Power Dense Induction Motor and Coordinated Inverter Drive

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Abstract

The technologists at the Electric Vehicle Institute (EVI) on the campus of Bowling Green State University have developed a unique liquid cooling system for induction motors that enables a highly power dense electric machine. The liquid coolant is delivered directly to the rotor and stator unlike traditional methods. The cooling system combined with winding adjustments to accommodate high frequency and high current has culminated in a family of induction motors capable of high power output relative to size and cost. These power dense motors have been rated from 50 to 300 peak kilowatts and fit NEMA frame sizes of 180 to 326.

The applications of these motors to date have required three-phase power operating from direct current sources. To provide for this a power matched variable frequency inverter was also developed. These compact inverter drives have been developed with both air and liquid cooling systems. The power dense induction motor and coordinated inverter

drive combination was first developed for a high performance battery powered racecar in 1994. Since then, EVI motor and drive systems have seen application in a large hybrid electric transit bus and a dynamic load simulator test rig for the development of flight control actuators of the next generation NASA space shuttle. Currently the motor and coordinated drive is being applied to a patented hybrid electric drive system using ultracapacitors for energy storage.

This paper focuses on the development, features, and applications of the unique power dense motors and coordinated inverter drives which were prototyped and tested at the Electric Vehicle Institute. The content is presented as a case study under the following headings:

- The "need for speed" - electric formula racing
- Principles of the power dense induction motor
- Principles of the power dense cooling system
- Coordinated inverter drive development
- Inverter drive ongoing research and development
- Interfacing inverter drive with high speed control networks
- Applications of the power dense motor and coordinated inverter drive

The "need for speed" - electric formula racing

In 1993 a novel approach to electric vehicle development was initiated by long time race promoter and enthusiast Ernie Holden. His premise was to develop electric vehicles through racing competition similar to what motor sports has done for traditional vehicles. Most automakers at the time balked at the development of electric vehicles and professional race teams were skeptical of electric vehicle performance. Undaunted, Mr. Holden realized that unbiased university student teams might be up to the task. Mr. Holden pitched his idea to electric utility companies that were looking for ways to promote electric power use. A group of electric utilities recognized the opportunity and provided the financial support to make the electric racing competition a reality.

The "Formula Lightning" university racing series, which he launched in 1994, ran for more than ten years and successfully demonstrated the viability of electric drive technology. Bowling Green State University (BGSU) was one of a select number of universities to participate in the Formula Lightning series. BGSU's Formula Lightning team, under the direction of the Electric Vehicle Institute, has been considered by many to be one of the most successful in transferring knowledge gained from the racetrack to practical application.

The fledgling team at BGSU received a rolling chassis in the fall of 1993 and was challenged with developing and installing an electric drive for the first race in less than six months. A major task facing the team was the selection of available motor technology to employ. Given the power requirements and weight of the racecar (including batteries), the decision was made to use a three-phase AC induction motor in conjunction with a variable frequency inverter drive. This was based on the fact that AC drive technology offered the highest performance to weight ratio and could be made cost effective for electric vehicles in the long term. The BGSU team soon began looking for a motor manufacturer that was willing to partner in the development of a specially suited induction motor. Lincoln Electric Motor Division of Cleveland, Ohio seized the opportunity and a relationship was born.

Shortly after deciding on AC induction motor technology, the Electric Vehicle Institute and the BGSU Formula Lightning team submitted designs to Lincoln Electric to build the first prototype liquid-cooled power dense traction motor. Improvements and revisions to the motor to increase power, speed and efficiency were made over the several seasons that followed. The power dense EVI motor currently powering the Electric Falcon was built in 1997. It has run all races since then without failure and has been the model for several commercially viable electric vehicle installations. The 254 NEMA frame liquid cooled motor produces 225 peak Hp and weighs about 200 pounds with a maximum speed of 12000 RPM.

The BGSU Formula Lightning racecar was christened the "Electric Falcon" after the school mascot and made a successful showing at the first race. The Electric Falcon won three championships including the 2004 series finale and finished in the top three positions in all but two races.

