Key Technologies for Future Motor Drives

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Abstract - This paper presents technologies that have strategic importance in future motor drives. The underlying strategic issue for motor drives is maintaining cost while increasing certain dimensions of functionality. The dimensions of functionality which should increase include reliability and added value features such as providing continuous energy optimization, providing sensing of the driven system suitable for application specific diagnostic purposes, and providing continuously optimal thermal utilization of the capability of the drive. This paper will address each of these issues and discuss the technology status for each case, with a focus on research needed to fully deliver the needed functionality.

Keywords: Integrated Sensing Systems, Energy Optimizing Control, Reliability via Self-Sensing, Relative Thermal Control, Integrated Sensing & Control

1. Introduction

The future of motor drives is dependent on adding new value while improving reliability and maintaining high levels of performance at no additional cost.

One of the key value-added technologies needed is the evolving methodology to make the motor drive system become the primary diagnostic sensor in the application. This need and opportunity is readily apparent in different aspects of future automotive, white goods, and aerospace applications where application-specific diagnostics add significant value to the end-user and thus inherently increase the value of the motor drive as a integrated sensing system.

Another value-added technology is energy optimizing control methods for motor drives that can achieve both static and dynamic minimization of energy needed for the application. As energy becomes increasingly important in the world, this technology has the potential to rapidly accelerate the application of such motor drives.

One of the key reliability-oriented technologies to be discussed is the evolving methodology to make the motor itself become the motion and flux sensor without adding any other motor-mounted sensors or additional cables beyond the power leads. This "self-sensing" methodology has the potential to transform machine design, as the optimal machine design paradigm will need to include sensing as well as power conversion objectives.

Another reliability-oriented technology is active thermal control as the highest priority control loop for parallel converters and/or modules as is common in high- and/or distributed power conversion systems. This active thermal control will necessarily deal with both power cycle-induced stresses as well as mean stresses and reliably prevent unwanted motor drive failures while maintaining highest possible power conversion capability.

Other reliability-oriented technologies with significant economic potential are the further integration of key sensors in power modules, such as current and multi-point temperature sensing as needed for the key control loops in future motor drives.

2. Motor Drives as Integrated Sensing Systems

For purposes of smooth operation, it has become recognized that observer-based motion controllers are superior to standard sensor feedback systems. The reduction in noise and quantization without adding any filtering lag has made motion control systems such as that in Fig. 1 become superior quality solutions [1, 2, 3, 4, 5].

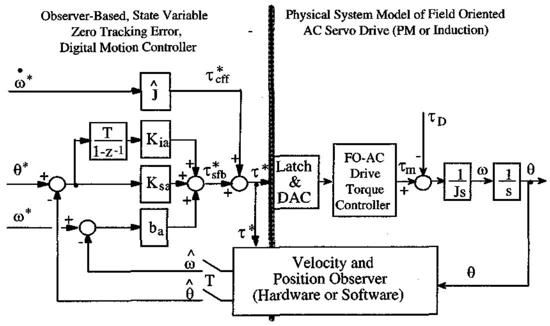

Fig. 1 Digital motion control system using observer state feedback based on position measurement [1,2,3,4,5]

This paper was received the best paper award from ICEMS 2005, which held in Nanjing, China from Sep. 27 to Sep. 29, 2005

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Received October 24, 2005 ; Accepted November 12, 2005

It is not as widely recognized that a properly formed observer automatically estimates disturbance torque (primarily shaft torque) as shown in Fig. 2 [3, 4, 5].

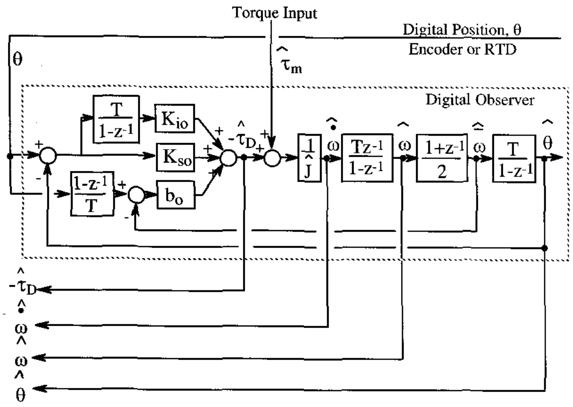


Fig. 2 Digital motion and disturbance torque observer, based on position measurement and electromagnetic torque [3, 4, 5]

The inherent zero-lag filtering of the estimated motion states facilitates closed loop control, but the estimated disturbance torque will inherently have traditional bandwidth limited filter properties as shown in Fig. 3 [2, 3, 4].

