Key Technical Challenges for Integrated Sensors in Power Electronics and Motor Drives

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Abstract - The paper presents technical issues which integrated sensors must address to be implemented in the next generation of power electronics and motor drives. The underlying goal of the sensor integration will be to improve reliability of power conversion systems while making the power converter and motor drive become the primary source of diagnostic signals for the application. The paper focuses on design methodologies that will allow this integration to succeed in meeting the technical demands for both reliability and for application level diagnostics.

1. Introduction

Integration of sensors in drives and power electronics has the potential to improve reliability and cost while adding increasing valuable functionality. The key sensors to integrate into power electronic modules are current, temperature, and thermal-mechanical strain. The key sensors to integrate in motor drives are for position (velocity & acceleration) and shaft (load) torque.

This paper focuses on integrated current and temperature sensors as part of integrated active thermal-mechanical strain control of power modules, and integrated position and shaft torque sensing in motor and motor drive design.

2. Integrated Current Sensing

Current sensing in motor drives and power electronics is generally implemented today with closed (or open) loop Hall effect sensors for high performance drives or current shunts for low cost, lower performance drives. The Hall effect sensors are embedded in completely separate systems that do not lend themselves to compact integration due to the rather large size of their flux concentrating core.

If however, the next generation of intra-module interconnects is based on deterministic geometry, then compact, point field detectors can be integrated into that spatial configuration and very compact, high performance integration can be realized. Suitably compact, low cost, point field detectors are widely used in the hard disk read/write head industry. Thus, detectors such as the multi-layer giant magnetoresistive (GMR) detectors with alternating, thin (2-4 nm) NiFeCo/Cu layers (as well as other such types) have been recognized as having very desirable properties for integration into power modules. [1-7]

2.1 Point Field Detectors

Multi-layer GMR field detectors have very high field sensitivity and very compact size, which makes them ideal for integration. Figure 1 summarizes the key operating principles of such multi-layer GMR point field detectors.

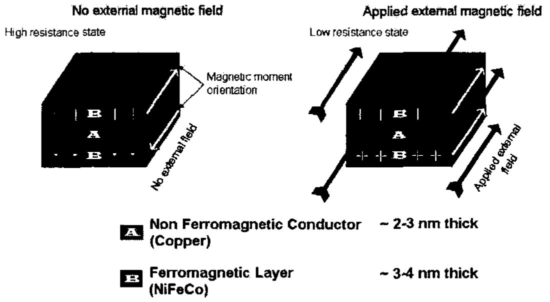

Fig. 1 Multi-layer giant magnetoresistive point field detectors

Similar to classical strain gages, GMRs are often configured in a serpentine (Fig. 2) to boost the series resistance into the integer kiloOhm region, simplifying signal conditioning [8].

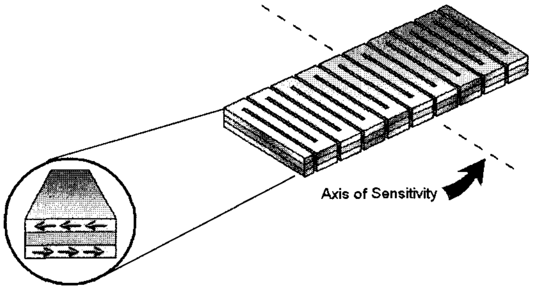

Fig. 2 Serpentine configuration of a GMR field detector [8]

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In such serpentine GMR detectors, a relatively linear, low hysteresis, unipolar 20% change in resistance is achieved in the presence of a bipolar magnetic as shown in Fig. 3.

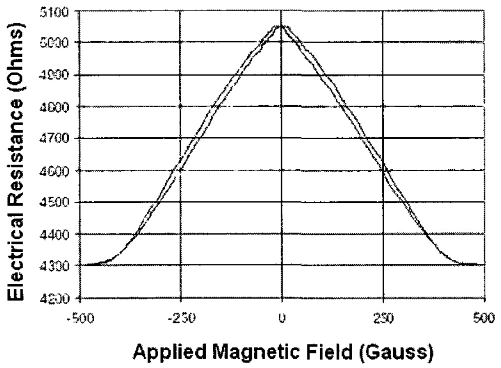


Fig. 3 Unipolar GMR field detector output [8]

The GMR linearity is dependent on the operating bias. If biased to it's midrange, then linearity of better than 0.1% have been achieved as in Fig. 4 [9].

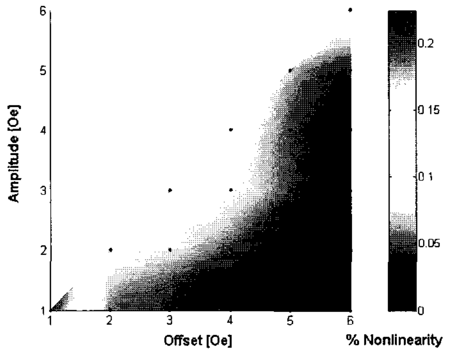


Fig. 4 Linearity of GMR detectors as a function of bias[9]

Similar to strain gages, GMR field detectors are often used in a Wheatstone bridge configuration as shown in Fig. 6 such that thermal effects are decoupled.

