Design and Optimization of Permanent Magnet Switch Reluctance Machine for Renewable Energy Application

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***Abstract* – Presentation of the design of a Permanent Magnet Switch Reluctance (PMSR) Machine for Renewable Energy Application. This is a hybrid machine, which may act both as a motor and generator. The PMSR machine efficiently drives a rotor containing embedded Permanent Magnets (PMs) through customized Electro-Magnets (EMs) attached to the machine stator. The EMs are excited via a controlled current source generating a magnetic field which interacts with the PMs on the rotor. Repulsion and attraction forces are applied via the EMs using appropriate current control. Unlike a standard reluctance motor, this device is able to store some of the Back-Electromotive-Force (Back EMF) within its driving power supply, allowing for reduced heat. We are developing an electro-magnetic simulation model within the ANSYS [1] Maxwell 2D and 3D software, which characterizes the preliminary PMSR machine design. Furthermore, the initial focus is on optimization of the PM material and structure, as well as optimization of the EM structure. The primary goal of the current research effort is lowering the cost of the machine and boosting the overall efficiency.**

***Index Terms*— Permanent Magnet, Switch Reluctance, Renewable Energy**

I. Introduction

RENEWABLE energy solutions are becoming increasingly important for future technologies and development. Electric machinery is at the forefront of this development. Small, cost effective, power efficient devices are some of the most critical priorities to be considered for the design of electric machinery. Among the various types of electric machines are reluctance motors, which typically consist of a stator with several salient poles interacting with a ferromagnetic rotor to generate torque.

We have designed a machine whose magnetic operation is comparable to that of a reluctance motor [2], [3]. It is a hybrid machine, which may act both as a motor and a generator. This PMSR machine efficiently drives a rotor with embedded Permanent Magnets (PMs) through a customized set of Electro-Magnets (EMs) attached to the machine stator. EM excitation is achieved via a controlled current source generating a magnetic field which interacts with the PMs on the rotor. By using appropriate current control, repulsion and attraction forces are applied to groups of EMs. Unlike a reluctance motor, the device is able to store some of the Back EMF within its driving power supply, allowing for reduced heat. Additionally, the rotor is non-ferrous, with embedded PMs which focus the interaction of their magnetic fields upon the state EMs. Essentially, the device is a new closed-loop energy generation machine based on the Halbach array of PMs and the Halbach array Direct Current (DC) motor generator. The EMs are controlled and driven using current from a power source or generated as a by-product of the moving components. The EMs are specifically designed to rapidly reverse magnetic polarity without degradation of their magnetic properties or significant residual magnetization [4].

The PMSR machine has significant potential application in electric generators and motors including, but not limited to: primary/emergency household power, commercial, industrial, remote, military and space applications [5]. It efficiently converts electrical and magnetic energy into rotational motion using variable reluctance and magnetic field lines produced by the careful control of electro-magnetic excitation. It is a renewable energy solution which is self-sustaining for a realistic period of time, independent of fossil fuels or other non-renewable energy sources.

II. Preliminary Design

A. Design Principle

The electromagnets are, as designed, energized by DC current, creating a magnetic field that interacts with the PMs to deliver alternating repel and attract forces at the appropriate times. The delivery is controlled by a Digital Signal Processor (DSP) with its algorithms. These attract-repel forces can be translated into useful rotational energy to further drive the rotor [6]. Modeling software is used to determine the precise geometry of interacting magnetic fields and maximize rotational energy, from which we can derive 1) exact angle data to maximize attract-repel forces 2) maximum "snap" from the "Halbach Bubble" and 3) optimum "coast" period to use the kinetic energy of the flywheel.

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We use high performance rare-earth PM material which requires no external power to produce a magnetic field, minimizing the power used by the EMs [7]. As this also maximizes the "free" attract-repel force of the PM while minimizing energy consumption, it is effectively a free contribution to the creation of electromotive force. The controller is adapted with circuitry and sensors which are capable of monitoring the exact position of the PMs with respect to the EMs at any given time.