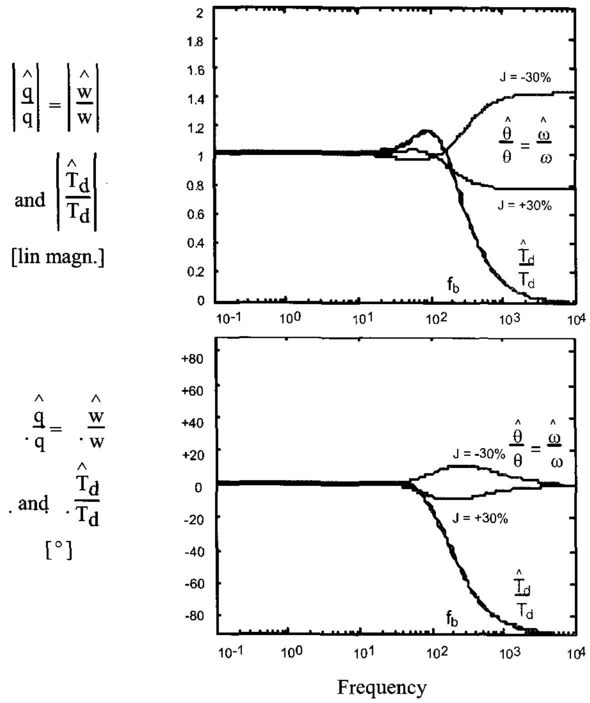


Fig. 3 Estimation accuracy frequency response a the closed loop motion state observer and disturbance state filter [2, 3, 4]

Thus, within the bandwidth of the observer, parameter insensitive "load torque" estimates are available. This feature converts the motor drive to a "system sensor" which enables the application-diagnostics without requiring any additional sensors. This is a key opportunity for future drives.

3. Energy Optimizing Control

For virtually all motor drives, efficiency can be statically and dynamically optimized with a controller of the structure shown in Fig. 4 [7].

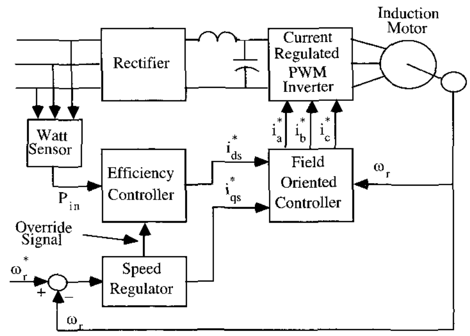


Fig. 4 Block diagram of optimal efficiency controller [7]

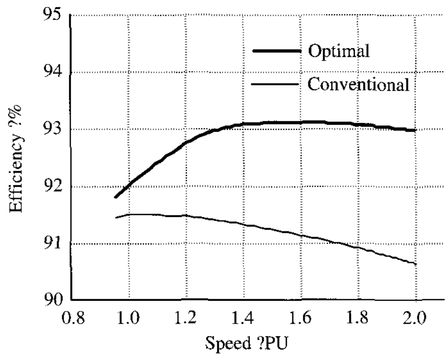


Fig. 5 Efficiency comparison for conventional vs. optimal constant rated power operation of a 5 Hp high efficiency induction motor [8]

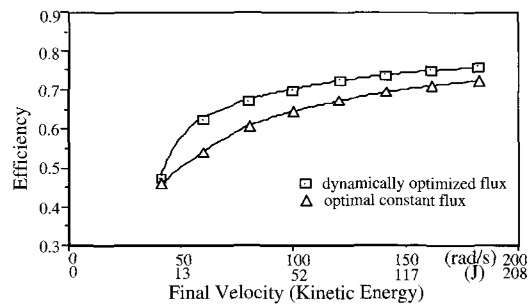


Fig. 6 Efficiency comparison of constant vs. dynamically optimized rotor flux for a fixed distance motion trajectory [9]

