REMY INTERNATIONAL, INC.

WHITE PAPER

Inside the HVH™ Hybrid Motor

Technical Insights on Remy's "Off-the-Shelf" Hybrid Motor Solutions

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Executive Summary

In a time of increasing energy costs and growing environmental concerns, the movement toward hybrid and electric vehicles is inevitable and inexorable. Most market projections show hybrid and EV production reaching 2-3 million passenger vehicles as early as 2013, and vehicle electrification is expanding even faster in commercial, military, and off-road applications. This fundamental shift in vehicle propulsion and power generation presents market opportunities for forward-thinking individuals and companies. By developing a family of off-the-shelf hybrid motors that can provide drive torque and power generation, Remy International, Inc. has significantly lowered the cost of entry into the hybrid market, both technologically and financially.

Remy off-the-shelf hybrid motors incorporate proprietary High Voltage Hairpin winding technology and unique cooling strategies that produce the highest efficiency and power density available on the market. Designed with customers' needs in mind, Remy hybrid motors can be integrated into a wide range of vehicle platforms and powertrains, and customized to meet specific requirements. With the largest hybrid motor test facility in America and more than a century of experience in large-scale manufacturing of electric motors and alternators, Remy is positioned to meet the growing demand for powerful, reliable, and economical hybrid motors.

The Heart of the Hybrid

The development and large-scale production of hybrid vehicles require sophisticated solutions for propulsion, energy recovery and energy storage, especially when operation at peak efficiency is the objective. Battery technology and control systems may occupy the media limelight, but the heart of the hybrid is the motor/generator. Responsible for propulsion and energy recovery, the hybrid motor is where motion and electricity converge.

The electrification of transportation is gaining momentum worldwide. Driven by social, political, environmental, and financial factors, the global movement toward alternative fuels and nontraditional power sources provides opportunities for innovation. It also offers a vast and potentially profitable market. Enterprising companies that can supply engineering solutions and products to meet the needs of this emerging market have a window of economic opportunity.

Hybrid Applications

While fuel cells, hydrogen, and solar power may prove be more marketable at some time in the undefined future, electric/internal combustion hybrid powertrains offer real-world benefits that are achievable with current technology. Hybrid power systems can deliver improvements in overall vehicle efficiency and reductions in operating costs while minimizing environmental impact. Hybrid technology can be applied to a wide range of transportation, specialized equipment, and power-generation applications.

Typically used in parallel with an internal combustion engine, hybrid motors replace and/or supplement the IC engine as the vehicle's power source and recharge the battery during deceleration. Hybrid motors used as traction motors provide power directly to the wheels for vehicle propulsion.

As the cost of energy continues to climb, hybrid vehicles offer substantial benefits. Delivery vehicles used in stop-start urban driving cycles can recover energy that is otherwise wasted. When used to supplement the output of an internal combustion engine for acceleration and high-load situations, hybrid motors allow the use of smaller displacement engines with greater fuel economy. In turn, the smaller IC engine permits downsizing of related components and support systems for additional mass reduction and improved efficiency, and lower emissions.

The future of hybrid vehicles reaches far beyond light-duty passenger cars —medium- and heavy-duty trucks, mass transit vehicles, agricultural machinery, heavy construction equipment, and military vehicles are just a few of the candidates for hybrid powertrains.

Hybrid motors can also be used to power electrically-operated auxiliary devices such as lifts, conveyor belts, mining equipment, threshers, etc. The use of hybrid motors provides a degree of freedom in design that is impossible with mechanical systems Supplying power directly where it's needed through electrical cables eliminates the weight, complexity, maintenance cost, packaging issues, and expense of conventional mechanical and hydraulic PTO systems. Electric drives also provide virtually silent operation in noise-sensitive areas.

Hybrid motors can also break the paradigms of conventional vehicle designs, fostering functionality and efficiency improvements. For example, hybrid motors can eliminate the need for driveshafts and axles, enabling new configurations that range from improved under-vehicle blast protection in military applications to reductions in overall vehicle height to improve highway fuel economy. Hybrid motors offer vehicle and equipment manufacturers significant improvements in design flexibility and opportunities.

Remy's Hybrid Solution: Standardization

The start-up costs to design, develop, validate and manufacture hybrid power systems are prohibitive for all but the largest OEM manufacturers. Fortunately, there is a solution: "off-the-shelf" hybrid motors from Remy International.