Energy utilized by the EMs is discharged in the form of a short-duration, high-voltage "spike" at the moment the electromagnet is switched off. As a result, subsequent excitation of the electromagnet typically requires 100% power. However, to reduce the power required, a technique called "back EMF harvesting" is utilized which captures back EMF energy and reuses it. As a result, the machine can maintain a constant RPM rate with 60% less power usage. This recycling process is achieved via the power electronics driving circuitry.

B. Key Design Methodology

The maximum rotor diameter needs to be calculated by

$$D_{r\max} = \frac{v_r(length/\min)}{1.2n_m(rev/\min)\pi} \quad (1)$$

where v_r represents the maximum peripheral speed of the rotor based on the material nowadays. The max peripheral speed is 35,000 *ft/min* in this design. The value of n_m is the mechanical speed or the rotor. After finalizing the design, we can use this equation to double check our rotor dimensions.

The next thing we need to is to fix the dimension of the stator by the equation below:

$$\frac{D^2 L}{\tau} = V_o \quad (2)$$

where D is defined as the stator bore diameter and l is the length of machine. The torque is represented by τ, which is determined by the output power divided by the rotor mechanical speed. The importance of this equation is to figure out how big the motor size can be in order to create a required torque. V_o is a constant value, depending on the cooling method. The cooling method is determined by the output power of the motor. Based on experience, air cooling is used if the motor is 10 *hp* or less. The cooling for this motor is therefore air and the coefficient is 9.5 $in^3/(ft.lbs)$.

We made the assumption which is the stator outer diameter is estimated to be 1.6 times the stator bore diameter. Due to the space limitation, we decided to make the diameter much larger than the machine length which would make the motor having a high inertia.

Slot pitch can be defined as

$$\gamma = \frac{\pi \cdot p}{N_s} \quad (3)$$

where p is the number of poles. *Ns* is the number of stator slots. Similarly, the coil pitch can be calculated by

$$\rho = \pi \frac{N_m}{N_p} \quad (4)$$

where $\frac{N_m}{N_p}$ represents the stator pitch.

The number of effective turns per coil can be calculated by the following equation:

$$N_c = \frac{1.1V_{\phi rated}}{2\sqrt{2}\pi f_e n k_w B_m D l} \quad (5)$$

where $V_{\phi rated}$ represents the phase voltage. f_e is the electrical frequency. n describes the number of groups windings per pole. The back EMF due to stator pitch is indicated by k_w. The net magnetic field, B_m , is a sum of the residual flux density B_r of the embedded permanent magnet by the rotor plates. The estimated diameter of the motor is defined by D, and the length of the motor. l

Besides, the effective turns per phase is calculated by

$$N_{eff} = \frac{pnN_c k_w}{1.1} \quad (6)$$

Rated phase voltage can be described as:

$$V_{\phi rated} = \sqrt{2}\pi f_e N_{eff} \phi_m \quad (7)$$

where ϕ_m represents the flux per magnet

$$\phi_m = \frac{2B_m D l}{p} \quad (8)$$

After this, we estimated the air gap, from which we can get the dimension of the rotor. With all those initial design dimensions ready, we used Finite Element Analysis (FEA) tool to further optimize the design.

C. Design Results

The general structure of the machine design is shown in Fig. 1 below.

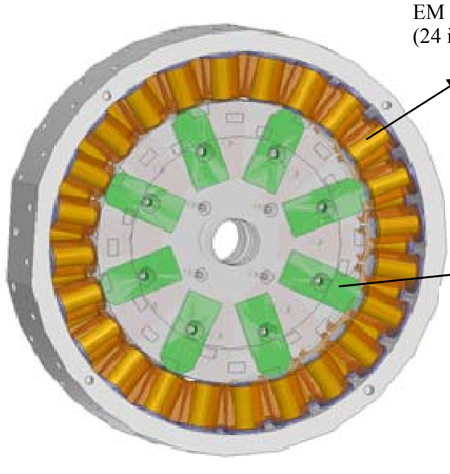


Fig. 1. Full structure of the machine

The basic dimensions of the machine we designed are 457 mm of stator diameter and 78 mm of machine length. We made the air gap to be around 0.3 mm.