In general, flux levels (stator and/or rotor flux) affect magnetic core losses, and thus must be optimized to balance Ohmic (i^2R) losses and eddy current losses and minimize total losses. This balance is achieved by regulating the flux levels actively, either in an open or closed loop fashion. The net result for steady state operation has been shown to be very significant as demonstrated in Fig. 5 [8]. In addition, control methods that dynamically minimize losses have been shown to have a very large impact on losses for applications with cyclical loading as shown in Fig. 6 [9].

For applications with low average loads (i.e. automotive traction), the losses can dominate the thermal sizing of the machine as depicted in Fig. 7 [9].

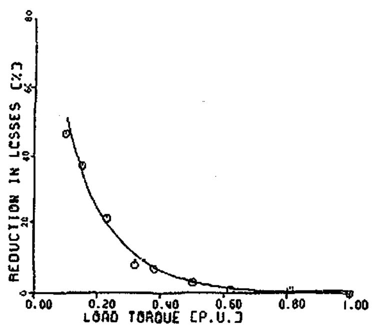


Fig. 7 Measured relative reduction in losses for a 3 HP test motor at 600 r/min [7]

The opportunity to very significantly reduce losses and energy consumption make this type of control very attractive. Since motor drives convert the majority of all energy to useful work, this feature should become a world standard for all future motor drives. It is interesting to note that this potential was recognized decades ago, but it is still not standard in commercial motor drives. With the growing acceptance of hybrid electric vehicles, this technology will likely become a salient feature of all future automotive drives, which will enable its use elsewhere.

4. Reliability via Self-Sensing Motor Drives

It is well accepted that flux and motion sensors degrade reliability as well as increase cost of motor drives. Thus, methods that eliminate the need for motor mounted flux and motion sensors are highly valued. In general, such methods use commonly found current sensors in the power converter and make the motor itself become a sensor, thus introducing the concept of "self-sensing".

4.1 Self-Sensing Principles

Self-sensing, (usint the motor "itself" as the sensor) has three fundamental requirements as depicted in Fig's. 8-10: 1) a deterministic machine saliency, 2) a persistent excitation via the inverter, and 3) saliency tracking with adequate bandwidth [10, 11, 12].

The persistent excitation that enables self-sensing to be independent of speed and load often takes the form of an injected carrier frequency voltage as shown in Fig. 9.

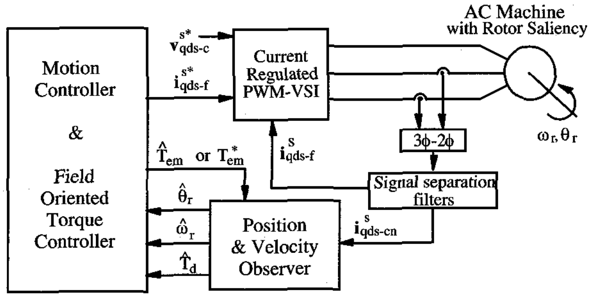


Fig. 8 Self-sensing via observer-based tracking of intrinsic machine saliencies with inverter-based carrier injection [10]

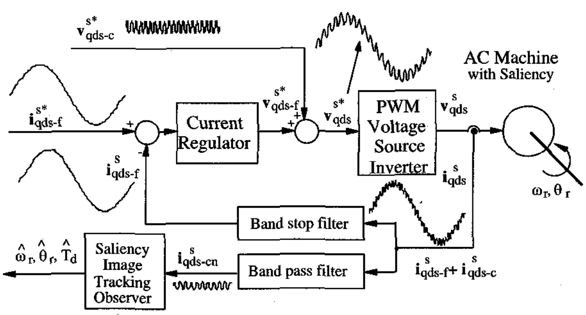


Fig. 9 Self-sensing carrier excitation in a motor drive [10]

The resulting carrier signal modulation can be tracked with a "saliency image tracking observer" to estimate motion and load torque with adequate bandwidth and noise filtering as shown in Fig. 10 [13].