Principles of the power dense electric motor

Electromechanical energy conversion in the induction motor as with any rotary dynamo occurs at the air gap between the rotor and stator due to the fact that relative motion is available. The power developed is the product of that motion and of force, or torque, at the axis of rotation. The force is produced by the interaction between the magnetic field and current carrying conductors. Therefore the power is product of three quantities; magnetic field, current and speed. The power can be increased by increasing any of these.

The magnetic field or flux is limited by the area of the air gap due to saturation of the steel structure. The typical motor design normally takes full advantage of this. Some incremental gains are possible through manipulation of the magnetizing current; however substantial increases require exotic means. Motors often employ field weakening for means of speed control. This reduces flux and therefore will reduce the maximum power density for a given size machine. The formula for the power dense motor does not use field weakening at peak power.

The armature current, that component which is responsible for torque production, is limited by the area of the air gap as well. However, this limit is not one of current saturation but one of thermal limit. High current density can be utilized in conventional motor designs with reduced duty cycle where sufficient time is allowed to cool components. For continuous duty, increased current density can be employed by improving methods of extracting the heat resulting from resistive losses, or by lowering those losses as with superconducting technology. Typical air circulating designs used in off-the-shelf industrial motors are not sufficient to remove such heat. Improved cooling methods must be employed. High current density designs will be of lower efficiency as compared to a comparably rated larger, non-aggressively cooled machine.

Power increase by means of increasing speed is perhaps the easiest to implement with the advent of modern motor drives (electronic converters). The shaft speed delivered to the load then must often be altered with mechanical devices. These mechanical devices, typically gearboxes, must be considered in the value assessment of weight, volume, efficiency and cost for the given power. As with increasing current density, increasing speed will adversely affect the efficiency of the motor primarily due to increased iron losses, friction and windage. The power dense motor design calls for a smooth rotor to reduce windage to a minimum and the use of high quality magnetic steel. A compromise between efficiency and power determines the optimum speed and size of the particular machine.

Many applications place a higher value on the mass of the motor package rather than the energy conversion efficiency. Mobile devices are a prime example of this where acceleration of that mass requires substantial energy. A high speed, highly loaded motor attached to a speed reducer and cooling system may accomplish the overall mission with less energy despite a lower efficiency than a traditional counterpart.

A case in point is the application of the power dense design to an actuator drive motor examined for airborne vehicles. Although the duty cycle is strictly intermittent, the specification was for 100 Hp continuous operation. Certain attributes were specified dictating an induction motor. The standard catalog TENV selection for such an application would weigh 1200 pounds with a 95% rated efficiency. Instead, a 10 Hp motor was selected weighing just 175 pounds with a 92% efficiency. The smaller motor was rewound for higher frequency raising the base speed up to 7800 RPM and equipped with the power dense liquid cooling and lubrication system. The modified motor was then capable of delivering a continuous 100 Hp, a ten fold increase in the continuous operating power. A close-coupled planetary gear reducer was attached to the output. At the 100 Hp load, an efficiency of 84% was measured from the DC power source through the inverter, motor and gearbox to the final output shaft.

This electromechanical energy conversion package realized more than a 4 to 1 reduction in mass while suffering a tolerable reduction in efficiency. With the intermittent actuator duty, the additional fuel load to power the actuator motor having lower efficiency was well below the fuel load which would have been required to launch the additional mass of the larger motor. Other considerations which eliminated the large motor alternative were space available and insufficient strength of the airframe.

For applications not as mass sensitive as the above example, the same power dense technique may still have appeal. The initial cost of the system as well as energy cost must be considered. Generally, a hundred pounds of gearing and cooling system will cost less than a thousand pounds of motor. However, in applications where weight and size are not a factor and the system operates continuously, the energy cost savings will eventually pay for a larger more efficient motor.

The design of the power dense motor (and also generator) is a viable approach in applications where mass and volume are a premium. It may also present a cost effective alternative to standard motors in situations where duty cycles are short and the energy cost penalty is low.

Principles of the power dense cooling system

The high torque and high currents that are needed to develop power from a small electric motor produces a proportional increase in heat. This heat cannot be dissipated efficiently in small envelopes using traditional air cooling methods. The Electric Vehicle Institute evaluated several alternative strategies for more effectively cooling an induction motor. A liquid coolant approach was the logical choice but none were commercially available with the performance required. With a design in mind, EVI committed to the development of an applicable liquid cooling system. The result was a rather simple yet very effective liquid cooling system that enabled the power dense motor design.