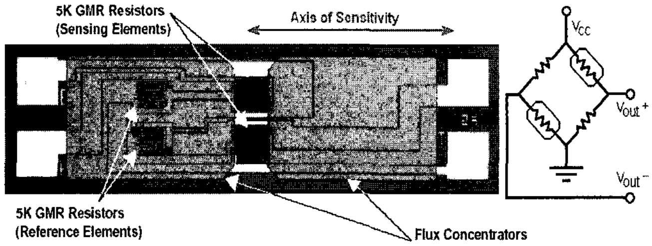


Fig. 5 GMR detectors in Wheatstone bridge layout for classical temperature decoupling [8]

It has been demonstrated that with proper design of the interface circuitry, bandwidths of over 300 kHz are achievable as shown in Fig. 6 [9].

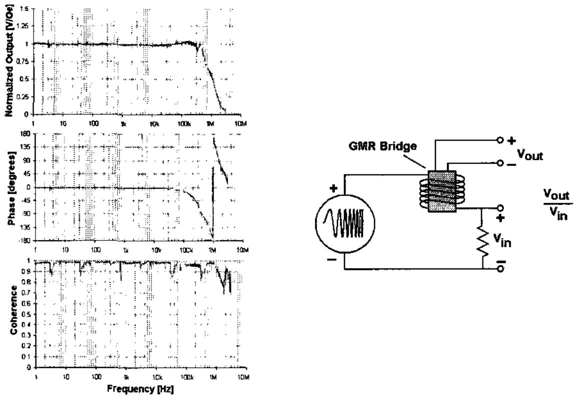


Fig. 6 Frequency response of GMR detectors [9]

When used for current sensing, the GMR field detector has been shown to yield results comparable to the accepted industry standard, as shown in the waveforms of Fig. 7.

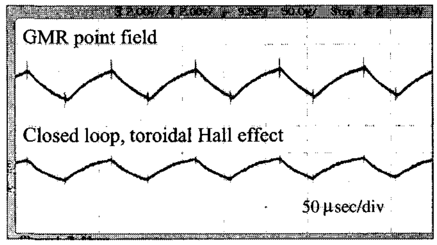


Fig. 7 Switching waveform comparison of GMR point field detectors with closed loop, toroidal, Hall effect sensors [9]

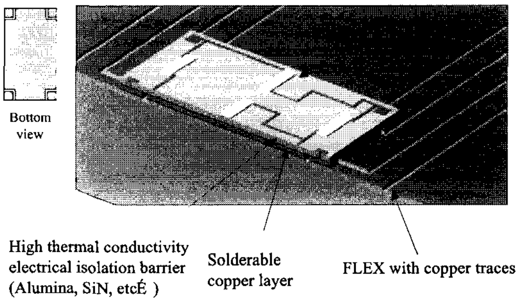


Fig. 8 Integrating GMR detectors in a flex interconnect [12]

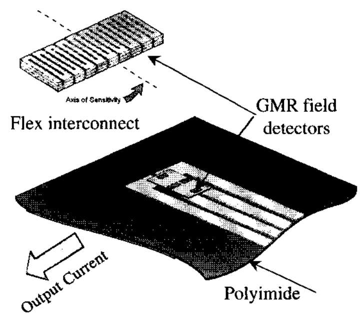


Fig. 9 Using GMR detectors for flex interconnect sensing[12]

GMR point field detector devices are very compact and can easily be integrated into module level deterministic interconnect structures such as the flex interconnect structure shown in Fig. 8 and Fig. 9 [12]

While the GMR is an excellent point field detector with high potential for integrated current sensing, its key limitation is the requirement for extensive 3-D analysis of fields during module layout.

2.2 Spatial Design as a Key Issue for Integrated Current Sensing

Fig. 10 shows two GMR point field detector locations in a 3-D half-bridge module layout using a flex interconnect structure. This 3-D spatial layout acts as the input to finite element analysis of cross-coupled fields from adjacent conductors.