The advantages of standardization are clear. By focusing on production of one common, reliable, well-designed component, Remy can design, build, test, and manufacture hybrid motors more economically, with the development and manufacturing costs spread across a family of related architectures and platforms. Just as manufacturers turn to specialist suppliers for tires, suspensions, and other key components, the availability of pre-engineered, standardized hybrid motors simplifies the design process for vehicle manufacturers, reduces up-front costs, and enhances performance and reliability.

The Remy Advantage: High Voltage Hairpin Stator

All hybrid motors are not created equal. Differences in the design and construction of the motor's primary components—the stator and the rotor—can significantly affect performance, size, weight, power density, efficiency, battery usage, durability, and reliability over the long haul.

Remy HVH™ hybrid motors owe both their name and their exceptional performance to the proprietary High Voltage Hairpin (HVH™) stator windings. In contrast to conventional round-wire windings, the HVH™ stator winding uses precision-formed rectangular wires. Multiple layers of interlocking "hairpins" produce a superior slot fill (up to 73 percent vs. 40 percent for typical round-wire windings). This patented design also creates a shorter end turn space than round-wire stators, thereby reducing heat and improving the motor's torque and power density, and lends itself to robust construction at the critical connections between the conductors. Combined, the high slot fill and shorter end turn space reduce the winding resistance causing less heat generation. The HVH™ windings are well-suited to liquid cooling that further enhances performance and reliability.

Figure 1
HVH Winding Configuration
Remy's proprietary High Voltage Hairpin (HVH™) stator windings improve performance and enhance cooling.

Reducing the overall size and mass of the hybrid motor with HVH™ technology drives cost reductions and performance improvements throughout the vehicle. A smaller, more efficient HVH™ motor can be more easily integrated in the vehicle. Battery size, inverter current handling capacity, and wire cable size can be reduced for additional savings. With its superior cooling capabilities and higher torque output, the HVH™ hybrid motor produces tangible gains in performance and customer satisfaction with continuous performance that is well above the peak levels offered by conventionally wound motors.

Tests have shown that an HVH™ internal permanent magnet (IPM) motor provides 27 percent higher torque and 34 percent higher power compared with the same size round wire winding IPM motor. At the same performance level, the HVH™ motor offers a 22 percent reduction in space requirements and 13 percent reduction in mass. In addition to documented fuel efficiency improvements, freight hauling capacity can be increased since more weight can be carried in the vehicle rather than in the hybrid drivetrain.

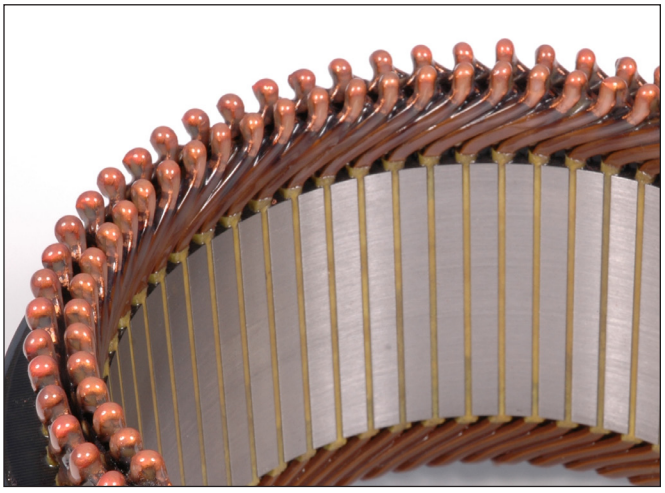


Figure 2
Remy HVH™ windings have a shorter end turn space than conventional round wires and are well-suited to liquid cooling.