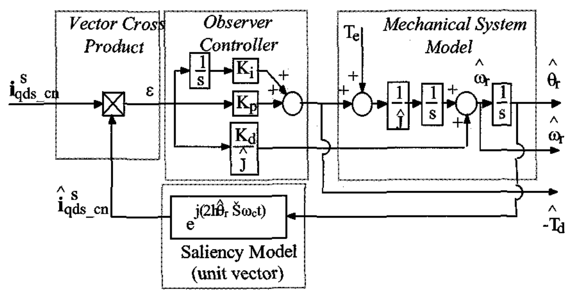


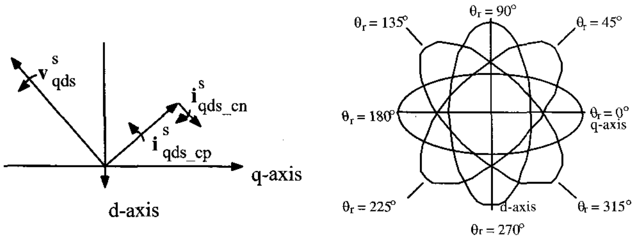
Fig. 10 Saliency tracking observer using carrier injection [13]

The saliency image tracking observer can be implemented in a variety of ways, but in all cases the suitability of the machine as a sensor is a major focus. For properly designed machines, the methodology has been shown to be essentially parameter insensitive [10, 11, 12].

4.2 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 [13, 14]. Fig. 11 shows the simplest image:

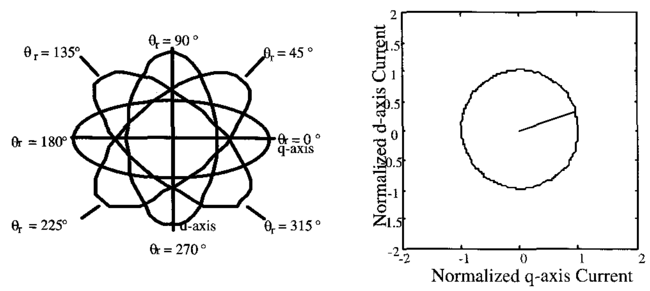
a single spatial harmonic. The ellipse simply rotates with the saliency motion, without parameter sensitivity. The method is thus very robust.



Voltage & current vectors Stationary frame dq currents

Fig. 11 Carrier frequency currents for a machine with a single harmonic saliency [13]

The image can also be viewed in the excitation frame. For an ideal machine the loci with continuous motion would be a circle as shown in Fig. 12.



Stationary frame image Synchronous frame image

Fig. 12 Frame dependent images for carrier frequency injection with a machine having a single spatial harmonic saliency [13-14]

The image can be made considerably more problematic if additional harmonics are present as shown in Fig. 14 for the induction motor rotor in Fig. 13.

The critical machine design challenge is to develop deterministic saliencies, such as the single harmonic saliency that can be tracked without knowledge of parameters, to create a robust self-sensing system. Fig. 15 shows how this has been implemented via optimizing of the flux barrier ribs in an IPM SM design.