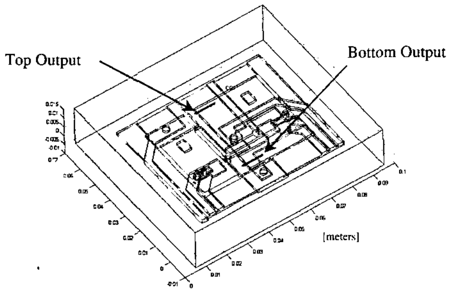


Fig. 10 Half-bridge, power module spatial layout with GMR detectors integrated into interconnect structure [10]

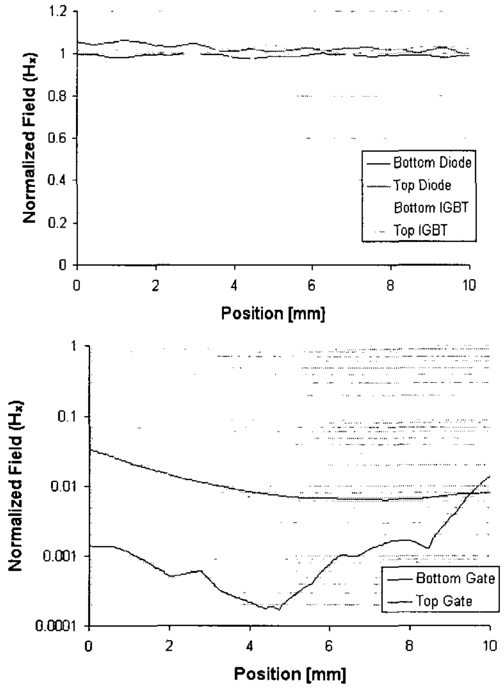


Fig. 11 Bottom output GMR desired signal coupling (top) and undesired cross-coupling (bottom) versus spatial position via extensive FE analysis [10]

Fig. 11 shows the results of such analysis of the spatial layout for desired field coupling and undesired cross coupling in the bottom output.

Fig. 12 shows the corresponding results for the top output GMR location.

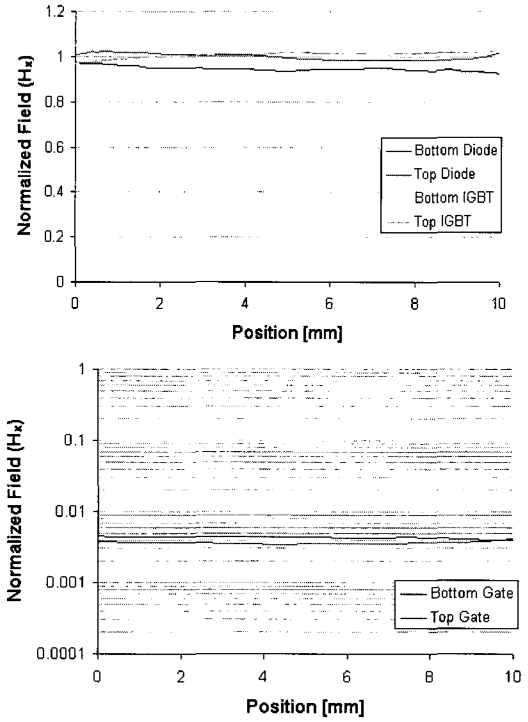


Fig. 12 Top output GMR desired signal coupling (top) and undesired cross-coupling (bottom) versus spatial position via extensive FE analysis [10]

It can be seen that spatial field analysis is a very intensive aspect of the spatial interconnect layout process for modules. This implies that design rules must be developed to simplify the design without compromising the layout possibilities. Early design procedures have resulted in layouts such as those in Fig. 13.

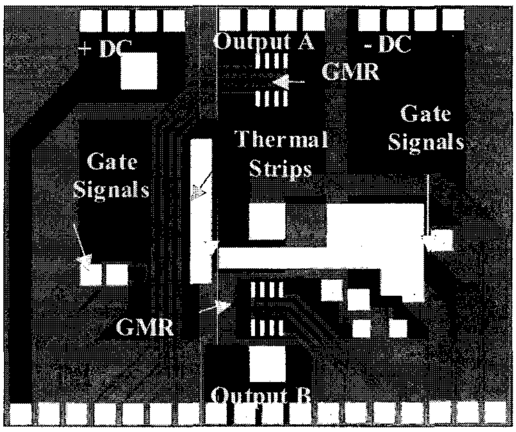


Fig. 13 Interconnect layout for GMR current sensing [12]

A test module using this flex interconnect with integrated GMR-based current sensing is shown in Fig. 14 [12]

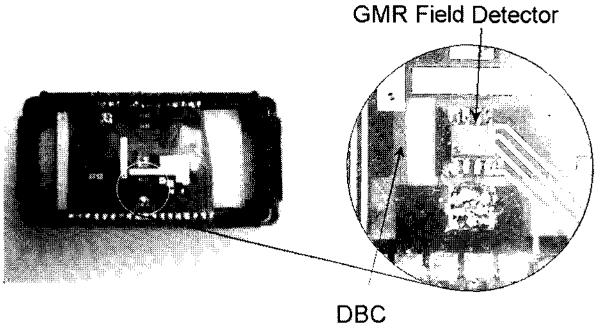


Fig. 14 Research implementation of power module with GMR detector integrated into interconnect structure [12]

While progress is being made, it can be concluded that a major issue for utilization of point field detectors is the lack of spatial design rules which at this point are still very much in development and not yet a mature solution.