The power dense cooling system developed by the EVI technologists, improves the effectiveness of heat removal by applying a liquid coolant directly to the heat sources inside the motor, namely the rotor and the stator windings. The preferred coolant is low viscosity oil with good heat transferability and dielectric properties. A readily available fluid that meets the criteria is automotive automatic transmission fluid (ATF). This coolant also provides optimum bearing lubrication and allows the machine to be operated at the highest speed the bearings will allow. This fluid can also provide lubrication to gear boxes that may be integrated with the motor in gear-coupled applications.

The system in its simplest form is applied to an induction machine with a slightly modified rotor and wound stator with exposed end turns. The system includes a sealed housing with fluid drains, an oil sump to serve as a reservoir, modified end housings incorporating the bearings and seals, and two coolant distribution cones. For stand alone applications, a coolant circulation system requires a small oil pump, driven either directly from the power dense motor or from an auxiliary motor, a filter and a heat exchanger.

A description of the operation of one version of the power dense cooling system follows. The coolant oil is pumped to each end of the motor and enters the motor through fittings connected to passageways in each of the end bells. The coolant path through each end of the motor is principally the same. A small passage from the passageway in the end bell branches to deliver “drip” lubrication to the bearing. Most of the coolant oil is directed to the end of the rotor, near the shaft, by the coolant distribution cone. The face of the cone is shaped with a ledge positioned between .050 and .100 of an inch from the rotor. This close proximity causes the oil to flow out around the cone face surface and coats the rotor end near the center. Even when the rotor is in a stalled condition this coating action will extract heat from the rotor surface. As the rotor turns, the coating action creates a sheeting effect which uniformly applies the coolant over the entire rotor face. The rotation of the rotor will cause the fluid to coat the end surface and travel outward in a radial direction because of centrifugal force. This coating phenomenon is sometimes called the Coanda effect. The fluid continues the coating and radial outward movement over the shorting ring, extracting heat from all surface it contacts. The shorting ring, which is electrically and thermally connected to the rotor conductors, will transfer heat from those conductors when cooled by the flowing oil.

An important consideration of the cooling path is the shape of the shorting ring on each end of the rotor. The shorting ring is machined with a gentle curve on the inner diameter so as to optimize the flow and sheeting action of the coolant. The surface tension of the oil is sufficient to keep the fluid flowing on the surface even at high speeds. When the fluid reaches the outer circumference of the rotor it flows off of the rotor in a near continuous sheet directly toward the end turns of the stator winding.

The end turns, or wires, of the stator winding are left free as possible of tape or insulation so that good contact occurs between the oil and magnet wire. The oil is traveling at a high enough velocity in the radial direction under centrifugal force to penetrate the gaps which exist between the wires and wire groups caused by the forming of the stator teeth. The wire bundles of the end turns are well coated with the coolant oil which extracts heat generated by the resistive losses.

Ultimately, the outward travel of the coolant oil is contained by the motor frame. Gravity is relied upon to collect the coolant in a sump attached to the bottom of the motor. The pump draws the oil from the sump and circulates it to a filter and heat exchanger prior to supplying it to the motor.

In version two of the system, oil is directed to the bearing side of the distribution cone. The side of the bearing facing the rotor is covered with a shield. The pressurized coolant is directed into a cavity formed between the bearing and the inside of the cone. A small opening in the bearing shield allows sufficient flow of lubricant to the bearing. The remaining fluid traverses between the rotor shaft and inner cone surface. The fluid absorbs heat from the shaft as it flows outward between the flat cone face and rotor face. Once the sheeting action is achieved the fluid cools the rotor and stator using the same principles as version one. Version two has apparent benefit in some applications although is somewhat more complex and expensive to make.

It is important to note that the power dense cooling system does not flood the motor with coolant. Only enough coolant to maintain circulation is required in the system. This keeps the weight of the installation down. Unlike flooded motors, the fluid flows primarily from the surface of the rotor end. Very little finds its way to the rotor/stator air gap. As the coolant is applied directly to the source of heat a minimal number of heat transfers are required. Sacrificial losses are low and overall operational efficiency remains high.