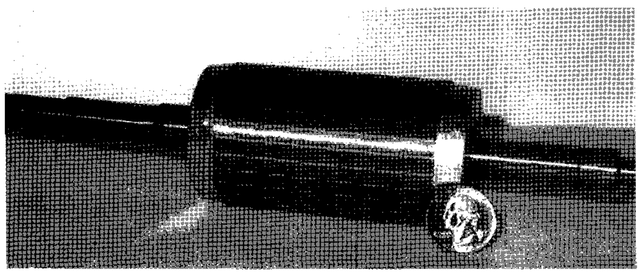
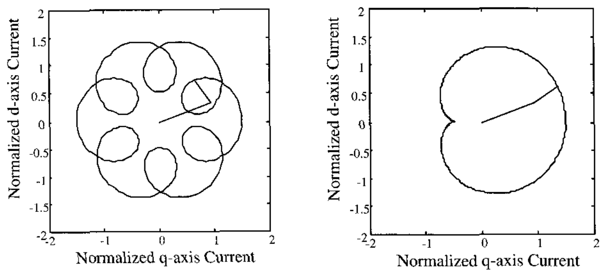
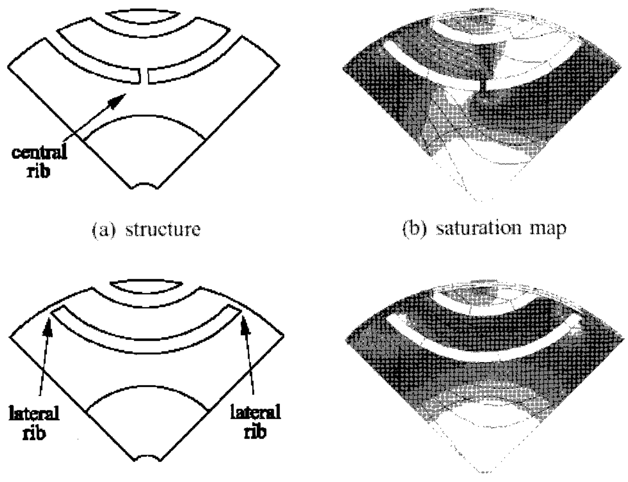


Fig. 13 Unmodified induction motor rotor with no skewing providing sufficient saliency for self-sensing with multiple saliencies



1^{st} & 7^{th} harmonics, 2:1 ratio 1^{st} & 2^{nd} harmonics, 2:1 ratio

Fig. 14 Synchronous frame images for carrier frequency injection with a machine having two spatial harmonic saliencies [13, 14]



(a) structure (b) saturation map

(c) structure (d) saturation map

Fig. 15 Saturation saliency design optimization for self-sensing via rib locations and numbers [15]

For this design, the saturation saliency has been optimized to assure robustness of the saliency image under load. The self-sensing design challenge is a foremost issue for machines in future motor drives.

5. Reliability via Relative Thermal Control

The most frequency failure mode for power converters in motor drives is due to thermal loading. One of the issues causing such failures is non-uniform distribution of the thermal load between devices sharing load. One control methodology to minimize this problem is relative temperature via a "virtual heat sink" as shown in the block diagram of Fig. 16 [16].

This methodology allows parallel load sharing with uniform thermal loading but allows the dynamics of the "virtual heat sink temperature" to be tuned for the best system transient properties. While this method has been shown to be easily tuned and robust, it requires sharing temperature information between the parallel devices or converters. This need for sensing and real time communication would be an unreasonable economic and reliability constraint. Thus, some form of integrated sensing and communication is needed. Fig. 12 depicts the basis of one such method which uses the inherent switching transients to both provide temperature information and to communicate the information automatically on the common DC bus [16].

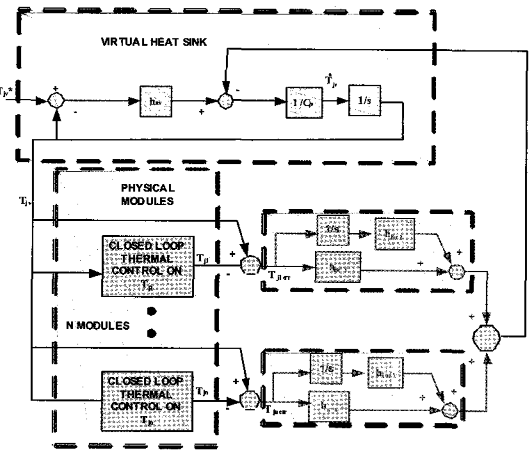


Fig. 16 Relative temperature control via a "virtual heat sink" [16]

