PERMANENT MAGNET MOTORS/GENERATORS FOR AUTOMOTIVE APPLICATIONS

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ABSTRACT

This paper presents the permanent magnet motors and generators for automotive applications. The automotive industry trend and prediction of the future electrical systems using permanent magnet materials are also presented. In this article, the three major motor configurations and enabling technologies that support higher power electrical systems are presented. Special focus is given to current and future permanent magnet devices for specific vehicle applications such as the starter-alternator, 42-volt issues, hybrid and electric traction motors, turbocharger generator, and vehicle cooling system using permanent magnet material.

I. INTRODUCTION

1. ELECTRIFICATION

Electrification of the automobile was the challenge at the beginning of the 20th century. At the turn of the century, there were more electric automobiles than gasoline powered automobiles in the U.S. In 1912 Charles Kettering introduced the first electrical system on a car (about 200W) making possible electric starting, lighting and ignition, forever changing the usefulness of the automobile. As we enter the 21st century, the same challenge resurfaces in light of the need to reduce emissions and dependency on foreign oil. Today's 2 kW platforms need to be replaced with the 20 kW or even 50 kW platforms on which a host of electrically generated functions will be enabled - some of which we have not even conceived. The mechanical powertrain will be augmented by rotating electric machines commutated by sophisticated power electronic controllers providing electrical power for more efficient systems such as electric power steering, electric passenger compartment heaters, electric coolant pumps, electrically active suspension, electric brakes, auxiliary power unit options and much more.

There are two reasons why the automotive industry needs high power density, high efficiency, and affordable electromagnetic devices for its ever-increasing customer and society demands. First, the total amount of petroleum is limited and second, the air needs to be cleaner. Fuel efficiency is getting more important in relation to air pollution and the supply of fossil fuels in the next 10-20 years.

The general worldwide trend in the automotive industry is to increase electrical power, while at the same time, the requirements for reduced fuel consumption and emissions are becoming more restrictive. The customer's demand for safety, comfort, and quality of driving is another reason for explosive growth in electrical power generation capability of automotive electrical systems.

2. AUTOMOTIVE INDUSTRY TREND

During the last two decades, the electric motor applications have increased almost exponentially, due to of the advent of low cost and high performance electronics with an accompanying improvement in permanent magnetic materials.

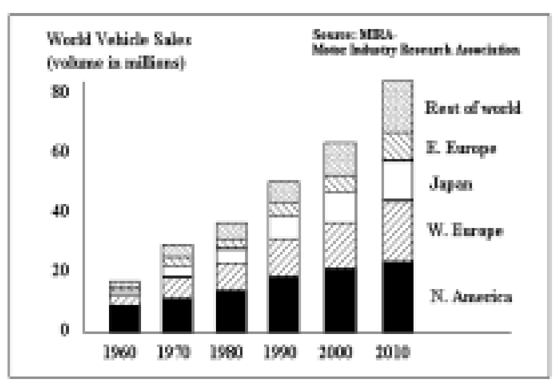

Figure 1. World Vehicle Sales Comparison and Forecast

The automotive electrical/electronics market is expanding at a phenomenal rate. Every year there are 45 million more cars on the street. Figure 1 shows world vehicle sales comparison and forecast. It has been predicted that the world vehicle sales will be 50% higher in 2010 than in 1990. Figure 2 shows the number of electric motors applied in an automobile.

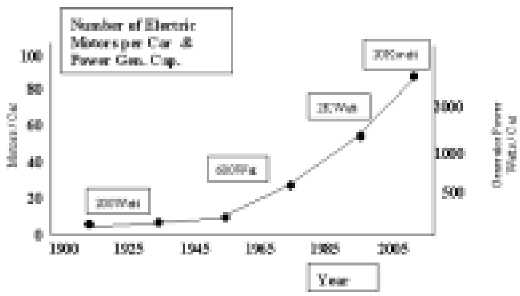

Figure 2. Number of Electric Motors in a Vehicle

Each vehicle has approximately 40-100 electromagnetic devices. In addition, there has been a substantial increase in the electronic content over the last two decades. Electric motors have also begun to play an important role along with energy storage devices in the future-vehicle industry such as the hybrid electric vehicle (HEV) and electric vehicle (EV). No matter what is the energy source for the HEV/EV, electric motor need to be there for propulsion.