The electro-magnet (EM) is basically made up of a core, a primary coil winding and a secondary coil winding. As shown in Fig 1, the primary coil is powered by external DC current supplied by batteries. With the interaction of the magnetic field, AC current is produced by the secondary coil as shown in Fig. 2. Simulations performed to predict performance have also provided input to decisions on the shape and material of the core, number of turns needed to make the coil, etc [8].

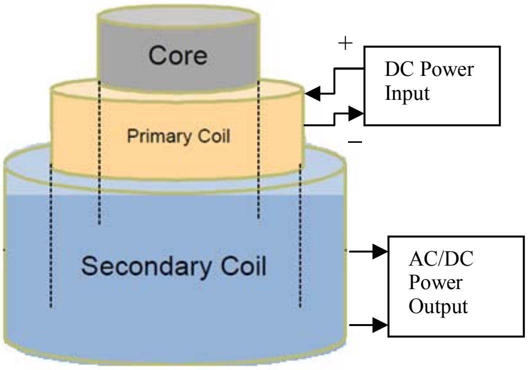
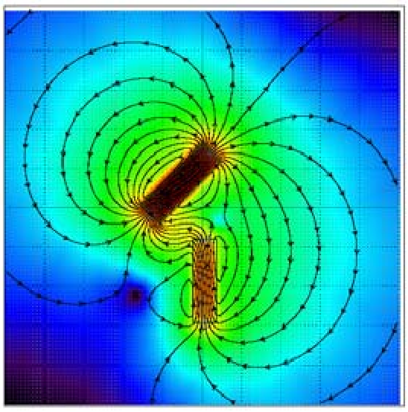


Fig. 2. Structure of EM

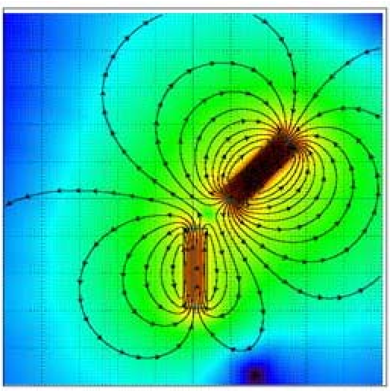
The current design calls for 945 turns on the primary winding, 2300 turns on the secondary winding with wire gauge types number 23 and 38, respectively, to generate enough rotational energy.

The PMs in this design are also very important. Current design calls for 8 PMs in each rotor plate (as shown in Fig.1), using Neodymium40 (N40) as the material.

The attract-repel reversing process as discussed before is shown in Fig. 3. The decision to switch the current polarity to match the exact attract-repel point is controlled by DSP and its algorithms.



(a) Attract process



(b) Repel process

Fig. 3. Computer-controlled Attract-Repel Simulation. (a and b)

The figure below shows the advantage of using "back EMF harvesting", i.e. when this technology is applied, power spikes are eliminated and thus energy may be saved and reused.

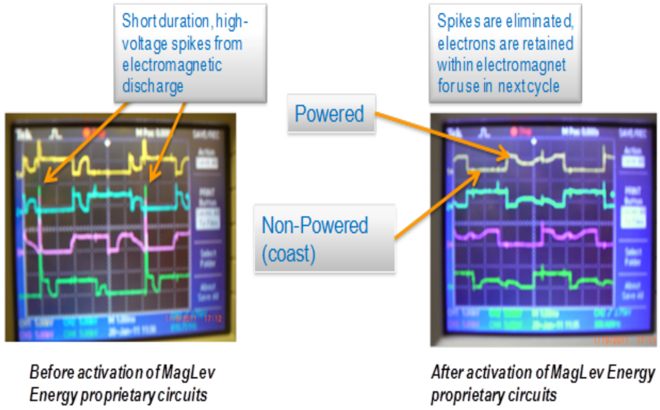


Fig. 4. Back EMF harvesting technology

D. *Prototype*

As shown in Fig. 5, the current prototype has dual rotor plates, which can accommodate 24 hybrid EMs each, for a total of 48 EMs. This configuration, with the DSP controller, will direct a portion of the device output to recharge the batteries, whenever this "closed loop" circuit is activated.