The power dense liquid cooling design has been incorporated into four NEMA frame size motors that cover an array of traction power requirements. These totally enclosed motors are high performance and highly reliable electric machines that can be packaged into many mobile and stationary applications.

Coordinated inverter drive development

While the motor development was under way in 1994, the EVI team searched for an inverter drive which was compatible with the power dense motor and could deliver the required performance in the Electric Falcon racecar application. The team evaluated several commercially available inverters. None satisfied all of the requirements. Of particular concern was incompatibility with the power dense motor, insufficient peak power, and the poor drivability of the vehicle.

EVI was fortunate to find EMS just weeks before the inaugural race. Electric Motor Sports (EMS) of Cincinnati, Ohio became aware of the Formula Lightning series and was eager to assist the BGSU team. EMS supplied an off-the-shelf industrial inverter that could meet the power requirements and provide reasonable drivability of the racecar. Preliminary tests proved that the EMS inverter could handle the power dense motor. However, the industrial drive as packaged would not fit into the Formula Lightning race chassis.

With little time to spare, the BGSU team with guidance from an EMS engineer disassembled the industrial inverter and began modifying it for the racecar. The heavy steel housing and bulky AC to DC converter components were discarded. DC contactors and fuses were added to allow the unit to run directly from a DC source. A new enclosure was fabricated from aluminum and made to fit inside the frame of the racecar. The original 200 pound industrial inverter from EMS was reduced to just over 75 pounds. Software parameter changes were made to the modified inverter drive controller to better suit the in-vehicle application. Assistance from EMS engineering proved invaluable.

The “coordinated” inverter drive was born from the modified EMS industrial inverter. Much of the development of the drive subsequently occurred on the Electric Falcon platform. The quest for ever faster top speeds guided the development to higher power and less weight. Three generations of inverter drives for the racecar were built. Improvements to the drive included: updated control boards with faster processors, firmware specific to electric vehicles, higher current transistors, a laminated DC electrical bus, and integrated DC bus capacitors. The three iterations of the racecar motor drives were all air cooled. The racecar application provided a clean, high speed air stream for cooling that was more than adequate.

The challenge of adapting an industrial controller to a battery powered electric racecar with a power dense motor provided EMS with valuable experience. EMS has used this experience and has been commercially successful with the adaptation of industrial controllers to other vehicle applications. EMS has combined the ease of programmability of the industrial inverter into an inverter packaged for the mobile environment. The result is a traction controller that can be easily adapted to many applications.

The latest generation of EMS mobile inverter is the Flux Drive 7 series. The Flux Drive 7 series of motor inverters provide true four quadrant torque (vector) control and are specially tuned for vehicle applications. Controllers that offer torque control are labeled vector drives, or flux vector control. This refers to the algorithm the control logic employs to control motor torque through pulse width modulation. It is imperative that the motor controller be able to operate in torque control for proper EV operation. The throttle pedal will increase accelerating torque and the brake pedal will increase decelerating or negative torque. This is the case regardless of speed. Closed loop vector controls require a motor shaft velocity sensor called an encoder or pulse generator. Although many drives offer sensorless vector operation, the EV demands the closed loop due to high torque demand at low speeds and stability.

Four quadrant torque control is obtained with the “flux vector control”. The result is the ability to demand, and get, any torque at any speed, within the operating area of the motor/drive combination. This eliminates the time/speed ramp associated with variable frequency drive operating in speed control. Any amount up to full torque is available in either direction of rotation within milliseconds of demand. This “closed loop flux vector control” also enables initiation of the drive while the motor is rotating at any speed. It is not necessary to start from zero. It was also found that it was possible to operate the motor at higher torque in this control mode than with simple frequency/voltage control.

EMS controllers can provide either dual pedal control or single pedal control operating modes. These modes are software driven and can be selected by the EV designer to enhance the drivability of the vehicle. In dual pedal control, the algorithm adds the positive signal from the accelerator pedal to the negative signal from the brake pedal to become the motor torque command. The brake signal takes precedent. This allows the vehicle to coast when neither a brake or accelerator signal is present. The EV racing application is a good application for this mode. Transit buses and frequent stop truck applications can benefit from single pedal control. The algorithm uses pedal input from the driver and vehicle speed to calculate the torque command to the motor. The zero torque point of the calculation is floating based on speed. The torque is controlled in both motoring and regeneration to give the driver full control of the vehicle without using the friction brake pedal except for panic stop. When the driver lets off the pedal at high speed, the motor regeneration feels like engine back pressure, working through a manual transmission. Single pedal driving technique comes naturally to the driver in a short time.

