Sensorless Digital Motor Controller for High Reliability Applications

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Abstract

Today, “electric platform” based commercial and military aerospace, land vehicles and weapon systems are using adjustable speed PM motor systems to replace older fixed speed motors that have mechanical gearboxes. A high reliability motion control “platform” for sensorless vector controlled PM motors has been created to facilitate this change-over from geared motors, with additional benefits of removal of hall sensors, improved efficiency, high starting torque, and lower mechanical noise, as well as improved Power Factor.

To speed development, a dedicated hardware motion control processor is used. This is an ASIC with embedded pre-configured sinusoidal FOC algorithm, ie the chip is 100% dedicated to motor control function, reducing certification requirements (no software is required). Powerful commissioning tools allow the user to quickly create a high performance adjustable speed system capable of high inverter frequency and wide speed range. Applications include pumps, fans, and compressors for use in more challenging settings like aircraft, combat vehicles, weapon systems and ships.

Features of a controller designed for low voltage PM 3phase motors are discussed including new iMotion$_{tm}$ ASIC, gate drivers, Mosfets, and feedback electronics which have been integrated into a very small package further reducing the overall controller cost.Test data will be shared showing important performance characteristics.

Mobile Electric Platforms use of PM Motor Controllers

A trend in Modern Electric Platforms is to utilize engine driven generators to power electric motors that have POL power conditioning to provide the required motor buses.(5) Platform designers are being asked to utilize permanent magnet motors because of their high torque to amp ratio, efficiency, and improved power factor as well as small size. Weight is a penalty in transportation, especially in aircraft. A reasonable solution is thus to use thermally efficient hybrid substrates for power devices mated with low cost SMT circuitry on multilayer PC boards for control hardware. This paper discusses the IRMCT3UF1 motor controller created for pump and fan use in commercial aircraft such as air transport, business and regional jets and also useful in military applications.

The particular application focus of this paper is a pump system for supplying cooling fluid to a weapon control system mounted on a Military Vehicle. The motor control must fit into a small package, within a housing integral to the pump, and will be air cooled. Figure 1a shows the controller end of the pump system and Figure 1b shows the IRMCT3UF1 controller, which is installed under the heat sink seen here.

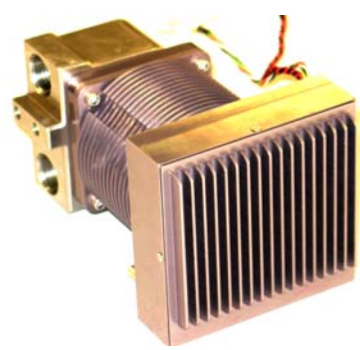

Figure 1a Coolant Pump

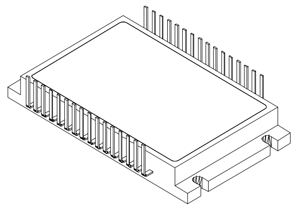

Figure 1b IRMCT3UF1 Controller

Configurable Integrated Motion Controller

Important “system level” features of this controller include:

- Sensorless – no hall sensors or position feedback required for commutation or speed control
- The operating temperature profile must include the temperature range of the cooling fluid, exceeding typical industrial specs and requiring the controller to operate over most of it’s –40 to +85C rating.
- Compact Integrated Power Electronics – Utilizing miniature hybrid packaging in the power section.
- Adjustable and Tunable Performance – Speed loop commanded digitally or with analog pot, and current/speed loops are tunable.
- Varied motor usage – Controller can accommodate PM motors with a wide range of parameters (inductance, speed, Ke/Kt, #poles)
- Protection features with override – bus over-overvoltage, undervoltage, overcurrent, over-temp, loss of phase, underspeed, overspeed.
- Configurable startup sequencing and operation – Including diagnostics for optimizing startup procedure.

The coolant pump motor requires a 28V DC bus for motor supply. Figure 3 shows the block diagram of the IRMCT3UF1 with required external I/O, Bus conditioning, power supply, and load for typical pump applications:

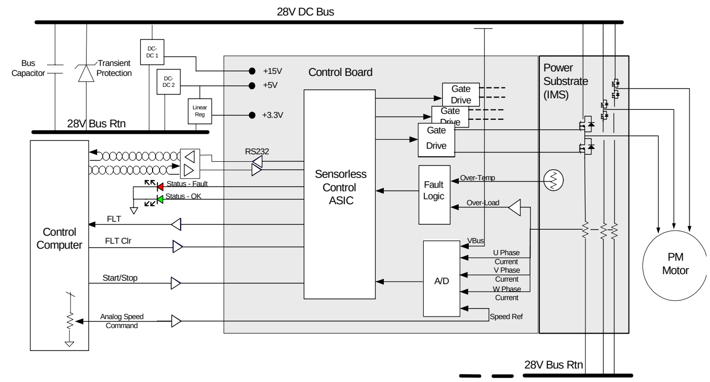

Figure 3 Coolant Pump Application Block Diagram

Hardware Based Control Technology

Validation of mature iMotion$_{tm}$ technology in high volume markets industrial and commercial white goods markets before use in HiRel applications eliminates much uncertainty. Before the controller described in this paper was developed, iMotion$_{tm}$ chipsets had already been used in dozens of products including factory automation machines, white goods, and automotive controls. These chipsets have also been designed into speed and position controls onboard commercial and military aircraft and land vehicles such as for compressors, pumps, fans and weapons positioning. Although prior use is re-assuring, High Reliability controllers often need some additional features beyond those typically available on industrial drives:

- Robust Sensorless Algorithm for Safety Critical applications
- Ruggedized Packaging suitable for high vibration locations
- Small footprint suitable for cold-wall or heat sink mounting
- Easily adaptable to different (custom) motors and loads
- Military or Commercial Airframe Qualification and Screening
- Long-term Availability
- Strong Customer Support

One important boost to reliability is the elimination of Hall sensors and feedback devices traditionally located inside the motor housing. Sensorless control technology eliminates the need for these devices, which in turn reduces motor size, cost, and improves overall reliability. The control processor block diagram for the IRMCT3UF1 is shown in Figure 4.

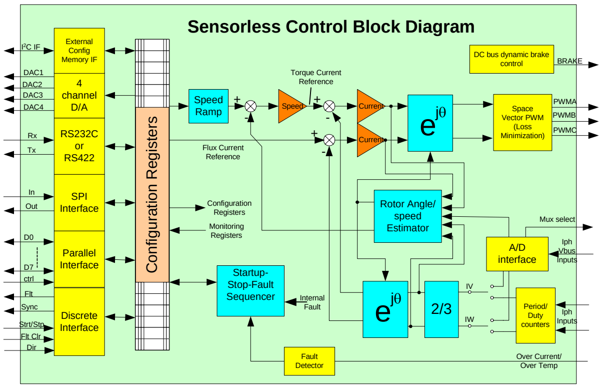

Figure 4) Sensorless Speed Controller Block Diagram

Recent developments in digital control have allowed practical implementation of true Sensorless Field Oriented Control with good bandwidth performance using hardware rather than software control processors. Advances in FPGAs and their support tools, have prompted conversion from software systems to faster, parallel hardware processing systems where dedicated processing is needed. IR's sensorless control algorithm was developed using commercial FPGAs and an ASIC was then created from this design. For the HiRel community this approach has an added benefit. Because the ASIC is dedicated *solely* to motor control, no unexpected operating modes or extra gates are found in the ASIC. This increased determinism has allowed some HiRel customers to work under relaxed certification requirements.(1) For the Low Voltage Controller discussed in this paper, the architecture in Figure 4 uses the leg shunt current sensing option and bus voltage measurement to close the current and speed loops. When current signals are properly reconstructed, this sensing method provides best quality signal feedback to the control algorithm as it is ground referenced and thus more immune to transient noise. Because the iMotion$_{tm}$ chipset utilizes parallel hardware processing (no software CPU), it is fast (11microsecond PWM cycle). It has been designed into products with up to 100Krpm motors while maintaining complete control of all protection functions.

Preconfigured Control Platform Speeds Development

Studies have shown that a preconfigured platform approach to motion control eliminates the need for digital drive specialists, DSP Programmers, Power Electronics Designers, and Thermal/Mechanical Designers. (3)(4)

In the creation of this controller we used such a platform, which is essentially a customized application interface with full-featured I/O as shown in Figure 5 (High Voltage Controller example shown). This platform brings out most of the I/O available in Figure 4 to enable more complete system understanding during development. Using this approach, designers can quickly bring up and validate their system without having to solder I/O cables to the controller, or design power supplies, I/O filters, and motor bus conditioning and storage caps.

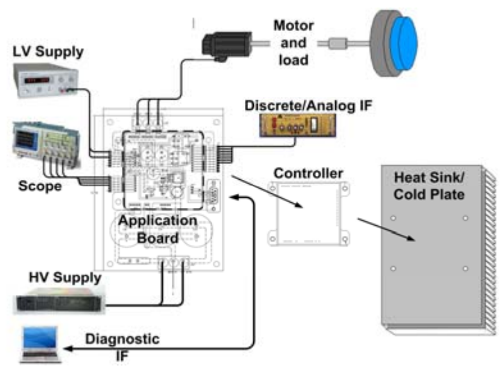

Figure 5 Application Interface

For the coolant pump controller, once the controller function and hardware had been fully tested, the "additional" diagnostic interfaces available in the platform were removed to facilitate volume production and reduce the risk of mis-wire during installation.

To commission the controller for the target motor, a set of tools called ServoDesigner runs on the control computer. A Drive Parameters Spreadsheet is available to enter data about the motor and application. The user enters their unique parameters which are translated into internal format and ultimately tansferred to the configuration registers in the control processor at run-time. This transfer occurs via the

ServoDesigner tool, which communicates with the controller via the RS232 communication interface.