2.3 Pilot Current Devices

An alternative strategy for full device level integration is to divert (pilot) current from a few cells of the device as shown in Fig. 15.

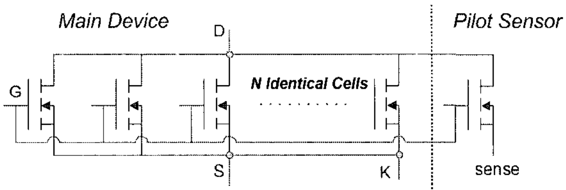
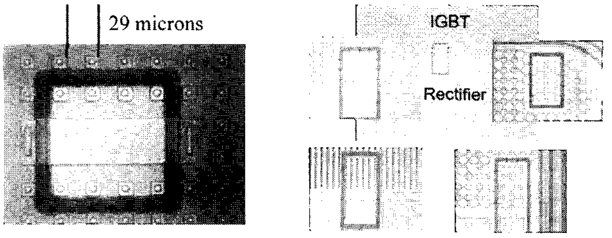


Fig. 15 Pilot current sensing in a MOSFET power device [13]

Fig. 16 shows the device level integration of such pilot cells in IGBT and rectifier structures.



View of pilot cells in PT IGBT

ALL/stripe-cell geometry of DMOS IGBT/MPS rectifier device (pilot sensor at center)

Fig. 16 Pilot current sensing cells in device structures [12,13]

Fig. 17 shows the device level integration of the pilot cell current. signals using standard signal conditioning methods.

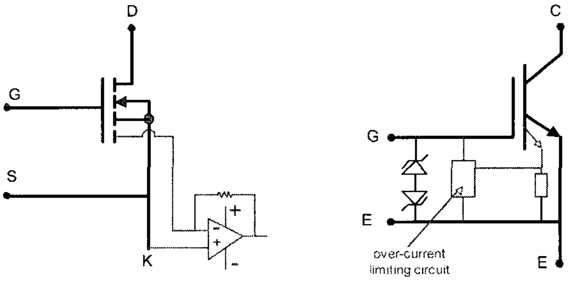
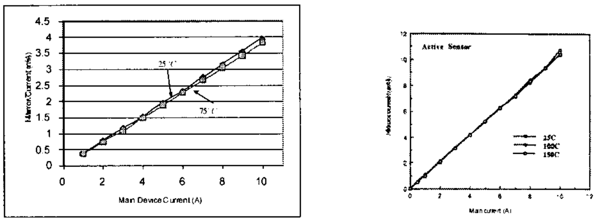


Fig. 17 Pilot current sensing signal conditioning interface issues

The linearity of these methods has been shown to be quite good, as seen in Fig. 17.



MOSFET IRC740

Research lab IGBT

Fig. 18 Pilot current sensing linearity [13]

Without galvanic isolation, the use of the lower side switches is preferred as shown in Fig. 19 [14].

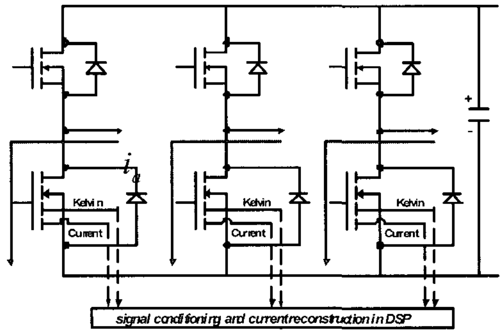


Fig. 19 Three phase VSI with integrated pilot current sensors in the three low-side switches[14]

The lower switch current yields three - 60 degree intervals of ac waveforms in Fig. 20 for which there is only one signal available to define the vector.

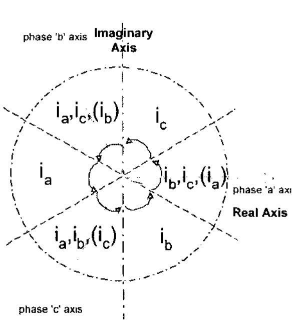


Fig. 20 Intervals of limitations of lower side switch currents [13]

Despite this limitation, a reconstruction method and variable structure control strategy have been developed as in Fig. 21 with results in Fig. 22-23.