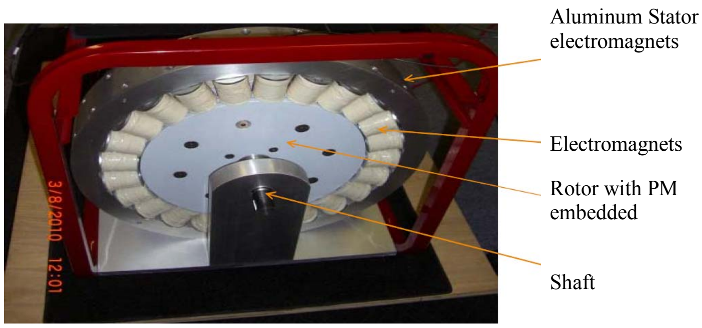


Fig. 5. Prototype of the PMSR machine

E. *Advantages of the Design*

With the current design, we have successfully eliminated the need for using fossil fuel to supply the power for the machine. Therefore, by using DC batteries, we produce clean energy with less noise. The batteries may be re-charged as well so that required maintenance is reduced. In addition, the system is in a sealed unit; the PMs embedded in the rotor have a useful life of over 90 years; the EMs do not wear out; and specifications for the solid state proprietary relays indicate an expected duty life of 10 years or more.

III. Optimization of the Design

A. *Optimize the Air Gap*

In the preliminary design, only the two corner points of the PM could achieve the smallest air gap. To more efficiently use the smaller air gap, the shape of the PM has been modified to describe the arc of a circle whose diameter matches that of the rotor, as shown in Fig. 6. Therefore, the air gap is always the same in relation to the PM position, as shown in Fig. 7. For low rotational speed machines the air gap may be smaller compared to high speed machines, because there is less centrifuge effect during the rotating process.

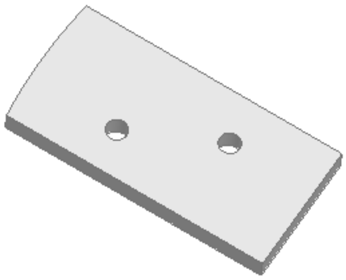


Fig. 6. Structure of the optimized PM

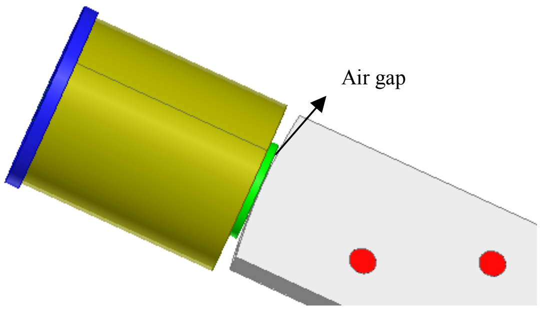


Fig. 7. New air gap

B. *Optimize the Length of PM*

In order to further optimize the preliminary design, an increase in the moving torque is achieved by changing the geometry of the PM. Based on simulation results, the PM length is shorter than in preliminary designs because of the shorter return path for the magnetic flux to travel. In other words, although the magnetic source is smaller, it simultaneously causes smaller air reluctance which leads to generation of a higher moving torque. The 2D model (shown in Fig. 8) allows for a quick PM length sweep in order to find the best torque value (as confirmed in 3D simulation).