The inverters can accept wide variation in input voltage and are well suited to both battery and ultracapacitor application. An extensive monitoring system provides status and warning information on all aspects of the inverter operation.

EMS controllers can handle battery powered electric and hybrid electric vehicles. In hybrid applications the EMS drive can control the direction and flow of energy between wheels and several power sources and can be electrically interfaced with driver controls.

The EMS Flux Drive 7 inverter drive is especially suited to the power dense motors but functions equally well with conventional AC induction motors. The EMS drives have been used successfully on various vehicle applications utilizing conventional motors. Some of the applications include electric distribution tractors for Douglas Equipment Ltd. of the United Kingdom, Mexico City electric delivery trucks for Electric Vehicle

International of Anderson, Indiana, electric and hybrid buses for EBUS Inc. of Downey, California, hybrid electric water bus for Canal Boats Inc. of Fort Lauderdale, Florida and monorail trains at Disneyland in Florida.

Inverter drive ongoing research and development

The Electric Vehicle Institute and EMS have continued their partnership beyond the racing venue. The partnership is presently investigating the SEMIKRON Advanced Integration (SKAI™) power electronics module for inclusion into the EMS product line. The SKAI offers among other things a reduction in cost, size and weight.

SKAI™ is a three-phase inverter that includes a controller, DC-link capacitors and power electronics module. It is available with either air or liquid cooling. The power electronics modules are available in IGBT or MOSFET versions. The IGBT modules are available with IGBTs rated at 600V or 1200V with output currents of 500 A and 400A respectively. The IGBT modules can deliver between 50 and 200 kW of motor power. The MOSFET modules are available with MOSFETs rated at 75V, 100V, or 150V with output currents of 700A, 600A, and 500A respectively. The MOSFET modules can deliver between 3 and 20 kW of motor power.

SKAI™ utilizes pressure contact technology which is used for all electrical contacts which makes them insensitive to impact and vibration unlike soldered contacts. The pressure contact technology is also used in the thermal contacts for the power semiconductors which allows for direct heat transfer to the heat sink, an extended lifetime, and better thermal cycling capability.

Texas Instruments TMS320LF2407A DSP in the SKAI™ controller is sold without software so development of the vector control of three-phase induction motors is underway at EVI. Programming the DSP can be done in either assembly or in C language. Texas Instruments (TI) has provided an array of utilities to facilitate in the DSP programming.

Interfacing inverter drive with high speed control networks

Simple electric vehicle applications can be interfaced and controlled directly by the EMS Flux Drive 7 inverter via discrete analog and digital signals. As system complexity increases, however, the number of discrete signals can quickly grow to an unmanageable number. Modern vehicles have evolved then to utilize control networks linking subsystem components with a single data bus. The EMS inverter must also be linked to the network to be effective in these applications.

Many contemporary vehicle interface and control networks are high speed serial buses that operate at speeds up to 1 million bits per second (1 Mbps) and greater. One such serial bus is the Bosch Controller Area Network (CAN). The EMS controller comes standard with an RS-232 serial port typically operating at 9600 bits per second (9.6 Kbps) using the Modbus RTU protocol. Other network interfaces are available for the EMS controller but only those that are popular in industry such as Ethernet and Profibus. The CAN automotive interface is not available.

A custom interface circuit was required in order to incorporate the EMS Flux Drive 7 in automotive applications utilizing CAN. This interface circuit, designed and built by the Electric Vehicle Institute, translates messages from the high speed CAN bus to the motor controller through the standard RS-232 serial port operating at a maximum speed of 31.2 Kbps. The mismatch in operating speeds prohibits the motor controller from utilizing the full bandwidth of the CAN bus. Despite this limitation, the interface card can transmit and receive data and control messages at up to 20 times per second. This communication speed is adequate for many applications.