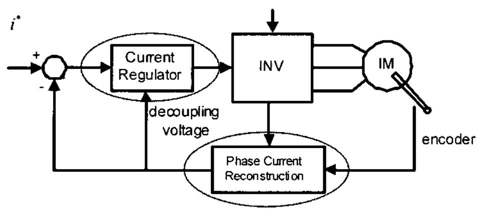


Fig. 21 Current regulation with reconstructed current [14,28]

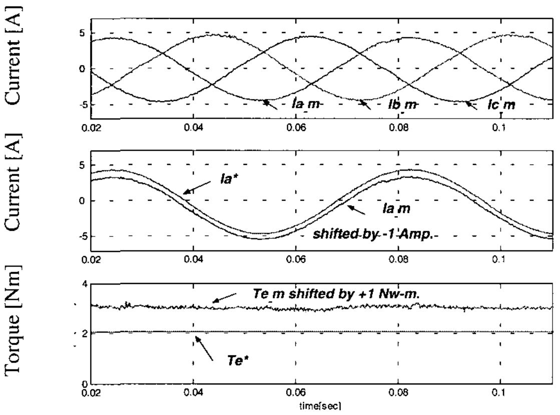


Fig. 22 Experimental results for 17 Hz fundamental [14,27]
1st row: three phase motor current measured (LEM)
2nd row: phase *a* command & measured current (LEM)
3rd row: command and estimated torque

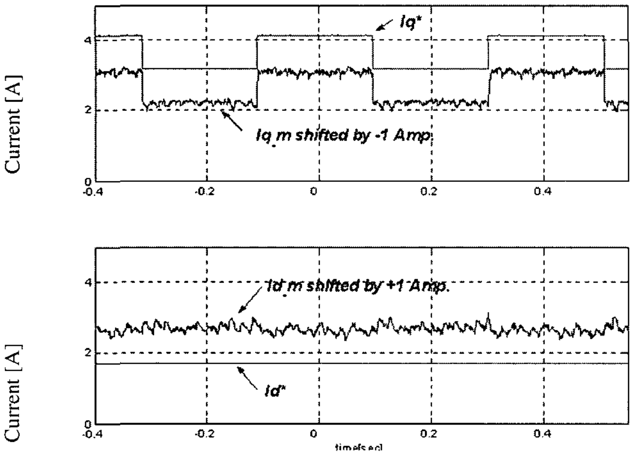


Fig. 23 Experimental results for a q-axis current step [14,27]
1st row: q-axis command and measured current
2nd row: d-axis command and measured current

For this phase current reconstruction, a synchronous frame controller with a variable structure (during each 60 degree interval) can be seen to yield good performance.

The primary integration challenge for this technology is the device integration issues which have yet to develop as a mature technology.

3. Integrated Temperature Sensing

It is widely recognized that thermal limits determine the rating of power converters. Thus, integrated thermal sensing is strategic. Such sensing can be implemented via inherent diode junction properties or by multi-functional use of existing sensors.

3.1 Diode-on-Die Temperature Sensing

If a diode is mounted directly on the switch die surface, its forward drop properties can be used to estimate temperature. Fig. 24 shows one such physical configuration

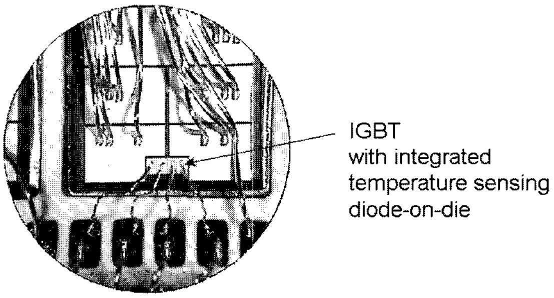


Fig. 24 Diode-on-die temperature sensing [10]

The disadvantage of this method is that the heat flux is constrained, which tends to produce an undesired, device limiting hot spot.

3.2 Thermal Field Detectors & Interconnects

An alternative to this approach is to use the temperature sensitivity of the GMR field detector as shown in Fig. 25. Since the GMR already has signal terminations, this integration approach reduces net interconnections, thus improving reliability and decreasing cost.

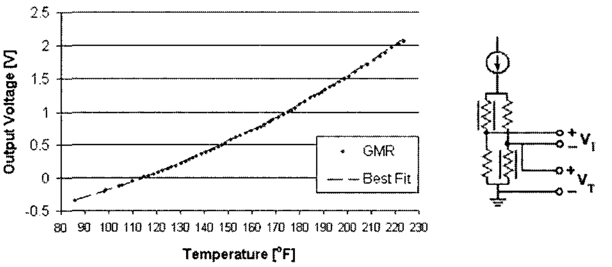


Fig. 25 Using GMR detectors with current source excitation for temperature & field (current) sensing, V_I – Field (current), V_T – Temperature [9]

The limitation of this method is the spatial placement of the detector and the temperature estimation dynamics which can be achieved when not directly sensing the key temperatures. The critical tradeoffs are shown in Fig. 26

and Fig. 27.