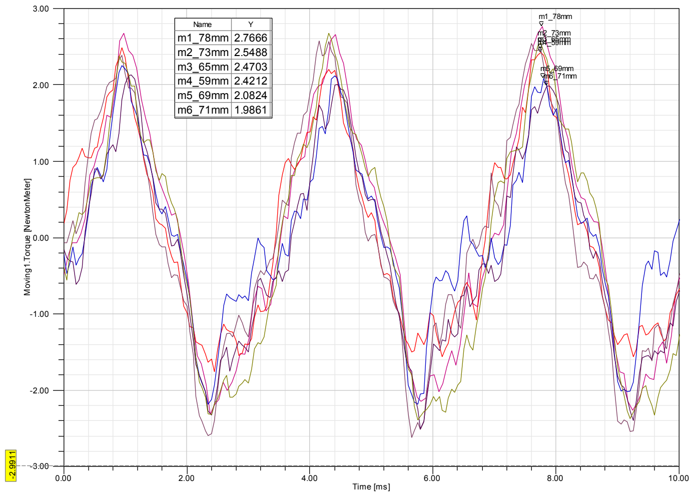


Fig. 8. Torque comparison by varing length in 3D simulation

The new PM is easier to fabricate because the edge of the PM sweeps over the EM coil exactly on the edge of the round rotor. Therefore, no special shape cutting is required. The new design calls for use of Neodymium42 (N42) as the PM. Better utilization of the air gap results in a stronger magnetic field interacting between the EM and PM. Use of two drill holes with smaller sizes make the machine more mechanically reliable. As it is possible that this design may be used in extreme temperature conditions such as a desert, aluminum rotor plates may be used to avoid expansion due to temperature, which would eventually result in shrinking of the air gap. Comparison of the optimized and existing PM design is shown in Table I.

TABLE I
COMPARISON OF OPTIMIZED AND PRELIMINARY PM DESIGNS

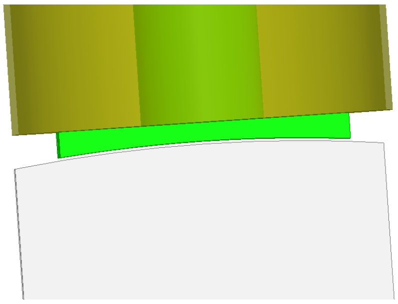
	Air gap (mm)	Hole (mm)	Length (mm)	Torque (Nm)
New	0.3	9.5 (one)	78	2.76
Old	0.43	6 (two)	87	1.5

PM optimization resulted in a decrease in the volume of PM material required, which is important given the cost of rare earth material.

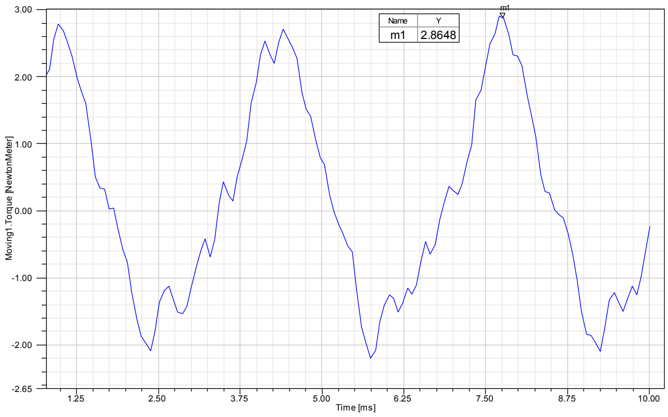
C. *Optimize the EM*

Torque has been significantly increased as a result of the new PM design, however, another important factor to be considered is the amount of material used in construction. The number of copper wire turns required by the EM may be reduced by as much as 60%, while still maintaining the desired level of torque in a low rotational speed machine application.

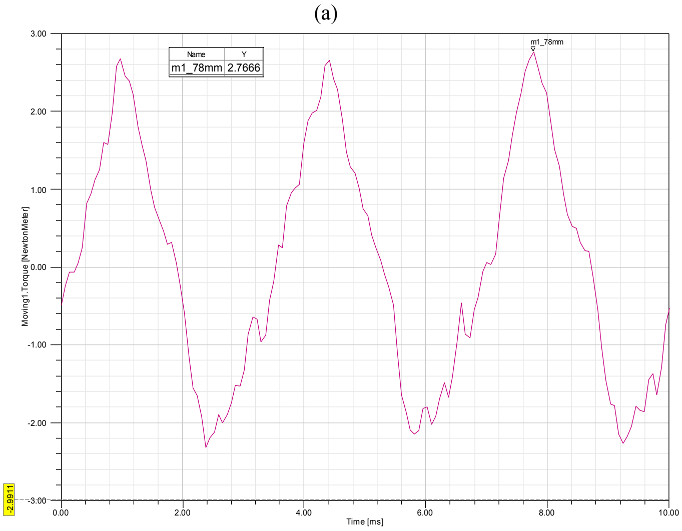
Optimization of the core shape to match the PM shape, as shown in Fig. 9 below, further minimizes the air gap so that the torque can be maximized accordingly. The use of a rectangular core as opposed to a circular one also contributes to torque maximization, as shown in Fig. 10(a) and 10(b).