The market value is estimated to reach $100 billion by year 2005, more than double its 1995 figure. According to the latest university and industry presentations, the vehicle electrical/electronics market is growing about 20 % annually. Even though the price of most electrical/electronics devices continues to decrease, their percentage of total vehicle cost is still predicted to rise steadily from about 20% to 25% by 2010. There are two major forces behind this increasing high efficiency: high power density, and affordable prices for electric motors in the automotive market to meet the requirements to increase fuel economy and consumer demands.

II. HIGH VOLTAGE ISSUES

1. MOTIVATION/BACKGROUND

Interest in higher voltage for automotive electrical systems has been increasing in the past couple of years. The interest has been driven by the need for increasing electrical power required for features and functions that would improve fuel economy and emissions, as well as customer comfort. Trade publication articles relative to higher voltage systems have appeared in August, September, and October of 1998, reflecting the increased interest in the subject.

In 1989 the North American car companies were recognizing the need for higher voltage systems to meet their future power needs. SAE, at the urging of the Ford Motor Co., established the “SAE Dual-High Voltage Committee” to develop guidelines for application of such systems. An early result of the SAE Committee effort was the publication of an Information Report J2232 identifying the maximum voltage (48 volts) that should be considered from an electrical shock safety perspective. An SAE Paper was published reviewing the pros and cons of higher voltage. As the anticipated cost of the move to higher voltage became clearer, some of the enthusiasm for higher voltage began to wane.

European car companies in 1996 began to be concerned about the future shortage of vehicle electrical power for the future. Mercedes led an effort to have MIT establish a Consortium of car companies, suppliers, and other stakeholders in vehicle electrical systems. Its goals are to identify the issues, potential solutions to the deal with the issues, and gain broader support in the industry for higher voltage systems. The European focus is on 12 - 36 volt (14 - 42 volt generator voltage), and this is the focus of the MIT Consortium effort. European car companies currently have programs targeting 2001and 2002 for introduction of these 14 - 42 volt systems in passenger cars.

2. BENEFITS OF HIGHER VOLTAGE

There are tangible benefits to the vehicle using higher voltage systems. Among them are:

- Current for high power loads is reduced in proportion to the increase in voltage. In the 36-volt system the currents will be reduced by a factor of 3.
- Overall system efficiency is increased by the reduction in current, which improves fuel economy and reduces emissions.
- Wiring systems are reduced in size and weight.
- The size and cost of power semiconductors are reduced at lower currents.

- Higher voltage enables the use of new features and functions that require high power:
- Starter – Alternator, like ISA (fuel economy and emissions improvement)
- Electric power steering (fuel economy and emissions improvement)
- Electric air conditioning compressor (fuel economy and emissions improvement)
- Electromagnetic engine valve actuation (fuel economy and emissions improvement)
- Damping of torsional vibration in the engine (improved operator comfort and engine reliability)
- Electric water pump (fuel economy and emissions improvement)
- Electrically heated catalytic converter (reduced cold start emissions)
- Steer by wire (reduced system complexity)
- Brake by wire (reduced system complexity)
- Electric turbocharger (improved performance and higher efficiency)
- Active suspension system (passenger comfort)
- Mobile office (operator convenience)

3. ISSUES to HIGHER VOLTAGE

The major down side is cost: The cost of the system, and the cost of making a large change to exiting production vehicle systems. The tendency is to view the cost of the higher voltage system in its relation to today's system cost, but this is not realistic. One has to view the cost of higher voltage systems in relation to the cost of meeting the new regulation (emissions and fuel economy) goals with alternative methods. The bottom line is that the regulatory requirements must be met.

Higher voltage system and issues

III. ELECTRIC MOTOR TECHNOLOGIES

In this section, the three most common electric motor technologies and the power electronic devices with control circuits in vehicle applications are discussed. The three motors are the permanent magnet (brushed and brushless type) motors, induction motors, and switched reluctance motors. Among those three motor configurations, the permanent magnet motor type is more widely applied in the vehicles because of its merits.