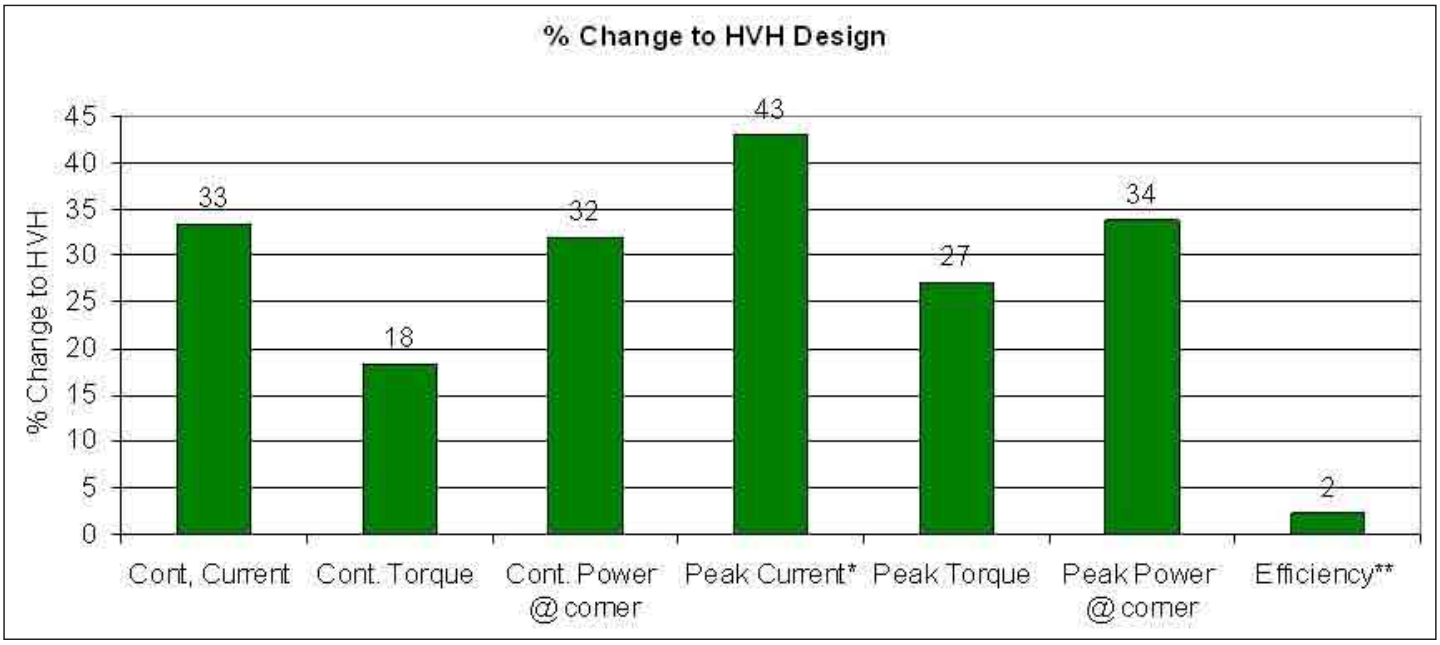
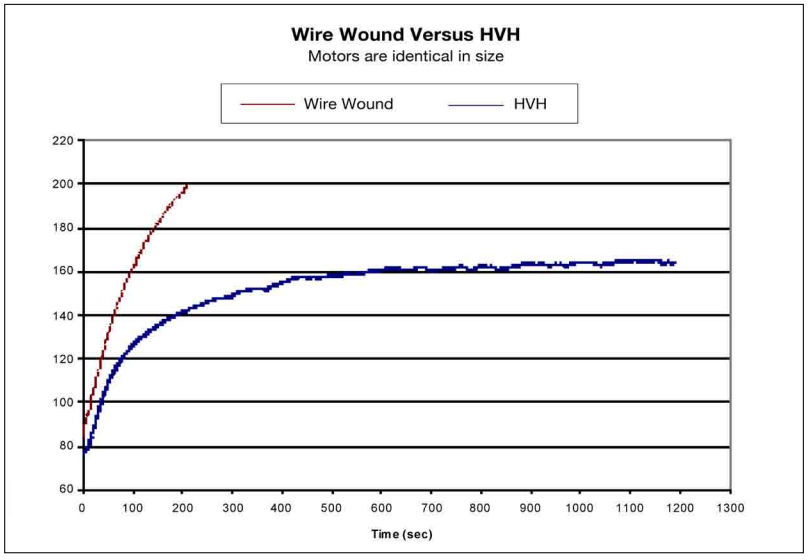


Figure 3 HVH Benefit vs. Round Wire
A Remy HVH™ internal permanent magnet hybrid motor produces 27 percent more torque and 34 percent more power than a comparable IPM motor with round windings.

