6.1. Integrated GMR Current and Temperature Sensor Technology

Primary Thrust:

☐ IPEMPCS ☐ EMTMIT ☐ IM ☐ HDI ☐ APS ☒ CSI ☐ TMI

Other Thrust(s) Supporting the Proposed Work:

☒ IPEMPCS ☒ EMTMIT ☐ IM ☒ HDI ☐ APS ☐ CSI ☐ TMI

Campuses Involved:

☒ VT ☒ UW ☐ RPI ☐ UPRM ☐ NCA&T ☐ Other: ______

Type of Proposal:

☒ Continuing work ☐ New proposal

Time Frame:

August 2005 to August 2008

A. Project Team

Faculty: PI: Robert D. Lorenz (UW); Co-PIs: Thomas M. Jahns (UW) , Zhenxian. Liang (VT)
Graduate Students: Erik Olson (UW), TBD (VT)
Undergraduate Students: R. Hejny (UW), TBD (VT)
Visiting Scholars: TBD (UW)

B. Project Goals

This project will develop and validate a general design methodology for integration of GMR point field detectors in power electronic modules and power electronic systems such that current and temperature can be reliably sensed.

The goals of this work are as follows:

- Develop 3-D field analysis methods suitable for GMR point field detection in IPEMs

  This effort is initiated by developing a 2-D design methodology which evaluates tradeoffs between flat bandwidth and signal-to-noise ratio. A 3-D evaluation is then developed as an extension of the 2D methodology, including the evaluation of cross-coupled fields.

- Use the 2-D and 3-D analyses to develop a generalized design methodology for point field detecting.

The evaluation of the tradeoffs between flat bandwidth, range-to-resolution ratio and cross-coupling of fields contribute to the proper layout of the power electronics module and location of the field detector.

- Utilize the Standard Cell IPEM for implementation of GMR integration concepts

  The tasks involve teaming with the Standard Cell IPEM effort such that GMR point field detectors are integrated such that current sensing properties and temperature sensing properties can both be evaluated and used for active control of the SC IPEM.

- Develop field analysis methods suitable for GMR detection of temperature in IPEMs

  The tasks involved in this work focus on further integrating the location of GMR point field detectors such that reliable current and temperature sensing can be achieved. This effort is also implemented concurrent with IPEM interconnect layout based on circuit parasitic considerations.

C. Support of the Strategic Plan

Current sensors play a critical role in modern power electronic equipment, in UPS systems, motor drives, and distributed power systems. Most of the existing high performance applications use flux-null regulating, Hall effect current sensors (e.g., LEM sensors) that are both bulky and expensive, making them incompatible with future IPEM designs. Device level temperature sensing also plays a critical role in future power electronic systems because device temperature and load cycle temperature variations are the most common cause of power electronics failures. To actively regulate the critical thermo-mechanical stresses, integrated and strategically placed temperature sensors are required.

The use of integrated giant magnetoresistive current sensors in power electronic modules makes it possible to improve the performance, reliability and cost of power electronic modules. Reliability can be enhanced since the number of interconnections will be reduced by integration inside the IPEM. Performance can be improved through the inherently high bandwidth of magnetoresistive field detectors. All of these metrics are consistent with the vision and goals of CPES.

D. Challenges, Impacts and Methodology

This project focuses on using field analysis to guide IPEM integration of point field detectors. The integration of this kind of field detectors produces several challenges. Since the electromagnetic environment inside a power electronics module is highly cross-coupled, resolving an accurate current phase signal is non-trivial. Another challenge to overcome is the frequency dependence of the magnetic field's spatial distribution due to the skin effect. The tradeoffs between flat measurement bandwidth and range-to-resolution ratio are optimized by detector location.

Finite element models are used to evaluate electromagnetic field distributions in geometric layouts. The insight gained from the numerical models is used in the design of embedded power prototype modules. Any differences between experiment and simulation will help refine the design rules for module layout, as well as aid in developing more efficient streamlined finite element simulation.

Initial results of the two dimensional finite element analysis are shown in Fig. 1. The plot shows the cross-sectional space of the region around the output trace. The colors represent the 5% flat bandwidth achievable at the various positions around the output trace. Notice that there is a narrow region of maximum bandwidth radiating from about 1.5 mm from the center of the trace. The peak value of the bandwidth maximum increases as the measurement location is moved vertically.