An electric motor is a well-known device that converts electrical energy to mechanical energy using magnetic field linkage. An electric motor consists of two major elements: (1) a fixed stator with current-carrying windings or permanent magnets, (2) a rotating rotor which, provides a magnetic field produced by additional current-carrying windings or attached permanent magnets between the rotor and stator magnetic fields.

Modern electric motor advances have resulted from developments and refinements in magnetic materials, integrated circuits, power electronic switching devices, computer modeling and simulation, and manufacturing technology, rather than by fundamental changes in operating and control principles. The dramatic improvements in permanent magnet materials and power electronic devices over the last two decades have led to the development of brushless permanent magnet motors that offer significant improvements in power density, efficiency, and noise/vibration reduction. Also, because there is no electrical sparks, there is less radiated noise.

1. PERMANENT MAGNET MOTORS

The permanent magnet machine is highly coveted for its high power density and high efficiency. This is mainly due to the high energy density NdFeB and SmCo magnets, which are commercially available today. In other words, advancements in high-energy permanent magnet materials and magnet manufacturing technologies enabled the manufacturing of high power density and high efficiency permanent magnet motors at a reasonable cost. Also, the availability of fast switching high power semiconductor devices with low on-state voltage drop such as MOSFETs and IGBTs. Ever increasing high-speed microprocessors/digital signal processors have contributed to permanent magnet electric motors. While the cost for semiconductors and the permanent magnets is still high at the present time, trends for cost reduction are continuing and encouraging.

A. Brush Type Permanent Magnet Motor

There are two types of permanent magnet motors: brush and brushless. Today's vehicle applications almost exclusively use brush type permanent magnet motors.

The brush permanent magnet motors have four general characteristics that cause them to be useful for vehicle application: 1) desirable torque versus speed, 2) simple control of torque and speed, 3) high electromagnetic power density, and 4) inverters are not required.

Nevertheless, there are six general characteristics that detract from more wide applications in the automotive industry: 1) friction between the brushes and the commutator, 2) brushes and commutators require maintenance, 3) current is supplied to the armature through the brushes and commutator, 4) brushes and commutators are open and produce sparking, 5) cooling of a DC motor is difficult, and 6) switching of large currents is required for control of DC motors.

The brushless motors are becoming stronger candidates over traditional brush type motors for the following reasons: higher efficiency, higher power density, better heat dissipation, and increased motor life. In addition, brushless motors experience no losses due to brush friction and they deliver higher torque compared to a brushed type motor of equal size and weight.

B. Brushless Type Permanent Magnet Motor

Electronically commutated, brushless permanent magnet motors are however, becoming prime movers in vehicle propulsion, industrial drives, and actuators as a result of improvements in permanent magnet materials, advances in the power electronic devices, and power integrated circuits in the last two decades. Not only have there been gradual improvements in Alnico and Ferrite (ceramic) alloys, but the rapid development of rare-earth magnets, such as samarium-cobalt (Sm –Co) and neodymium-boron-iron (Nd B Fe) around 1980, have provided designers with a significant increase in available field strength. This new high density, brushless, permanent magnet motor system provides a very high torque to inertia ratio. Figure 3 shows radial and axial field permanent magnet motors.

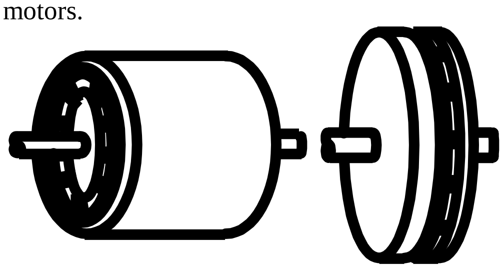

Figure 3. Schematics of radial field and axial field permanent magnet motors

C. Permanent Magnet Materials

Figure 4 summarizes the four most common permanent magnet materials used today by motor manufacturers. In most cases, the higher remanence with higher coercivity in a permanent magnet is desired by motor designers.

The alnico magnet provides a fairly high remanence flux density but a low coercive force. When the coercive force is low and two opposing magnetic poles are in proximity of each other, the magnetic poles can weaken each other and there is a possibility of permanent demagnetization by the opposing field.