The HVH™ stator design is compatible with both permanent magnet and AC induction rotors, giving engineers more options to achieve their design objectives. Although the data is for IPM, the gains are similar when HVH™ is used in AC induction machines. The difference between the two rotor constructions is analogous to the choice between a sports car and a family sedan: permanent magnets deliver higher performance at higher cost, while induction rotors offer moderate performance at a lower price. Acknowledging that both designs have a place in the market, Remy manufactures hybrid motors with both types of rotor construction, offering its customers options in performance and cost.

Cooling system efficiency has a significant impact on hybrid motor performance. Operating temperatures must be controlled to maintain output and to protect components that are susceptible to heat damage. While automatic transmission fluid is most commonly used as the cooling medium, Remy hybrid motors have also operated successfully with hydraulic oil.



In concert with an efficient cooling system, Remy's HVH™ stator design allows motor operation at higher power levels. During continuous operation, the HVH™ motor stays cool when a conventional winding has reached its thermal limit. In all competitive motor evaluations, Remy HVH™ motors were able to operate continuously at power levels that were peak power levels for rival motors.

Figure 4
Temperature comparison at full output torque of 3100Nm
Remy HVH™ windings combined with coolant enable continuous motor operation at high power levels.

Standardization Benefits

Remy's off-the-shelf hybrid motors make it possible for entrepreneurs, start-ups, and established companies to enter the hybrid market with a proven solution for integration. The availability of reliable, pre-engineered hybrid motors, in combination with compatible third-party controllers, jumpstarts the development process. Remy's modular designs provide a logical progression of sizes, performance levels, and capabilities that meet the requirements of many applications.

Remy has simplified vehicle integration by sizing its hybrid motors with SAE standards in mind, and has incorporated SAE bellhousing and transmission bolt patterns in its hybrid motor housings. More integration flexibility is achieved by offering a menu of motor and housing options:

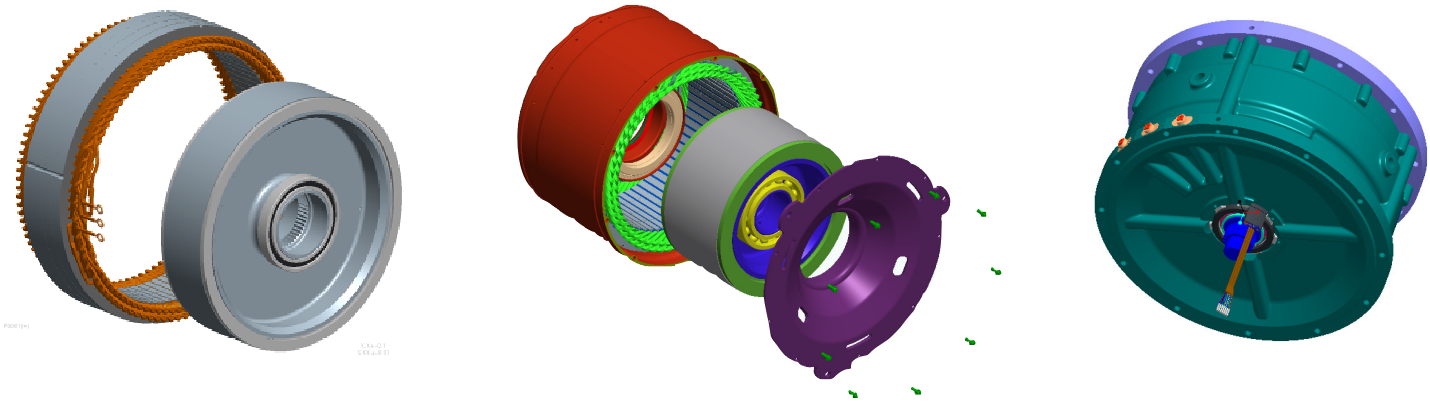


Figure 5
Motor and Housing Options

- Remy rotors and stators ready for customer installations into housings
- Remy motors delivered as "cartridges" of fully assembled and tested hybrid motors ready for installation
- Complete Remy hybrid motor and housing assemblies that use cartridge configurations or direct, shrink fit into housing stators.

Within this framework of "off the shelf" hybrid motors there is latitude to meet specific customer requirements. Motor length, winding pattern, voltage and current can be adjusted to achieve a variety of torque and power outputs. For example, Remy lowered the peak output of a hybrid motor from 2100 rpm to 1680 rpm to complement the vehicle's operating range. This was achieved with no loss in output torque, improved efficiency, and a 20 percent reduction in current, all of which resulted in improved customer satisfaction.