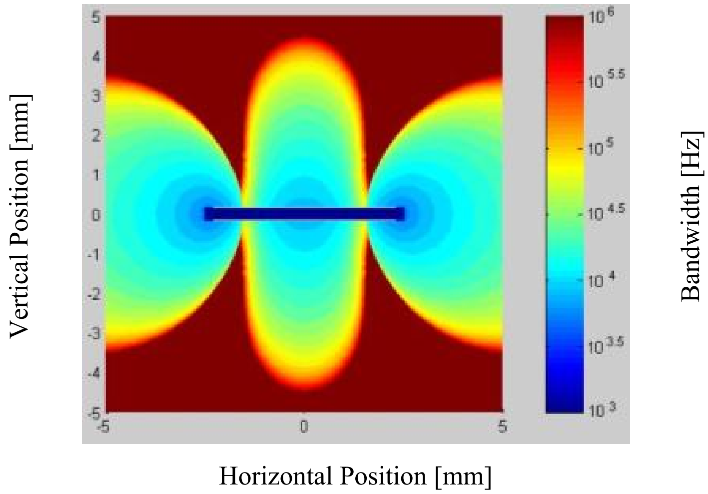

Fig. 1. Bandwidth map about the output trace

Other conductor geometries are also being investigated. Rectangular conductors with rounded corners are also being analyzed. Figure 2 shows the 5% flat bandwidth spatial function for such a conductor. It can be seen that although the bandwidth plot in Fig. 2 looks similar to the one shown in Fig. 1, there is a larger region of high bandwidth closer to the conductor.

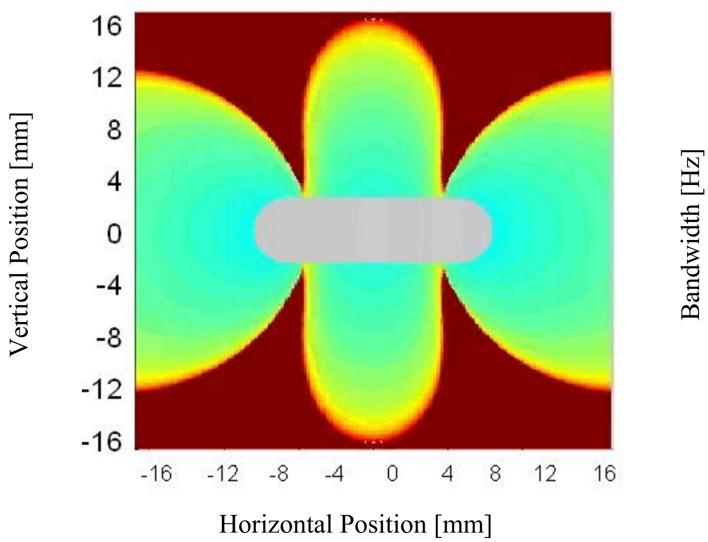

Fig. 2. Bandwidth map about a rectangular conductor with rounded edges.

In order to determine the best place to place the field detector for maximum flat bandwidth and maximum field strength, optimization functions are being used. Figure 3 shows different view of such an optimization function. The conductor geometry is a single rectangular conductor with an air gap in the middle. Both sides of the conductor carry the same amount of current in the same direction. The optimization function clearly shows the best possible location to place the detector. Because of the symmetry of the conductor, there are four different optimal places.

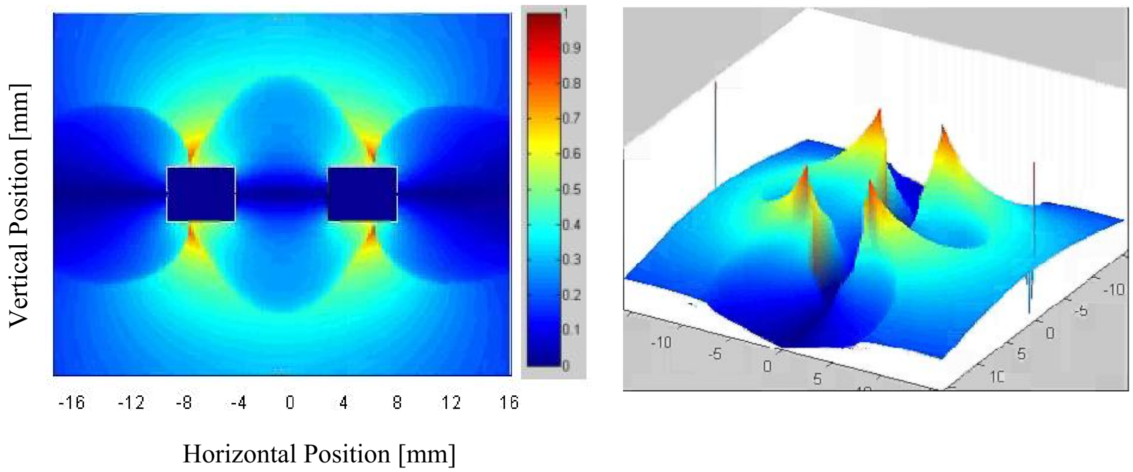

Fig. 3. Bandwidth map about the output trace

Figure 4 shows another optimization function for a double conductor. This conductor geometry consists of two equal rectangular conductors, each carrying equal and opposite currents. The optimization function shows that there are two distinct regions between the two conductors that offer both high field strength and a high amount of flat bandwidth.