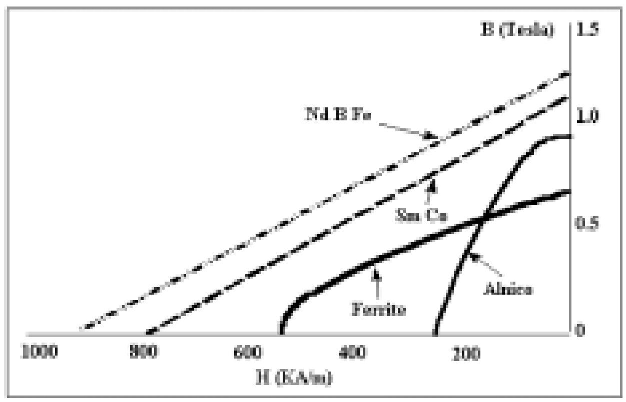

Figure 4. Demagnetization Characteristics of Permanent Magnet Materials

Unlike an alnico magnet, the ferrite magnet has a low flux density, but a high coercive force. It is possible to magnetize the ferrite magnet across its width as a result of this high coercive force. Ferrite magnets are most widely used in electric motors because their material and production costs are low. The cost of a typical ferrite magnet material at this time is about 6-8 times lower than the Nd B Fe. Nonetheless, output power to weight ratio is 1.22, ferrite, vs. 1.36, Nd B Fe. This means that the ferrite magnet motor will be about 20% heavier for the same output compared with the Nd B Fe magnet motor. Another measurement is an output power per unit cost of active material. It is predicted that the output power per unit cost is about 4 times lower for ferrite magnet motor compared to the Nd B Fe magnet motor. Delco Remy uses the ferrite and Nd B Fe magnets for different starter motor applications.

Rare-earth magnets have both high magnetic remanence, and high coercive force. Since the initial cost is high, these permanent magnets are used in applications such as high performance and high-energy density motor applications. For a given volume, the flux density is twice that of the ferrite, leading to a larger torque production. Nd B Fe magnetic materials are superior to any other magnetic material now on the market. The only disadvantage of using an Nd B Fe magnet, as opposed to an Sm Co magnet, is that the high-energy density Nd B Fe permanent magnet has a maximum operating temperature of 100 to 150 degrees C, as compared to 200-300 degrees C for Sm Co, alnico, and ferrite.

2. INDUCTION MOTORS

Alternating current (AC) induction motors are the most common of all types of electric motors manufactured for the general use in household applications, industrial drives, and electric propulsion. These motors are rugged, relatively inexpensive, and require very little maintenance. They range in size from a few watts to about 15,000 hp. The induction motors have certain inherent disadvantages including speed which, is not easily controlled, plus it runs at low lagging power factors when lightly loaded, and the starting current is usually five to seven times full-loaded current. Figure 5 depicts a typical induction motor stator and rotor.

Figure 5. Typical Induction motor stator and rotor.

The stator is composed of laminations of high-grade steel with slotted inner surface to accommodate the current carrying wires. The stator lamination and windings are essentially the same as those used for the brushless permanent magnet motor. There are two common rotor constructions in induction motors. The squirrel-cage rotor is built with a very small air gap and equipped with close-fitting ball bearings rather than sleeve bearings. The second type of rotor construction is the wound rotor. Regardless of the rotor construction employed, the rotor currents in an induction motor are induced by the stator's changing, or rather, rotating magnetic field. This induction action is the central operating principle of AC induction motors.

An AC induction motor, when driven from a battery source by an appropriate inverter, has external characteristics that are well suited to vehicle propulsion and other applications. Unlike brushless permanent magnet motors that must have rotor position sensors to be operated from inverters, rotor position feedback is not needed for inverter drive of induction motors. It is useful however, to have feedback of rotor speed when an induction motor is to be operated from an inverter because, although it is not required for operation, feedback of rotor speed provides the means to have closed-loop control of induction motor speed and slip.