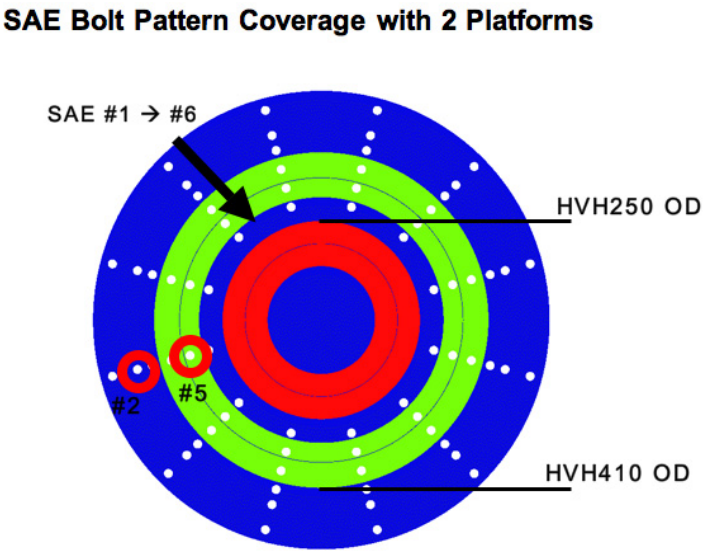


Figure 6
SAE Bolt Pattern Coverage
Remy has incorporated standard SAE bellhousing and transmission bolt patterns in its off-the-shelf hybrid motor housings.

Hybrid Motor Standards: Apples and Oranges

The criteria for evaluating hybrid motors include peak and continuous power, peak and continuous torque, temperature of operation, cooling system flow temperature, system configuration, physical package size, reliability, durability, and lifecycle cost. Unfortunately the industry has not yet developed standard test procedures to measure hybrid motor performance and efficiency. Consequently comparing different hybrid motors can be an "apples and oranges" situation. Without a recognized universal standard, test parameters such as current input, torque output, operating temperature, etc., can be skewed to favor one design over another. Remy cuts through this confusion by providing reliable test data under clearly specified operating conditions.

The U.S. Department of Energy has issued long-range target goals for hybrid traction motors in 2010, 2015 and 2020. Remy hybrid motors in current production already meet or surpass the DOE goals in important attributes such as power density and efficiency, with less coolant flow and lower current amperage than the DOE's targets.

LEADING THE MARKETPLACE IN HYBRID TECHNOLOGY

AHEAD OF DOE TARGETS

	2010 DOE Target	2020 DOE Target	2009 Remy Built
DC Bus Voltage (VDC)	325		325
Max Phase Current (A rms)	400		300
Coolant Temperature (°C)	90	105	105
Max Coolant Flow Rate (L/min)	10		6
Power Density (kW/kg)	1.2	1.6	2.3
Power Density (kW/L)	3.7	5.7	11
System Efficiency (%)	90	94	93

Figure 7 Remy Traction Motor vs. DOE Future Targets
Remy hybrid traction motors already meet or exceed DOE future targets.

Testing and Validation

Due to the high cost of repairing or replacing a hybrid drivetrain, either under warranty or as a service expense, a hybrid motor must be expected to operate reliably for the life of the vehicle. Moreover, the motor must provide this trouble-free operation while functioning in an extremely hostile environment.

With the largest hybrid motor test facility in America, Remy has the capability to perform accelerated lifecycle testing in-house. With decades of experience in high-volume manufacturing to a broad market, Remy has developed testing procedures for starter motors and alternators that have been adapted to the distinctive demands placed on hybrid motors. These tests subject the motors to extreme temperatures, vibration, environment and mechanical condition extremes. This rigorous testing program is a key element in Remy's zero-defect approach to hybrid motor production.

In recent automotive application testing, Remy hybrid motors ran as a population average to 840,000 vehicle-equivalent miles, with the longest motor operating to 950,000 vehicle-equivalent miles. The vehicle intended life for this application is 150,000 miles. This exceptional component life demonstrates Remy's commitment to reliable products through intelligent engineering.

