with an induction motor will tend toward a relatively high gear ratio to minimize torque on the motor, current in the rotor that produces this torque, and losses from this current. This gear ratio, about 10:1 in the case of the EV1, requires multiple stages, which are relatively easy to achieve with a double-offset (i.e. countershaft) gearing arrangement. The choice of an induction motor and a high-ratio double-offset gearing is a good pairing, and this combination of was used for the EV1.

For the Spark EV, high-energy magnets were already in production as relatively mature technology, so a permanent-magnet motor along with a single stage of planetary gearing and a relatively low gear ratio were selected, but only after an extensive study showed that this combination would be the best choice over induction and other types of electric motors and other types of gearing. Another factor, in addition to efficiency, that contributed to the selection of the single planetary reduction is the simplicity and proven durability of the gear set and differential assembly, which is also used as the final drive in GM automatic transmissions such as the GM 6T40 transaxle. This was part of a strategy to reuse parts already in production for other GM applications, to reduce cost, and improve quality and reliability.

METHODOLOGY

The first step was the determination of the appropriate DU architecture which needed a clear definition of the key customer performance requirements. The two most important requirements were to provide customers with a competitive driving range and a true fun-to-drive experience over a wide range of vehicle speeds. As with all BEV vehicles, driving range is paramount, which translates into high electrical efficiency and low mechanical drive rotational losses. BEV and HEV vehicles, historically, provide excellent low speed acceleration response due to the electric machine's inherent high low speed torque characteristic. However, providing both high efficiency and acceleration at a wide range of vehicle speeds usually results in a trade-off between range and performance.

Chevrolet Spark Electric vehicle's necessity to have competitive range on a wide variety of drive cycles translates to maximizing the range not only the EPA Urban and Highway but also the LA92 drive cycle. Various DU mechanical configurations and electric machine sizes were studied in order to select the correct system that met both range and performance requirements. A sample set of three DU concepts studied in the Chevy Spark vehicle are referenced in [Figure 1](#).

It is important to note that each of the three DU options shown in [Figure 1](#) where sized to provide enough peak axle torque for adequate low-speed vehicle grade-ability. Also all gear ratio values quoted in refer to the numerical speed ratio between EM and DU axle output speed. Option one, shown in green triangles, uses the GM EV1 design which was a high ratio (e.g. 10:1) double-offset gearing (three mechanical axes) paired with a high speed, low peak torque induction electric machine. Option two, shown in blue diamonds, uses a Chevy Volt type Motor B traction EM which is a larger diameter shorter length design with high-energy permanent magnets. Additionally option two used a single off-set gearing arrangement (two mechanical axes) to obtain a 6:1 ratio. Option three, the selected 1ET35 DU, shown in orange squares, is a coaxial low numerical gear ratio (e.g. 3.17:1) single planetary gearing paired (single mechanical axis) with a smaller diameter longer length EM with high peak torque and high-energy permanent magnets.

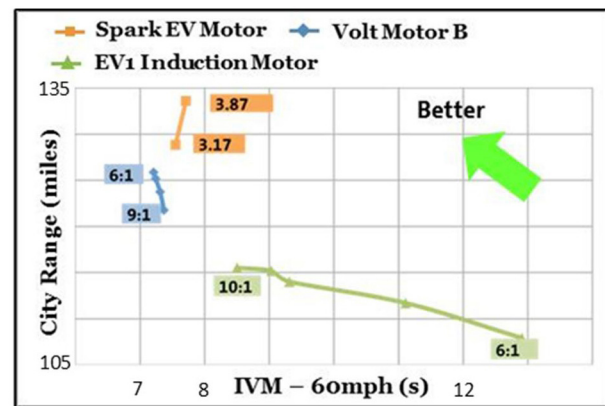


Figure 1. Single Speed Drive Unit Concepts Evaluated for Range and IVM (Initial Vehicle Movement) to 60 mph

As was previously stated the EV1 DU with a low peak torque high speed electric machine yields the best IVM (Initial Vehicle Movement) to 60mph acceleration and range at a 10:1. The Volt motor B results indicate that both range and performance are maximized by lowering the numerical ratio from 9:1 to 6:1. The Spark EV EM with its low speed high torque density design performs the best in range and performance at the 3.17:1 ratio and approaches but does not match the Volt motor B design in performance. It should be noted that the 3.17:1 ratio was selected over the 3.87:1 ratio in the 1ET35 because the lower ratio provided higher drive cycle range on the EPA Highway and LA92 drive cycles

Axle torque and power capability of the 1ET35 are shown in [Figure 2](#). Output torque capability is approximately 1700 Nm, which can be sustained to approximately 50 km/hr (30 mph). The Spark EV has very good low-speed acceleration, and under some conditions the torque from the DU must be torque limited to prevent wheel spin. The output power capability of the 1ET35 peaks over 100 kW and exceeds 90 kW throughout the usual speed range for highway traffic