Induction motors have relatively low manufacturing cost and are mechanically rugged because they can be built without slip rings or brush and commutators. Consequently much attention has been given to induction motors for automotive applications in the areas of vehicle propulsion, engine starting, braking, electricity generating, speed reversal, speed change, etc. In spite of many interests in vehicle applications, the costs of the power electronic components are still relatively high, especially in the low power region. Furthermore, in many automotive applications it is either not possible or not desirable to use a mechanical sensor for speed or angle, etc. This means, a simple and affordable control system, using only the voltage and the current of the induction motor as measured quantities, is necessary. A sensorless controller technology has been demonstrated using a switched reluctance motor by many academia and industrial teams.

3. SWITCHED RELUCTANCE MOTORS

Permanent magnet motors and induction motors are the most commonly used in drive motors for HEV and EV as well as other electric motor applications in the vehicle. Recently there have been increased activities in switched reluctance motor technology due to the high performance, fault tolerance operation, simplicity of construction, and better cost-effectiveness than, rare earth permanent magnet motors.

There are four reasons that support the switched reluctance motor technology as another widely developed motor type:

1. Economical yet powerful computational computers and its software
2. High frequency power electronic devices such as MOSFETs and IGBTs with affordable cost
3. Better understanding of the switched reluctance technology
4. Integrated design of motor and electronics capability.

Despite their gaining popularity, further work is necessary and is being applied to improve torque ripple, noise, and other unsolved systems design issues.

The switched reluctance motors have demonstrated performance comparable to induction motors and permanent magnet motors in terms of specific torque, power, operational speeds, and overall system efficiency. In addition, switched reluctance motors also have the potential of operating in severe environmental conditions, being simple to manufacture and hence less expensive, and having excellent fault tolerance characteristics.

The construction of a switched reluctance motor is shown schematically in Figure 6. Typically a switched reluctance motor has salient poles (i.e. poles having a well defined, protruding, geometric shape) on the rotor and also on the stator, hence the name 'doubly-salient' motor. Only the stator has current-carrying conductors; the laminated rotor is made up of salient poles and the core, without any windings or permanent magnets. The stator and rotor cores are laminated to reduce eddy currents, and the coils are wound around each stator pole, see Figure 6. This construction feature makes the rotor very rugged and easy to manufacture. One important feature of the switched reluctance motor is the different number of poles on the stator and the rotor. The windings of diametrically opposite stator poles are connected in a series to form the electric phases of the motor. For each electric phase, a power electronic circuit with one or two electronic switches is necessary for the control of unidirectional current flowing during appropriate intervals for the torque production. Exciting the stator coils in sequence produces the torque in the motor. This requires an inverter (i.e. a set of electronic switches such as MOSFETs or IGBTs), which drives the motor from the battery's DC voltage supply.

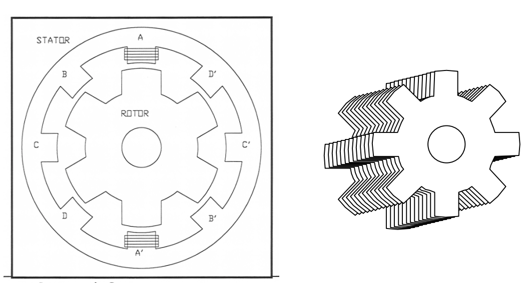

Figure 6. Schematic Cross-section of a Switched Reluctance Motor with 6 Stator Poles, 8 Rotor Poles.

In conclusion, the switched reluctance motor has several good features that make it attractive for a range of variable automotive application. These include:

- High efficiency over a wide range of torque and speed.
- High torque capabilities at the low operational speeds.
- Simple and rugged rotor construction.
- Fault tolerant, four-quadrant operation.
- Suitable for extreme condition operation.
- The wide use of switched reluctance motor technology requires that improvements need to be made on noise and torque ripple.

IV. STARTER, GENERATOR, AND ISA

In this section, three magnet devices are presented. Two major electromagnetic devices, starter and generator are presented and the integrated starter/alternator (ISA) is also discussed.

1. STARTER AND GENERATOR

The automotive starter (sometimes called a cranking motor) dates back to the early part of the automotive industry. In 1912 the Cadillac Motor Car Company introduced the electric self-starter to replace the hand crank. Frank and Perry Remy of the Remy Electric Company were also early innovators in the automotive industry. Remy Electric also developed and introduced starting motors in the same time period. This innovation in essence broadened the accessibility of the automobile from those strong enough to hand crank to virtually everyone.