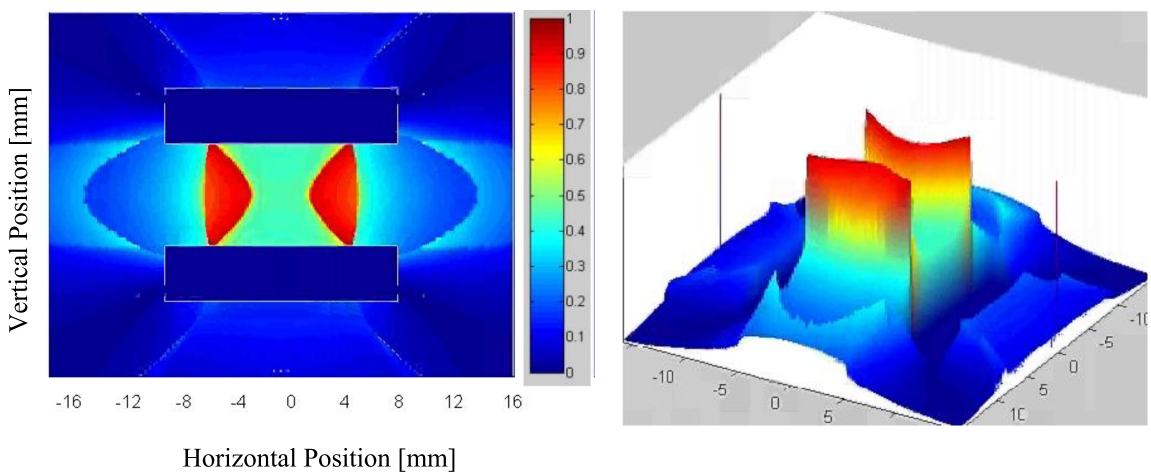

Fig. 4. Bandwidth map about the output trace

In addition to the field analyses shown above, this project also will include transient thermal modeling of conductor structures to develop design rules for GMR detector placement for temperature sensing. The placement of the GMR for temperature detecting will include the use of an observer to estimate the junction temperature of the IGBT. This will make the dual use of the GMR as both a temperature and current sensor possible, since these two measurements typically have conflicting design requirements.

E. Expected Outcome

The current achievements of this project are as follows:

- The use of two dimensional finite element models to analyze detector placement for current sensing with high bandwidth and accuracy.
- Vertical position has been shown to be an optimization problem. Useful tradeoffs between flat bandwidth and range-to-resolution of the signal lead to a relatively wide, 1 mm, vertical position range centered about 2 mm for current designs. Such heights are well-suited embedded power implementation.
- Horizontal position has been shown to be a more critical optimization problem. Useful tradeoffs between flat bandwidth and range-to-resolution of the signal lead to a narrow, 0.5 mm, horizontal position range centered about 2 mm for current designs.
- A prototype, spatial location optimization methodology has been developed.
- Design of an embedded power module as a test vehicle using multi-point field detecting for comparing against field simulations.

This project will deliver new conceptual ideas for the assembly, layout and design of power electronic modules with integrated current sensors using point field measurement. In-depth analysis of the frequency dependence on magnetic fields has been carried out in two dimensions. The interpretation of these analytical results in addition to experimental results gained from the embedded power module design will produce specific guidelines on detector location for optimizing flat measurement bandwidth and range-to-resolution ratio. The next phase of this research will be to extend these design rules to three dimensions, combining the effects of cross-coupled fields in multi-phase modules. This will require possibly another generation of embedded power modules that incorporate the concepts learned in this year's generation. The final phase of this research will be to incorporate the GMR's temperature sensitivity into the design rules of detector placement, for the purpose of simultaneous current and temperature sensing. This will follow the same methodologies used for developing field detecting design rules.

F. Other Related Work

Within CPES, other work has been done on integrated current sensing in power electronic modules. The most recent of these efforts involves using Rogowski coils to measure IGBT currents in PFC circuits.