Figure 8 Largest Hybrid Motor Test Facility in America
Remy operates the largest hybrid motor test facility in America

Manufacturing Capability

Although the hybrid vehicle industry is in its infancy, Remy is an established manufacturer with more than a century of experience and know-how in the complementary fields of electric motors and generators. Founded in 1896 as Remy Electric Company and operating as the Delco Remy division of General Motors until 1993, today Remy International, Inc., is an independent, global corporation with 48 facilities in 11 countries that employ 4,900 people and generate annual sales of $1.2 billion. In addition to producing more than 12 million starters and alternators annually, Remy is the world's largest independent producer of hybrid motors.

Designing, validating, and manufacturing hybrid motors is a complex process that requires a substantial commitment in both technical and human resources. Remy has the capacity to manufacture 100,000 hybrid motors annually with clients such as GM, Daimler, and Allison Transmission. Remy's investment in engineering, prototyping, testing and manufacturing facilities—and the people who staff them—provides a strong foundation and supports the complex infrastructure that is required to manufacture technically advanced hybrid motors.

Remy's experience and expertise in large-scale manufacturing of alternators and starter motors provides a strong foundation for its hybrid motor program. Remy produces over 10 million starters and alternators annually, and uses these technologies in the design of hybrid motors. For example, Remy routinely applies copper conductors in starters that carry 3400 amperes of current—more than 10 times the current than a typical hybrid motor requires. Remy's high voltage hairpin winding technology has been proven in decades of starter and alternator production.

Remy has already demonstrated its ability to mass produce high-quality hybrid motors while meeting its customers' quality, performance, and delivery standards. Remy has produced more than 4,000 electric motors for hybrid mass-transit buses since 2003, and has supplied more than 70,000 electric motors for hybrid cars, trucks and SUVs. These hybrid motors have been durability tested to 700,000 miles and meet stringent performance standards for noise, vibration, and seamless integration with the powertrain.

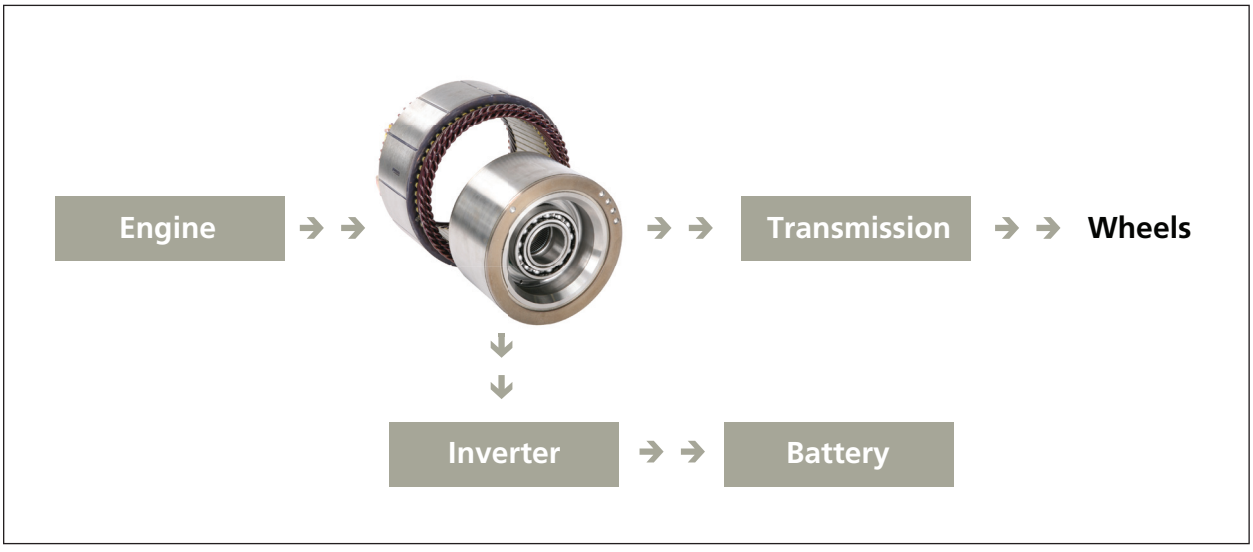


Figure 9: Remy hybrid motor
Remy electric power system for trucks and SUVs can use one or two high voltage hairpin electric motors.