(a) New Core
Fig. 9. Structure of optimized core



(a)



(b)

Fig. 10. Torque generated by (a) new designed core (b) preliminary designed core

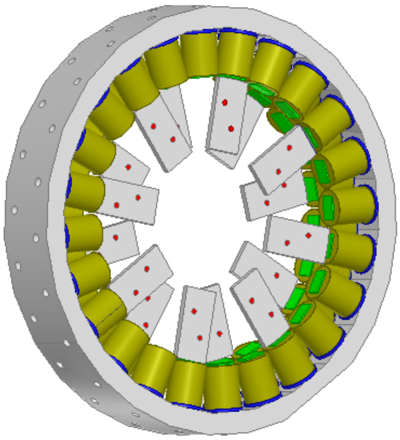


Fig. 11. Structure of the machine with optimized PM and EM

IV. CONCLUSION

We have successfully developed the PMSR machine for renewable energy application purpose. We provided the methodology of the design and the simulation results. Furthermore, we optimized the preliminary design by modifying the structure of PM and EM, and we also modified the number of turns of the copper wire wrapped around the EM.

V. ACKNOWLEDGMENT

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VII. BIOGRAPHIES

Hanzhou Liu received the M.S. degree in electrical engineering from University of Central Florida, Orlando, in May 2010. Currently, he is pursuing the Ph.D. degree at the University of Central Florida, Orlando. He is now a research assistant and his research focus is electrical machines and drives.

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Jon Harms has more than 23 years of Tandem and IT experience in all areas of Information Technology specializing in systems, front, middle, and back-office financial processes along with resource integration. At HP, Jon led worldwide business development in 3 vertical segments and was responsible for Financial Services implementations in several Fortune 500 institutions. Expert at leading technical personnel in support of business objectives; contract negotiations; design architecture and pursuit of cost-effective technology, his projects continue providing competitive advantage in the technology marketplace. Jon's career includes long-term tenure with Tandem, Compaq, and HP; world-wide owner of HP's Real Time Financial Services program; project control and solution architecture for many large institutions, governments, and communications companies. Jon is President, CEO, of MagLev Energy, Inc. and is one of principal inventors of MEI technology.

Wei Wu received the B.S. degree in mechanical engineering from Southwest Jiaotong University, Chendu, China, in 1993 and the M.S. and Ph.D degrees in mechanical engineering from Tsinghua University, Beijing, China and Israel Institute of Technology in 2002 and 2007 respectively. From 1993-1998, he worked as an engineer on air-conditioning, refrigerating system for ChangChun Car Company, Changchun, China. From 2002-2003, he served as the chief engineer for ShenYang WINT HVAC (Heating, Ventilation, Air-conditioning, Refrigerating) equipment Co, Shenyang, China. He is currently with UCF (University of Central Florida, Orlando, Florida) on thermal management of electrical device projects such as truck APU unit HVAC design, packaging of DC/DC & DC/AC inverter stages for direct energy conversion from solar panel to power grid, and high power LED thermal stress control, etc.

Yuanli Bai received his BS degree and MS degree from the Department of Automotive Engineering of Tsinghua University, Beijing, China in 2000 and 2003. He received his PhD degree in Mechanical Engineering from Massachusetts Institute of Technology (MIT) in 2008. Dr Bai is currently an Assistant Professor of the Department of Mechanical, Materials and Aerospace Engineering at the University of Central Florida (UCF) at Orlando. Prior to joining UCF in January 2011, he was a mechanical engineer of General Electric Global Research Center (GE-GRC) at Niskayuna, New York. Dr. Bai has published over 25 papers in journals and conference proceedings.

Martin Epstein has over 25 years of experience in the analysis, management, marketing and development of businesses, business opportunities and real estate from New York to Alaska. He has been instrumental in negotiating complex transactions including natural resource development (oil, gas, mineral, forest products and coal leasing) as well as large scale real estate development projects. Martin has been responsible for multiple, simultaneous projects from concept through completion. He was also responsible for licensing and managing hundreds of major metropolitan area businesses. Marty is EVP and CFO of MagLev Energy, Inc. and is one of the principals inventors of MEI technology.