Figure 7. Delco Self-starter-generator unit - 1912

There have been many developments and refinements in the starting motor since its introduction in 1912 (see Figure 7). The primary innovations focused on the engagement method, changing from six to 12 volts, and gear reduction. From the 1980s to today the industry has focused on size and weight reduction as well as reliability and durability improvement.

2. OTHER ELECTRIC MOTOR APPLICATIONS IN VEHICLE

The following list is a partial summary of current electric motor applications and near future products under development.

Power train:

starter motor, alternator, electric engine cooling, air conditioning compressor drive, idle speed control, engine throttle control, intake manifold valve actuator, transmission shifter, electrically variable transmission, engine coolant pump motor, electrical valve, EGR actuators

Chassis:

electro-power steering system, ABS pump drive, electro-hydraulic power steering, brake-by-wire actuators, active suspension actuator, 2-4 wheel drive actuator

Body:

windshield wipers, window lifts, seat adjuster, seat vibrators, sunroof actuators, sliding door closers, doorlock mechanisms, headlamp adjuster, mirror adjusters, steering column adjuster, HVAC blower, cruise control, headlight wiper motors, power antenna, headlight doors, trunk closer, auto-leveling system.

Figure 8 shows a pictorial view of those electric motor applications in a vehicle.

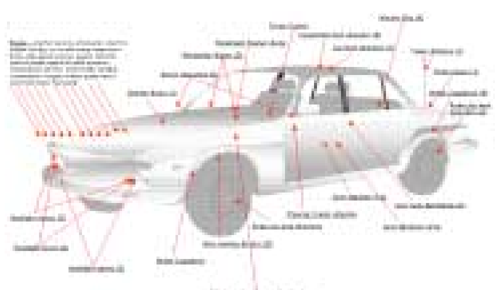

Figure 8. Electric Motor Applications in a Vehicle

4. ALTERNATOR (GENERATOR)

Another major electromagnetic device used in the vehicle is an alternator (generator). The most common generators in the markets are a non-permanent magnet wound field type.

There will be many opportunities to apply the permanent magnet material technologies to generators if it is possible to do without adding extra cost and sacrificing performance of current product.

5. INTEGRATED STARTER/ALTERNATOR SYSTEM

A. Background

This section presents an integrated starter-alternator (ISA) system developed for IC engines and HEV applications to reduce the fuel consumption, reduce emissions, and enhance energy efficiency. The new starter-alternator combination provides a more efficient and higher output platform, which will enable the vehicle designer unique ways to reengineer many functions under the hood. Virtually any accessory which is presently belt driven, may be converted to an electrically powered counterpart with the ready availability of more electrical energy from the larger alternator component of the system. Hydraulic power steering units, belt driven air conditioning compressors, and various fluid pumps and their components could be replaced with more efficient electric motor-driven systems powered by the ISA. Figure 9 shows Honda ISA system.

Figure 9. HONDA ISA with IC Engine

Starting motor advantages of the new ISA system include a quiet start feature because the gears and whine of the traditional starter will be eliminated. This system will be able to increase the starting speed and also support the acceleration phase. Less part count will further decrease the total system weight and increase the system reliability. The ISA system has all the functions of the engine starter motor and alternator in one electric system installed between the engine and gearbox without significantly increasing the weight and volume of the vehicle.

B. ISA System Description

The ISA system will provide more electric power than is currently available to satisfy the medium and heavy-duty vehicle requirements of future vehicle generations. Functions like the automatic start-stop feature and the absorption of torsional vibrations provide additional customer value in terms of fuel costs savings and comfort.

The machine can be an induction, permanent magnet, or switch reluctance configuration with its rotor mounted directly to the engine crankshaft at the location of the flywheel. The stator is mounted in the bell housing of either the engine or transmission.