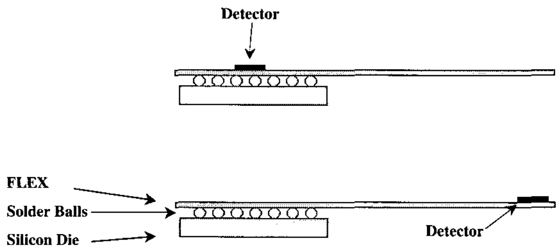


Fig. 26 Detector spatial location options [10]

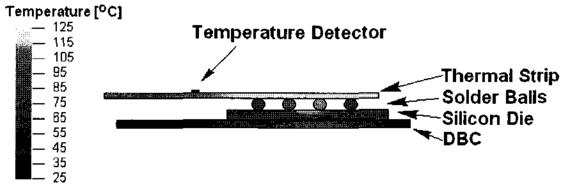


Fig. 27 Detector location and thermal modelling [10]

The avoid any device hot spots, the detector should be located away from the junction. Thus, an accurate thermal model (observer) will be needed to estimate the desired junction temperature. A deterministic interconnect will also facilitate an accuracte observer model since accurate spatial parameters will be known by the module designer. Figure 13 showed one such layout in which thermal strips were integrated into the flex interconnect to conduct heat from the junction for remote steady-state and transient junction temperature estimation. Figure 14 showed a laboratory module fabricated using this flex interconnect and using the GMR for both temperature and current sensing.

Accurate, spatial thermal dynamic characterization is thus critical for the next generation of modules. A deterministic interconnect structure is a key element.

4. Active Thermal-Mechanical Control

Active thermal control of power modules is critical to improve robustness of applications such as motor drives. The fully integrated temperature sensor greatly facilitates this.

4.1 Power Cycle Thermal Mechanical Stress

Power cycles cause thermal mechanical fatigue of the interconnects. This type of stress can be characterized with both a temporal and a spatial ΔTj as shown in Fig. 28. The spatial ΔTj is most appropriate for real time control implementation because it relates directly to strain.

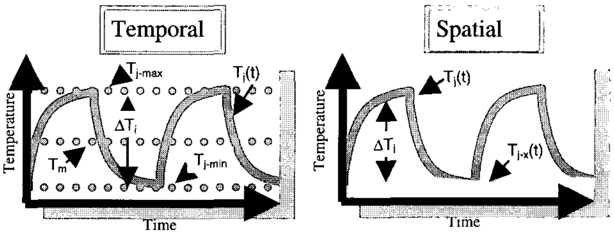
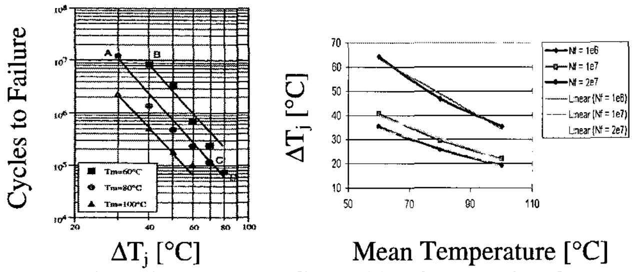


Fig. 28 Temporal and spatial ΔTj and thermal-mechanical stress cycles [21]

4.2 Power Cycle Temperature Control

The thermal mechanical fatigue properties [15-18] of the module interconnect structure are depicted in Fig. 29, which shows both the traditional fatigue plot and a plot suitable for control implementation.



Fatigue format Control implementation format

Fig. 29 Device failure constraints in two formats [20,21]

Fig. 30 shows a region-based controller that implements power cycle temperature regulation by manipulating switching and conduction losses.

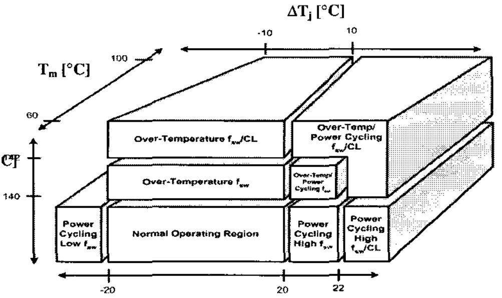


Fig. 30 Region-based thermal-mechanical controller [20,21]

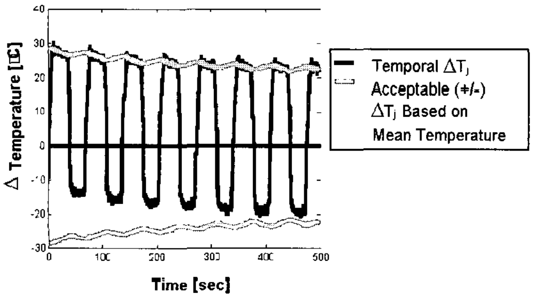


Fig. 31 Implementation results using active thermal mechanical control of power modules[21]

Fig. 31 shows how this controller actively limits the peak-to-peak ΔTj stresses.

This regulation allows the power module and drive to be run in a sustained fashion at appropriately varying thermal cycle limits without causing fatigue life deterioration.

The critical issues for this technology are the need for integrated sensing and for integrated thermal-mechanical modeling of the spatial thermal properties of the module.