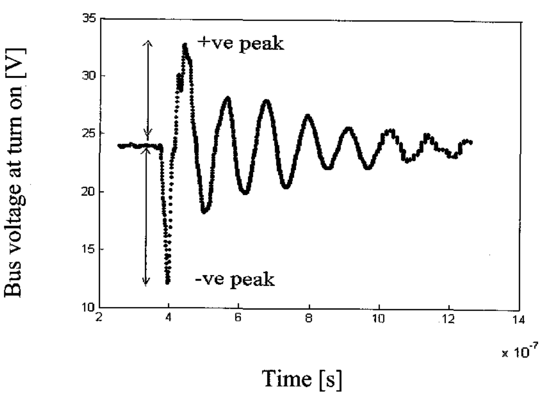
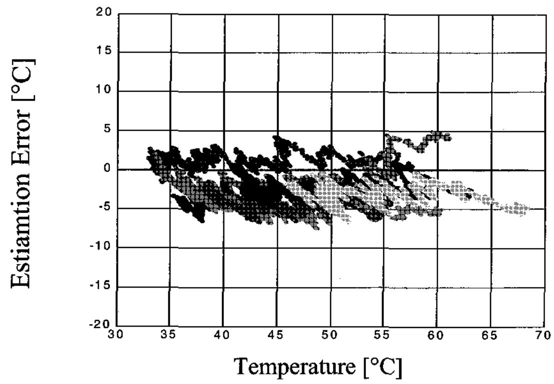


Fig. 17 Junction temperature sensing via "bus ringing" [16]

The principle of operation is based on the inherent temperature sensitivity of the forward voltage drop in junction devices (for example IGBTs). The forward voltage drop causes power dissipation which appears during the transient ringing. Since the damping of the transient is a function of dissipation, the complex exponential damping can be extracted to provide an estimate of junction temperature. Fig. 18 shows the temperature deviation when estimating temperature using this inherent bus ringing [16].

The key opportunity here is to improve reliability via robust relative temperature control methods but to provide the temperature signals needed via the inherently connected DC bus. Thus, no increase in hardware complexity is incurred to achieve the improved reliability. This type of integrated sensing and control are key elements of future high reliability, low cost motor drives.



Legend output voltage Red V = 31 Green V = 34 Blue V = 37 Cyan V = 40 Magenta V = 44 Black V = 50 Yellow V = 57

Fig. 18 Temperature estimation using bus ringing [16]

6. Reliability via Integrated Sensing & Control

The need for integrated sensors is valid at both the system level and at the component level in future motor drives At the component level, current sensing is one of the most widely used signals required for proper control of motor drives. The opportunity to integrate this current sensing into future generations of interconnects within power electronics modules is key to simplifying the system without compromising complexity, cost, and performance constraints. Fig. 19 shows a recently developed interconnect structure named "embedded power". It is based on layered construction of modules with planar interconnects via sputtering processes.

Fig. 20 shows the layers of copper artwork including the power buses which are accessible for current sensing via point field detection. The point field detectors are miniature (less than 1 mm x 1 mm) GMR or EMR devices that are inherently galvanically isolated and have the potential for megahertz bandwidth current sensing.

To achieve adequately high bandwidths requires a full understanding of the effects of high frequency eddy currents on the field distribution as a function of frequency. Fig. 21 shows the effect on measurement bandwidth of two spatial locations on the buses shown in Fig. 19 & 20.

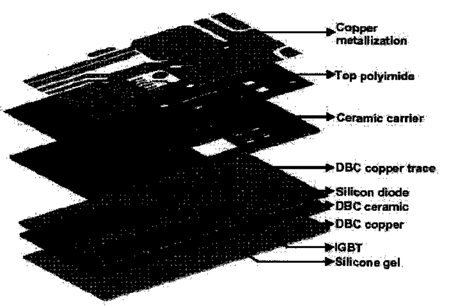


Fig. 19 Advanced power semiconductor packaging with integrated sensing [17, 18, 19]

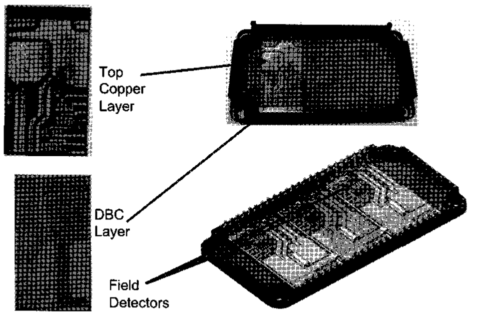


Fig. 20 Advanced power semiconductor packaging with integrated sensing [17, 18, 19]