The ISA system makes it possible to dispense with the conventional starter motor including the magnetic solenoid, conventional alternator, a V-belt or flat-belt pulley, a vibration absorber on the crankshaft. The ISA system is comprised of the electric motor, power electronics, and battery or starting electrochemical capacitor. In conclusion, the ISA system can achieve almost twice the efficiency at >80% compared to the conventional alternator at 50%, fuel consumption is reduced, reduction in emissions of CO, HC, Nox, and particulate, reduction in air pollution caused by CO2, and reduction in cyclic irregularities and engine vibrations by more than 70%. The generic 3D model of Figure 10 depicts the location of the rotor and stator of the ISA system relative to other engine components.

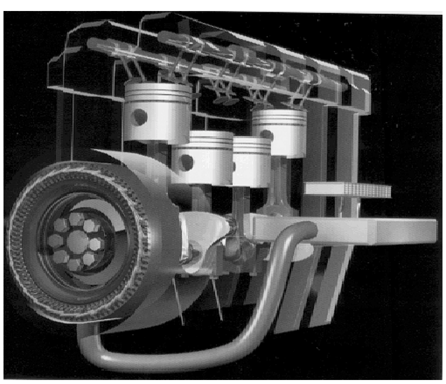

Figure 10. Continental-Delco Remy ISAD 3-D Solid Model

The higher efficiency electrical system can reduce fuel consumption and emissions because less fuel is wasted in the production of heat in the various parts of the vehicle system. These reduction amounts can be estimated based on information already available. The higher voltage, higher power system enables other features to be added to the vehicle which can further reduce fuel consumption and emissions by improving the basic control of the engine. The results of adding these features cannot be estimated quantitatively at this time because these features have not yet been developed to point where the estimates can be made.

The engine can be cranked up to its normal idle speed before fueling begins. Because of the heat this high speed cranking produces in the combustion chamber the fuel, when injected, is more readily vaporized improving combustion and reducing cold start emissions. Audible noise normally associated with engine cranking is almost eliminated as an added feature of the system.

The power available with this system will be high enough to operate electromagnetic engine valves. The control flexibility of electromagnetic valves can lower emissions as well as improve fuel economy and engine performance.

The higher power capability could make electrically powered exhaust stream after treatment systems more viable as a means of further reducing emissions.

As in the case of emissions, probably the more significant fuel economy improvements will result from the new features the higher power electrical system will enable.

The ability to use electromagnetic engine valves will enhance fuel economy as well as emissions. The system can function as a retarder in which a portion of the kinetic energy of the vehicle can be recovered during coasting and braking and stored the battery. The amount of regenerative braking energy that can be recovered and used will depend on the storage capacity of the battery system, and this will establish the actual fuel economy improvement.

Some devices on the vehicle that are now driven mechanically could be driven electrically, since the needed power will be available. Components such as the air conditioning compressor, the water pump, and the power steering system can then be operated only on demand, instead of remaining a continuous parasitic load on the engine when they are in the "off" part of their operating cycle. This will further reduce fuel consumption and emissions.

V. NEAR FUTURE APPLICATIONS

- Camless electromagnetic valve system.
- Turbocharger generator
- Permanent magnet traction wheel motor
- Electric variable transmission
- Vehicle magnetic air conditioner

VI. CONCLUSIONS

The automotive industry trend and prediction of the future electrical systems using permanent magnet materials is presented. The higher power density of electrical systems requires more powerful and affordable permanent magnet materials for the near future devices.

Today's 2 kW platforms need to be replaced with the 20 kW or even 50 kW platforms on which a host of electrically generated functions will be enabled - some of which we have not even conceived.

The three major motor configurations and enabling technologies that support more electrical systems to vehicle application are presented. Special focus is given to the three current specific vehicle applications such as the starter motors, alternators, and integrated starter/alternator system.

In recent years the demands for higher electrical power, as well reduced fuel consumption and emissions, are placing pressures on the electrical system that are pointing to the need for alternative technologies to meet the needs of the future. There are some methods of reducing fuel consumption and emissions that could use 3 to 4 times more power, but current high volume alternators cannot be modified to deliver this amount of power. The ISA system is a candidate technology to provide the necessary paradigm shift to meet this future needs.

Low cost materials, affordable power electronics, multi-functional control circuits, and advanced manufacturing technologies will expand more electrical systems in the future vehicles.

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