5. Machine Design for Self-Sensing

The key sensors to integrate in motor drives are for position (velocity & acceleration) and shaft (load) torque. The position sensor lends itself to being included as part of the machine design such that "self-sensing" of the motor rotor "itself" can then become the standard. Evolution of multi-functional motor design promises to facilitate this opportunity for reliability enhancement of motor drives.

5.1 Self-Sensing Principles

Self-sensing, (use of the motor "itself" as the sensor) has three fundamental requirements as shown in Fig's. 32-34: 1) a known saliency, 2) persistent excitation via the inverter, and 3) saliency tracking using the persistent excitation [22].

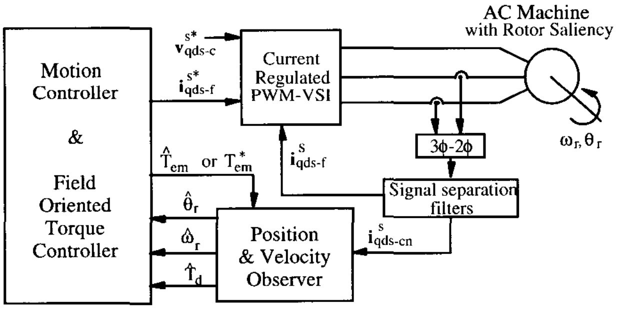


Fig. 32 Self-sensing via tracking intrinsic machine saliencies [22]

The persistent excitation can take the form of an injected carrier frequency voltage.

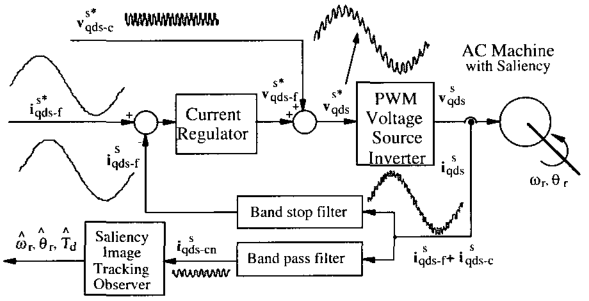


Fig. 33 Self-sensing carrier excitation in a motor drive [22]

The carrier signal modulation can be tracked to estimate position with adequate bandwidth and noise filtering.

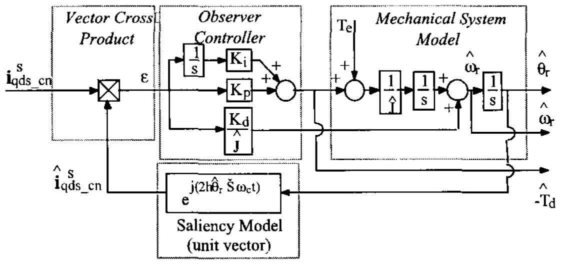
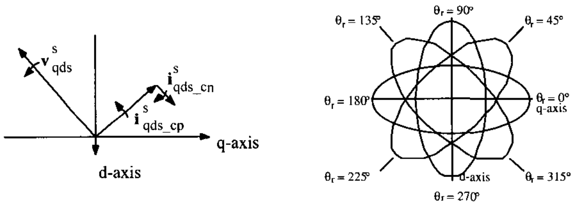


Fig. 34 Saliency tracking observer using carrier injection [22]

This methodology can be implemented in a variety of ways, but in all cases the suitability of the machine as a sensor is a major focus.

5.2 Machine design for self-sensing

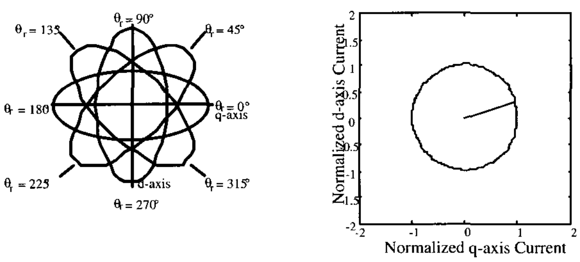
In effect, the various self-sensing methods are all tracking the "electromagnetic spatial image" of the machine. The robustness and accuracy of the methods depends on image directly [22-26]. Fig. 35 shows the simplest image: a single spatial harmonic. Properly implemented, it has no parameter sensitivity and is very robust.