An 8-bit microcontroller provides the message translation logic on the CAN interface card. Signal level translation from CAN to RS-232 is provided by an optically isolated RS-232 bridge and CAN 2.0B controller with transceiver. The interface card is mounted internally to the controller with the CAN port extended to an external connector. Some of the run time parameters (monitors) that are transmitted and the commands received by the EMS controller via the CAN link are shown below.

Transmitted monitors include dc bus voltage, dc bus current, motor speed, motor current, drive operational status, drive elapsed hours and inverter temperature. The received commands include forward run, reverse run, stand by/neutral and torque request.

The EMS Flux Drive 7 controller with CAN interface has been successful in a number of automotive applications. The EMS controller equipped with the CAN interface behaves as a node on the network and transmits and receives messages like the engine and transmission.

Applications of the power dense motor and coordinated inverter drive

Availability, ruggedness and affordability lead scientists of the NASA Glenn Research Center in Cleveland, Ohio to select the power dense liquid cooled induction motor and EMS inverter drive to power the Ohio Hybrid Electric Transit Bus (HETB) in 1997. The HETB was the first heavy hybrid vehicle to successfully use ultracapacitors as the energy storage device. The system design was so unique that two EVI technologists and an EMS engineer were issued a patent on both a series and parallel version.

Following the Hybrid Electric Transit Bus project, EVI and EMS again teamed up to supply NASA with motors and drives for the Modular Electric Actuator System test rig. The test rig is a platform for development of electromechanical flight actuators for the next generation space shuttle as well as commercial aircraft.

The Hybrid Booster Drive™ (HBD) under current development is a parallel, electric, hybrid, vehicle system born from the HETB project. The HBD integrates an ultracapacitor-based electric drive system with a traditional engine driveline in Class 4 to Class 6 vehicles. These vehicles include medium size shuttle buses and parcel delivery trucks which require numerous stops. The electric drive provides the vehicle with power assist during acceleration and captures braking energy during deceleration. The Hybrid Booster Drive™ is a simple design with only four major components: a power dense motor and close-coupled gear box, the EMS Flux Drive 7 inverter, an ultracapacitor energy storage module, and the supervisory controller that blends power from the engine and electric drivelines. The system has been recently selected by Goshen Coach of Elkhart, Indiana for introduction into their line of mid-sized buses.

Authors

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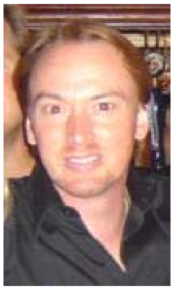
Jeff Major, Chief Engineer, Electric Vehicle Institute, Bowling Green State University, Bowling Green, OH 43403. Jeff has been with the Electric Vehicle Institute for the past eight years and has been a significant contributor in motor and controller development. Jeff holds a BSEE form the University of Toledo. He has served as a part time instructor at the University of Toledo, College of Engineering in energy conversion and at Bowling Green State University, College of Technology in electronics. Jeff completed eleven years experience in industry with the Prestolite Company, Toledo, OH. He held positions of Product Engineer and Manager of Engineering for the motor group with responsibilities for product engineering and R&D. He has seven patents issued for motors and related apparatus. Jeff has extensive experience and expertise in electric vehicles, electromechanical energy conversion and power electronics.

Aaron Bloomfield, Data Acquisition Engineer, Electric Vehicle Institute, Bowling Green State University, Bowling Green, OH 43403. Aaron has recently joined the institute to provide full time expertise in data acquisition and programming. He has BS in Computer Science from BGSU. Aaron participated as the DAQ specialist in several other projects working as a consultant for EVI. He has expertise in computer applications, recovering real time test data and implementation of controls in the automotive environment. Prior to coming to BGSU, Aaron spent 5 years at Libbey Inc. as an Applications Support Specialist.

Robert Gruenwald, President, Electric Motor Sports, Cincinnati, Ohio. Bob graduated from the University of Cincinnati with a degree in Electrical Engineering Technology. After 17 years of industrial experience with motors and drives he founded Electric Motor Sports to fill a perceived void for reasonably priced traction controller products for electric vehicles. Bob became involved with Bowling Green State University in 1994 building an electric race car to compete in the Formula Lighting racing series. To date Electric Motor Sports has supplied over 200 controllers that are running in electric buses, amusement park rides, dock side tractors, trams, and subway cars.



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