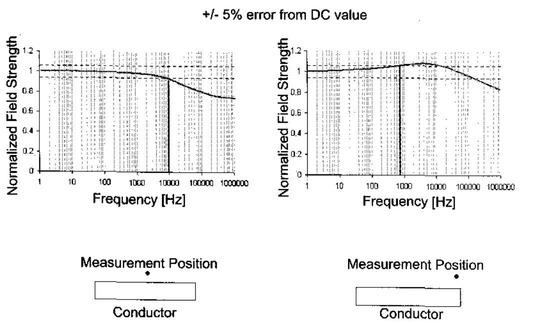


Fig. 21 Advanced power semiconductor packaging with integrated sensing [18, 19]

From Fig. 21, it can be seen that the "flat bandwidth" of the point field detector used for current sensing is very dependent on the spatial location of the detector. This effect has more extreme ramifications if one simultaneously considers the two dominant effects: 1) the spatial distribution of magnetic field intensity as a function of frequency, i.e. the signal-to-noise ratio, and 2) the spatial distribution of the regions of adequate flat bandwidth.

The explicit spatial evaluation (using finite element analysis methods) of the magnetic field intensity and the regions of flat bandwidth are shown in Fig. 22 [18-19].

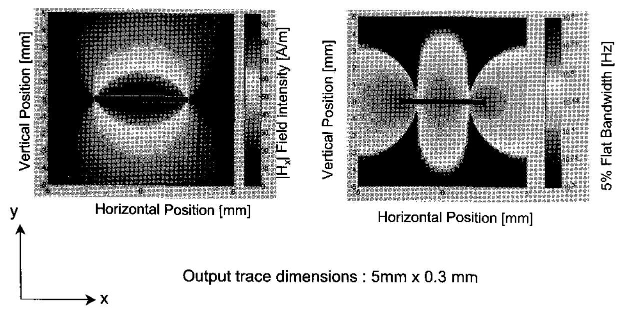


Fig. 22 Advanced power semiconductor packaging with integrated sensing [18, 19]

The key opportunity here is to optimally integrate point field detectors as the current sensors for high performance motor drives. This will achieve both significantly improved reliability and lower costs, without compromising performance.

7. Conclusions

The key opportunities for future motor drives lie strongly in the integration of sensing.

The largest value-added sensing issue is in making the motor drive the primary application sensor, without adding any additional sensors to the motor drive system. It was been shown that this can be achieved via proper integration of observers which inherently estimate the shaft torque with very little sensitivity to parameters.

Since energy consumption is rapidly becoming a worldwide issue, the ability of future motor drives to continuously optimize efficiency of the power conversion process will play a major role in the rapid acceptance of future motor drives. It will be a major issue for all applications, but for some applications (such as the automotive traction drive) it will dominate the selection of the motor drive.

The demand for improved reliability will dictate the need for all future motor drives to use self-sensing principles in the design of the machine and drive. The integrated objectives of sensing and power conversion will need to become the standard design paradigm for future machines.

The reliability of parallel active converters and devices in motor drives will force the active relative temperature control structures to become the norm in future motor drives. This will also require integrated temperature sensing and bus communication methods including the elegantly simple bus ringing methods presented in this paper. Reliability will force the design to integrate such sensing and communication to achieve reliable and robust load sharing methods.

The integration of miniature point field detectors into new interconnect structures will be required in future motor drives so that very high levels of reliability can be achieved at much lower cost than is possible today. This type of "design-for-sensor-integration" will become the norm for all aspects of future motor drives.

Acknowledgment

The author wishes to acknowledge the motivation and financial support provided by Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC) of the University of Wisconsin-Madison. The work made use of ERC Shared Facilities supported by the National Science Foundation (NSF) under AWARD number EEC-9731677 (CPES).

References

[1] R.D. Lorenz and K. Van Patten, "High Resolution Velocity Estimation for All Digital, AC Servo

Drives," *IEEE Trans. on Ind. Appl.*, July/Aug., 1991, Vol 27, No. 4, pp. 701-705.

[2] R.D. Lorenz, T.A. Lipo, and D.W. Novotny, "Motion Control with Induction Motors," in *IEEE Proceedings Special Issue on Power Electronics and Motion Control*, Vol 82, No. 8, pp. 1215-1240, August, 1994.