Tad Chalfant has more than 25 years of experience in Information Technology that led to his position as Chief Software Architect at MagLev. During his tenure at such companies as Verizon Data Services and Chase Paymentech, Tad has been an integral part of systems design, programming, testing, implementation, performance enhancement and front line support for applications at the forefront of communications and financial technology. As an expert in both hardware and software, he has often been sent to various locations around the world (Japan, Holland, Portugal, Denmark, South Africa) as the sole representative of the company's Information Technology department, performing not only as liaison but also implementation manager, training lead, and front line support manager.

Anthony Camarano received his BS degree in electrical engineering from University of Central Florida, Orlando, in May 2011. Currently, he is pursuing the Ph.D. degree at the University of Central Florida, Orlando. He is working on research project with electric machine related topics.

Yang Hu received his BS degree in electrical engineering from Tsinghua University, Beijing, China in 2009. Currently, he is pursuing the Ph.D. degree at the University of Central Florida, Orlando. He is working on sensorless control research project for electric machines.

Louis Chow received his BA in Physics in 1972, MS and Ph.D. in Mechanical Engineering in 1974 and 1978, respectively, all from the University of California at Berkeley. He was on the faculty at Texas A&M University (1978-1981), Washington State University (1981-1985) and University of Kentucky (1985-1995) prior to joining University of Central Florida in December 2005. Between December 1995 and December 2000, Dr. Chow was the chairman of the Department of Mechanical, Materials and Aerospace Engineering. During his tenure, MS degree in Aerospace Engineering, MS and Ph.D. degrees in Materials Science and Engineering were established. In addition, a new MS track in Miniature Energy Systems was created. He served as Interim Dean of the College of Engineering and Computer Science in 2003-2004. Dr. Chow was Lockheed Martin Professor in 2001-2002 and has held the University Chair of Mechanical Engineering since 2002. He is also a professor (joint appointment) of Optics and Photonics and a member of the Center for Research and Education in Optics and Lasers (CREOL). Dr. Chow is the pioneer of the low surface superheat, high heat flux spray cooling technique. This technique is recognized as an enabling technology in the thermal management of high power electronics and electro-optical devices. He has extensive research experience in the area of two-phase flow, heat and mass transfer, system integration and optimization. Research projects that Dr. Chow has carried out include experimental and computational investigation of heat pipe/thermosyphon operation, jet impingement cooling, spray cooling with vapor-atomizing and pressure-atomizing nozzles, and micro channel cooling. Other research projects include the development of efficient, compact and reliable systems such as compact cryocoolers for distributed cooling at liquid nitrogen and hydrogen temperatures; portable vapor compression refrigerator; and portable power generation based on turbomachineries. Dr. Chow was elected associate fellow of AIAA and fellow of ASME, both in 1992.

Thomas Wu received his Ph.D. degree in Electrical Engineering from the University of Pennsylvania in 1999. In the Fall of 1999, he joined the University of Central Florida (UCF) as an assistant professor. He was promoted to associate professor in 2005, and professor in 2011. He also got his tenure in 2005. Prof. Wu was chairman of IEEE Orlando Section in 2004. He is currently a senior member of IEEE. He was awarded Distinguished Researcher of the Department of Electrical and Computer Engineering in 2003, Distinguished Researcher of College of Engineering and Computer Science in 2004, and University Research Incentive Award in 2005. Prof. Wu is also an outstanding teacher at the university. He was awarded Excellence for Undergraduate Teaching Award from the School of Electrical Engineering and Computer Science in January 2006, and Excellence for Undergraduate Teaching Award from the College of Engineering and Computer Science in February 2006. He was awarded Excellence for Graduate Teaching Award from the School of Electrical Engineering and Computer Science in January 2007, and the University Teaching Incentive Award in May 2007. In January 2010, he was awarded Distinguished Researcher of the School of Electrical and Computer Science. From May 2010 to August 2011, he was on sabbatical at the Air Force Research Laboratory (Wright Patterson Air Force Base, Ohio).