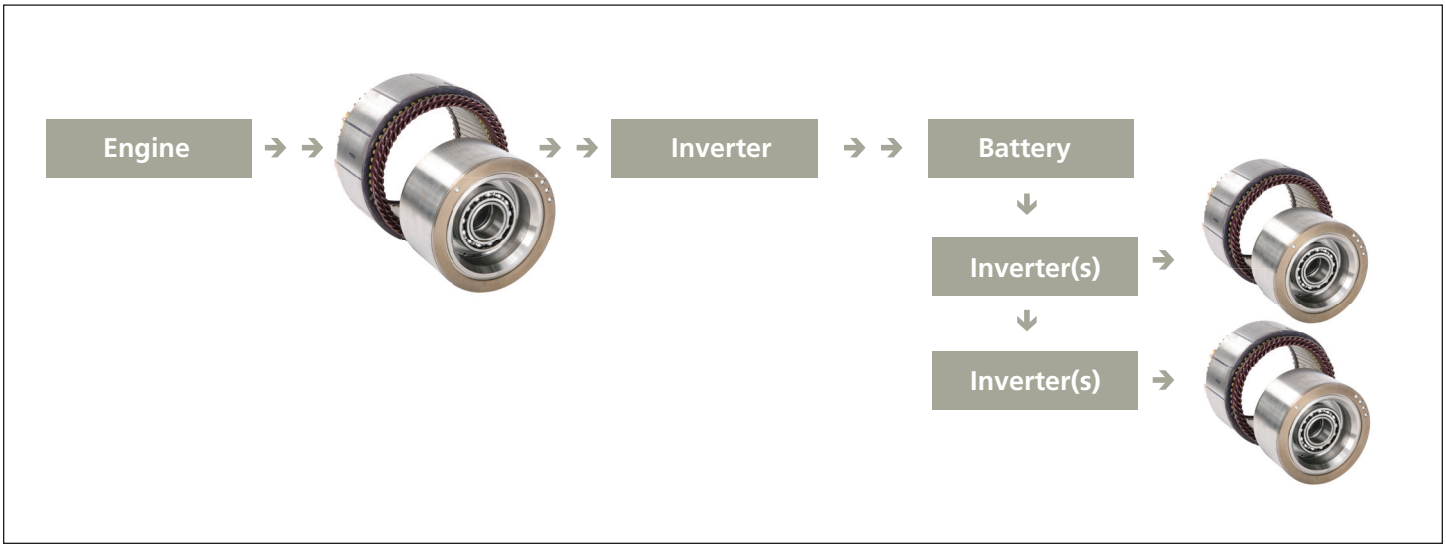


Figure 10: Remy power system
Remy three-motor system for traction and auxiliary power.

Future Motor Advancements

Although electric motors and generators are ubiquitous, their evolution is far from complete. A Remy alternator produced today has a power density approximately three times greater than the original design. Hybrid motor development is on a similar upward trajectory. Remy is employing sophisticated computer simulation programs to optimize magnet size, location and orientation. This in-depth analysis allows Remy to minimize undesirable torque ripple and cogging during hybrid motor operation, while offering maximum power and torque density with peak efficiency. This rigorous design process, in combination with precision machining and balancing of internal motor components, promises to yield a more comfortable, quieter, and vibration-free driving experience.

Department of Energy Grants

Remy has been nominated to receive a $60.2 million grant under the "American Recovery and Reinvestment Act—Electric Drive Vehicle Battery and Component Manufacturing Initiative." This is a matching funds grant to support U.S. manufacturing of components used to produce hybrid electric and electric vehicles.

Remy will use these funds to expand their portfolio of off-the-shelf products. The funds will offset manufacturing, tooling, and non-recurring engineering costs, thereby making hybrid systems more readily available to the industry. Funds are also available to help Remy customers apply these motor/generators to their vehicles. For example, Remy can provide custom housings for various commercial application configurations through the use of DOE grant funds.

Conclusion

Remy International Inc.'s family of off-the-shelf hybrid motors is designed to meet customers' needs for pre-engineered solutions. With proprietary features and advanced cooling technology, Remy hybrid motors offer best-in-class performance, efficiency, and power density. Designed for easy integration with vehicle platforms and powertrains, Remy hybrid motors are suited to a wide range of commercial, industrial, agricultural and military applications. Remy is a center of excellence for electric motor technology, with the engineering experience and manufacturing capabilities to provide customers with economical, reliable, high-performance hybrid motors for today and tomorrow.