[3] R.D. Lorenz, "Advances in Electric Drive Control," *IEEE International Electric Machines and Drives Conference*, May 9-12, 1999, pp. 9-18.

[4] R.D. Lorenz, "Robotics and Automation Applications of Power Electronics," *IEEE Proceedings Special Issues on Power Electronics Technology: Present Trends and Future Developments*, Vol. 89, No. 6, June 2001.

[5] R.D. Lorenz, "Observers and State Filters in Drives and Power Electronics," *Journal of Electrical Engineering*, Vol. 2, No. 2, 2002, pp. 4-12.

[6] S.K. Sul and M.H. Park, "A Novel Technique for Optimal Efficiency Control of Current Source Inverter Fed Induction Motor," *IEEE Power Electronics Specialists Conf.*, 1986, pp.486-493.

[7] D.S. Kirschen, D.W. Novotny and T.A. Lipo, "Optimal Efficiency Control of an Induction Motor Drive," *IEEE Trans. on Energy Conversion*, Vol. EC-2, No.1 Mar. 1987. pp. 70-76.

[8] R.D. Lorenz and D.W. Novotny, "Optimal Utilization of Field Oriented Induction Machines in Field Oriented Drives," *Journal of Electrical and Electronics Engineering*, Vol. 10, No. 2, June, 1990. pp. 95-101.

[9] R.D. Lorenz and S.M. Yang, "Efficiency Optimized Flux Trajectories for Closed Cycle Operation of Field Oriented Induction Machine Drives," *IEEE Trans. on Ind. Appl.*, May/June 1992, pp. 574-580.

[10] P.L. Jansen and R.D. Lorenz, "Transducerless Position and Velocity Estimation in Induction and Salient AC Machines," *IEEE Trans. on Ind. Appl.*, March/April 1995, pp. 240-247.

[11] P.L. Jansen and R.D. Lorenz, "Transducerless Field Orientation Concepts Employing Saturation-Induced Saliencies in Induction Machines," *IEEE Trans. on Ind. Appl.*, Nov./Dec. 1996, pp. 1380-1393.

[12] P.L. Jansen, M.J. Corley and R.D. Lorenz, "Flux, Position, and Velocity Estimation in AC Machines at Zero Speed via Tracking of High Frequency Saliencies," *EPE Journal*, Vol. 9 , Aug. 1999, no 1-2.

[13] M.W. Degner, R.D. Lorenz, "Using Multiple Saliencies for the Estimation of Flux, Position, and Velocity in AC Machines," *IEEE Trans. on Ind. Appl.*, Sept./ Oct. 1998, pp. 1097-1104.

[14] M.W. Degner and R.D. Lorenz, "Position Estimation in Induction Machines Utilizing Rotor Bar Slot Harmonics and Carrier Frequency Signal Injection," *IEEE Trans. on Ind. Appl.*, May/June 2000 pp. 736-742

[15] N. Bianchi, S. Bolognani, M. Zigliotto, "Design Hints of an IPEM Synchronous Motor for an Effective Position Sensorless Control," *IEEE Power Electronics Specialist Conf.*, 2005, pp. 1560-1566.

[16] J. L. Barnette, A.Nahar, M.R. Zolghadri, A. Homaifar, R.D. Lorenz, F.C. Lee, "Relative Temperature Control in Parallel-Acting Power Modules," *Proc. of Annual Conf. of the Center for Power Electronic Systems*, 2005, pp. 243-252.

[17] E.R. Olson and R.D. Lorenz, "Integrating Giant Magnetoresistive Current and Thermal Sensors in Power Electronic Modules," *IEEE APEC Conf.*, Miami, Feb. 9-13, 2003, pp. 773-777.

[18] E.R. Olson, R.D. Lorenz, T.M. Jahns, "Integrated Current Sensing in Embedded Power Modules using GMR Field Detectors," *Proc. of Annual Conf. of the Center for Power Electronic Systems*, 2005, pp. 27-32

[19] E.R. Olson and R.D. Lorenz, "Integrated Current Sensing for Power Electronic Modules using GMR Field Detectors," *EPE Conf.*, Dresden, Sept. 13-15, 2005.

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