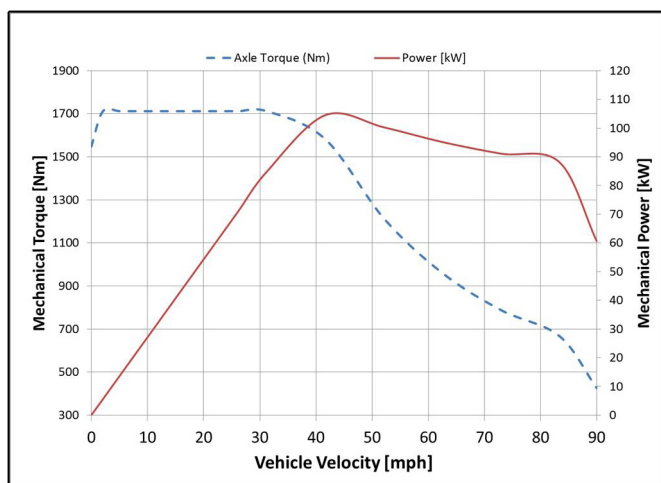


Figure 2. 1ET35 Tractive Effort

The Spark EV DU is more efficient than either alternative shown in Figure 1 due to its low mechanical losses and high electrical system efficiency. Low mechanical losses are achieved by implementing the same low speed compact planetary gear used as the final drive in GM's conventional automatic transmissions. The relatively low input speed results in low electric motor windage and oil drag losses. The utilization of an electrical oil pump reduces the oil churn losses caused by splash lube type designs by providing the exact amount of oil required for all driving conditions. Figure 3 outlines the mechanical spin losses as a function of axle shaft speed for the Spark EV compared to the GM EV1 and a competitor's electric rear drive module tested by GM.

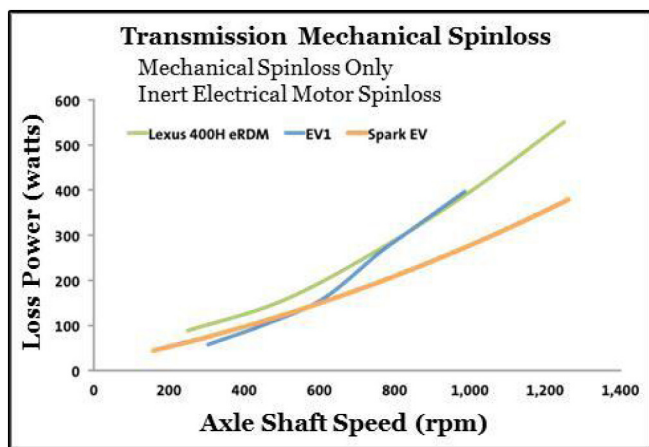


Figure 3. Mechanical Loss Comparison

ELECTRIC MOTOR

The key machine parameters are shown in Table I.

Chevrolet Spark BEV motor is permanent magnet alternating current synchronous motor type. The stator of the motor has bar wound construction. Bar wound construction has several advantages compared to the more conventional stranded type design, such as: higher slot fill, shorter end-turn length, improved cooling performance, fully automated manufacturing

process, and improved high voltage durability. Figure 4 below shows a partial view of the end of the Spark EM bar wound stator.

Table I. Chevrolet Spark BEV Motor Key Parameters

Motor peak torque	540 Nm
Motor Peak Power	105 kW
Peak motor speed	4500 rpm
Nominal DC bus voltage	350V
Rated motor current	450 Arms
Motor Outer Diameter	213 mm
Motor stack length	125 mm

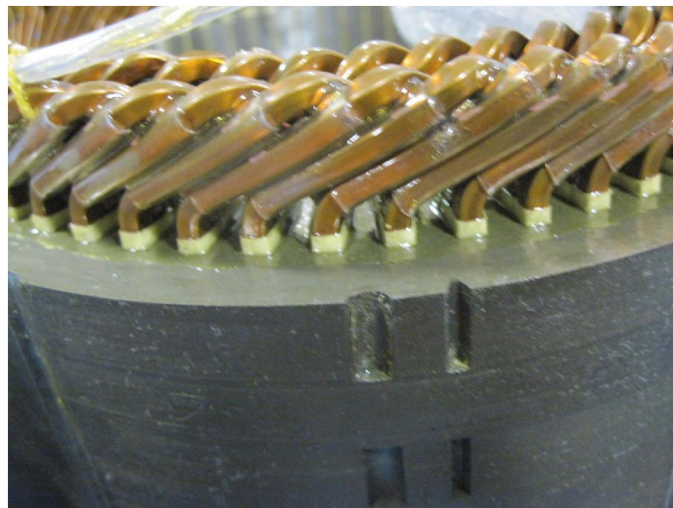


Figure 4. Bar Wound Stator End Turns of Spark EV Motor

The Chevrolet Spark EV bar wound stator has a wave winding layout, whereas lap winding is typically used for stranded design. Segments of the bar-wound stator winding called "hairpins" are pre-formed as shown in Figure 5 (a) and then inserted in the slots. A twisting operation bends them into a frog-leg type shape as shown in Figure 5 (b). The ends are then welded together to form the wave-winding pattern.

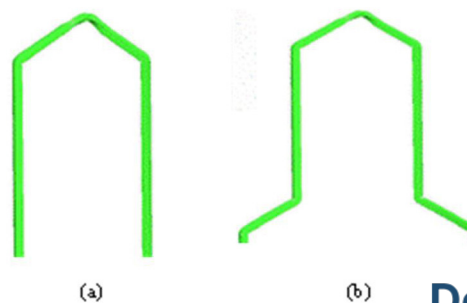


Figure 5. Hairpin shape before and after insertion (a) and after twist (b)