Voltage & current vectors Stationary frame currents

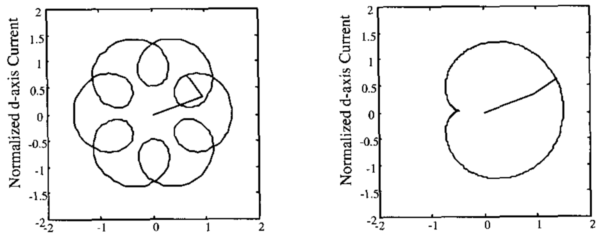
Fig. 35 Carrier frequency currents for a machine with a single harmonic saliency [24]

The image can be made considerably more problematic if additional harmonics are present as shown in Fig's 36-37



Stationary frame image Synchronous frame image

Fig. 36 Frame dependent images for carrier frequency injection with a machine having a single spatial harmonic saliency [24]



1st & 7th harmonics, 2:1 ratio 1st & 2nd harmonics, 2:1 ratio

Fig. 37 Synchronous frame images for carrier frequency injection with a machine having two spatial harmonic saliencies [24]

The critical machine design challenge is to develop deterministic saliencies, such as the single harmonic saliency which can be tracked without knowledge of parameters, to create a robust self-sensing system.

5.3 Drive design for integrated shaft torque (load) sensing

Observers can be used to extract load torque estimates in motion control systems using position sensors as shown in Fig. 38 [29].

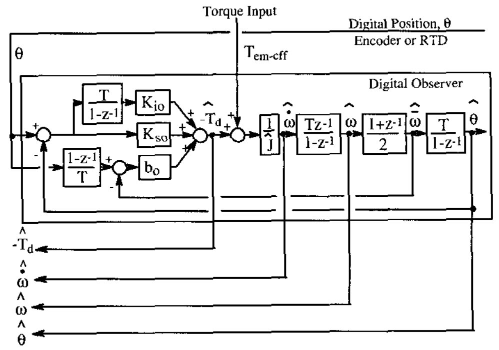


Fig. 38 Observer with load torque estimation [29]

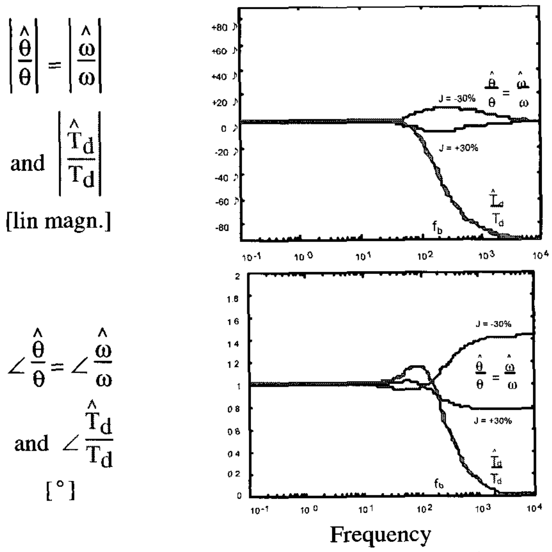


Fig. 39 Observer estimation accuracy: motion & load torque [30]

When properly formed, observers have very desirable estimation accuracy properties as show in Fig. 39 [30].

These same load torque properties are also inherently estimated by the self-sensing observers used with injection (Fig. 34) or when simply tracking backemf at high speeds as shown in Fig. 40 [31].

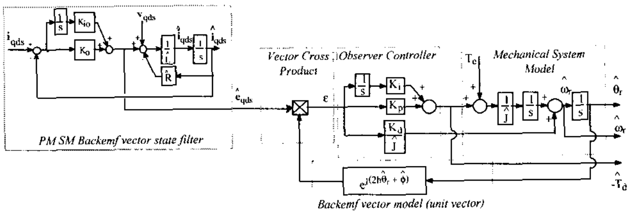


Fig. 40 Back EMF tracking observer estimating load torque [30]

As in all cases using self-sensing principles, the critical issues in this technology is the quality of the machine as a sensor. The higher order effects limit the accuracy and thus "design for self-sensing" is the major challenge for both integrated load sensing and integrated motion sensing.

6. Conclusions

Integration of sensors in drives and power electronics has the potential to improve reliability and cost of these key enabling technologies.

The key sensors to integrate into power electronic modules are current, temperature, and thermal-mechanical strain. The key sensors to integrate in motor drives are for position (velocity & acceleration) and shaft (load) torque.

Isolated current sensing can be implemented using point field detection methods which take full advantage of the next generation, deterministic interconnect structures in power modules. The key challenges are spatial design techniques and guidelines that enable point field estimation during layout of complex structures such as power modules.

Alternatively, current sensing can be implemented with pilot current devices and proper signal reconstruction. The development of power devices with access to pilot current cells is a key challenge to the evolution of this technology.

Temperature sensing can be implemented using the same devices and terminations used for isolated current sensing, yielding both cost and reliability advantages. However, spatial design for thermal mechanical strain sensing using temperature is a key challenge.

Active thermal control of power modules is critical to improve robustness of applications such as motor drives. A fully integrated means of thermal-mechanical strain sensing is the key challenge.

The motor drive position sensor and load torque sensor lend themselves to being included as part of the machine design such that "self-sensing" of the motor rotor "itself" can easily and robustly extract the signals. Evolution of machine design for both sensing and power conversion is the key challenge.

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