The importance of having highly sensitive field detectors for integration is being realized by many manufacturers. Integrated anisotropic magnetoresistive (AMR) current sensors are now available in some power electronic modules [1] [2] [3]. There are now also several different field detecting technologies that are approaching the small size and sensitivity of the GMR field detectors. Among these, surface-mount open-loop Hall-effect field detectors are being made that can detect 0 to +/- 30 Amps with a 100 kHz bandwidth [4]. Although these technologies are becoming much more comparable to the GMR's ability of field detecting, none of them are considering simultaneous temperature detecting, which will be one of the cornerstones of reliability for future power electronic modules. Other types of field detector technologies are emerging, such as Colossal Magnetoresistance (CMR) and Extraordinary Magnetoresistance (EMR) [5].

G. Interaction with Other Project(s)/Thrust(s)

This project is highly related to both the SC-IPEM thrust and the HDI thrust. The SC-IPEM thrust has proven to be an excellent vehicle to evaluate the capabilities and limitations of the core technologies when implemented in the realities of complex IPEMs. The HDI thrust core technology of integration of field elements is intrinsically related by having a complementary need for field-based optimization of designs. Thus, collaboration between these thrusts is essential. For this reason, the two Co-PI's are from these respective thrusts.

H. References

[1] Parasiliti, F, Petrella, R., Tursini, M., "A Novel Solution for Phase Current Sensing in PWM-VSI Based AC Drives" 9th European Conference on Power Electronics and Applications, Graz, 2001.

[2] R. Dickenson, S.Milano, "Isolated Open Loop Current Sensing Using Hall Effect Technology in an Optimized Magnetic Circuit", Allegro Microsystems, Inc., July 2002.

[3] Karrer, N., Hofer-Noser, P., Henrard, D., "A New Current Probe with a Wide Bandwidth", 8th European Conference on Power Electronics and Applications, Lausanne, Switzerland, Sept. 1999.

[4] J.A. Dieker, "Temperature Compensating Hall Generators", F.W. Bell, Technical bulletin, No. H-102.

[5] Y. Soh, G. Aeppli, "Applied Physics: Making Sense of Magnetic Fields", *Nature* 417, 392 - 393 (23 May 2002);.

[6] Ackerman, D. W., "The Rogowski Coil Revisited", 9th European Conference on Power Electronics and Applications, Graz, 2001.

[7] Qiu, D., Hui, S., Chung, H., "A Single-Sensor Principle for Power Converters", 9th European Conference on Power Electronics and Applications, Graz, 2001.

[8] E. R. Olson, R. D. Lorenz, "Integrating Giant Magnetoresistive Current and Thermal Sensors in Power Electronics Modules", Applied Power Electronics Conference 2003. APEC '03, Volume: 2, pp. 773-777, 9-13 Feb. 2003.

[9] "Engineering and Application Notes, Giant Magnetoresistive (GMR) Sensors", Nonvolatile Electronics, Inc., www.nve.com, September 1998.

I. Statement of Work

Project:	Integrated GMR Current and Temperature Sensor Technology															
Statement of Work		**Schedule**												**Milestones (Mx), Deliverables (Dx)**		
No.	Task Description	2005-2006				2006-2007				2007-2008				Description	Thrusts	
		Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2		To	From
1	Design rules for optimal detector location for I sensing		M1	D1										M1: Complete electromagnetic testing of SC-IPEMs D1: Develop 2-D design rules for detector location		CSI
				M2	D2									M2: Begin 3-D FEA modeling of 3 phase geometries D2: Develop 3-D design rules for detector location		CSI
					M3	D3								M3: Develop next generation design with I sensing D3 Optimized layout for I sensing in IPEMs.	SC IPEM	CSI
2	Development of full scale, 3-D integration methods for both I and T sensing						M1	D1						M1: Develop next generation modules with I sensing D1: Evaluate performance capabilities achieved	SC IPEM	CSI
								M2	D2					M2: Begin 3-D FEA temperature sensing evaluation D2: Develop 1st Gen. design rules for detector location		CSI
									M3	D3				M3: Begin next generation design with I & T sensing D3: Develop optimized layout for I & T sensing	SC IPEM	CSI
3	System evaluation of I and T sensing and overall optimiztion										M1	D1		M1: Develop next generation modules with I & T sensing D1: Evaluate performance capabilities achieved	SC IPEM	CSI
												M2	D2	M2: Formalize paradigms for integrated I & T sensing D3: Develop optimized layout methods for I & T sensing	SC IPEM	CSI