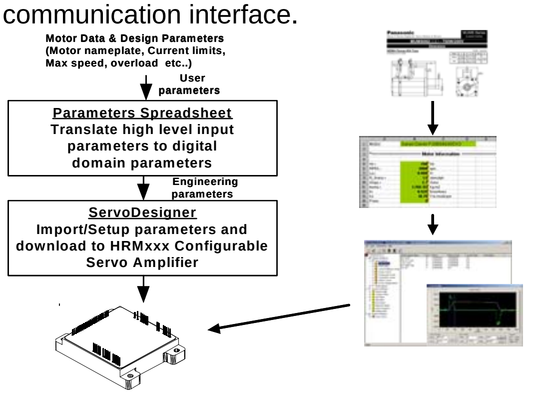

Figure 6 Drive Commissioning Process and Tools

The Drive Parameters Spreadsheet helps automate the commissioning process by calculating the appropriate values for configuration and tuning parameters. In the spreadsheet, you enter motor nameplate and application data, and embedded formulas calculate the appropriate values to be written to the control's internal registers via the ServoDesigner GUI. A portion of the parameter spreadsheet is shown in Figure 6 with values appropriate for a typical servomotor shown. When the spreadsheet calculations have completed, ServoDesigner is booted up on the control computer. This tool allows the user to access and change any of the configuration registers in the controller. Also supported is the ability to write 'functions' or test routines, supported by looping and delay constructs. Figure 7 shows a test routine called "demo run" which is a test sequence to demonstrate the ability of the controller to respond to multiple commanded speed settings.

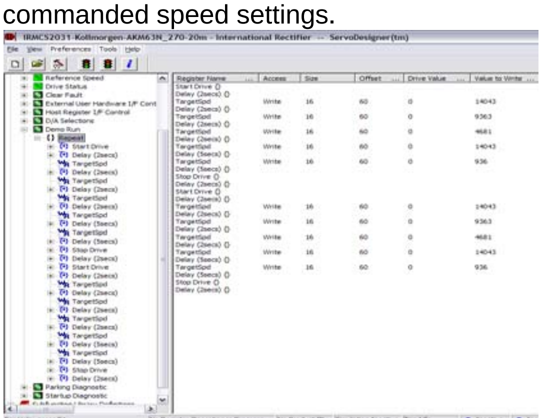

Figure 7 Demo Run – ∆Speed Test

Performance Goals and Test Results

Table 1 shows the most important spec's for the IRMCT3UF1 motor controller:

Parameters	*Values*
Voltage	28 to 48VDC
Max/Min DC bus voltage	48V (contact High Rel sales/FAE for more options) 18V
Power Rating	500VA continuous
Current	20Arms nominal @ 28VDC 30Apeak Overload (1min)
Host interface (SPI Port)	N/A (optional high speed interface-contact High Rel sales/FAE)
Speed Cmd	0 to +/-2.5V or RS232 (RS422 with ext xcvrs)
Discrete Input	START, STOP, FLTCLR, PWM ENA
Discrete Output	FAULT, SYNC
Current feedback	Three low-side leg shunts with 12 bit resolution Analog to Digital Converter
Output current trip level	40A peak, ±10%
Over-temperature trip level	Up to 110C (resistor adjustable)
Short circuit response time	5 µsec to shutdown
Power Stage	6 low $R_{ds\text{-}on}$ MOSFETs + advanced HVIC gate driver on low Rth IMS
System environment (Case) *Operating Temperature* *Storage Temperature*	 -40 to 85°C -55 to 125C

Figure 8 shows the current into one phase at startup of the pump under load. At turn-on, DC current is intentionally injected into the V and W windings of the motor in order to align it to begin the startup sequence. Though some applications need high torque at low speed, the pump in this paper requires only a brief elevated current condition at startup as shown.

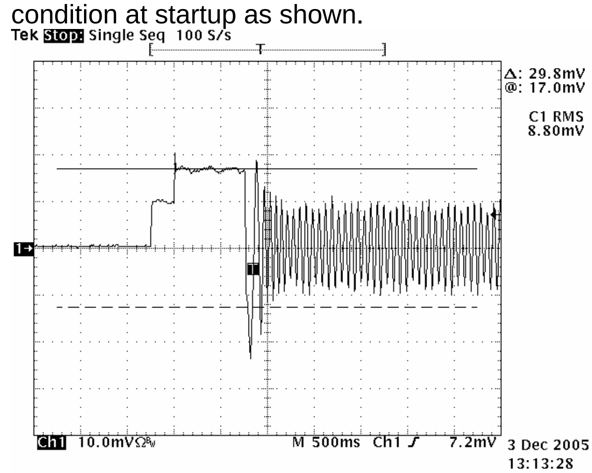

Figure 8, Pump Startup

The controller running the pump at full rated speed is shown in Figure 9. The current waveforms are sinusoidal, typically with <5%

harmonic distortion once the system is tuned:

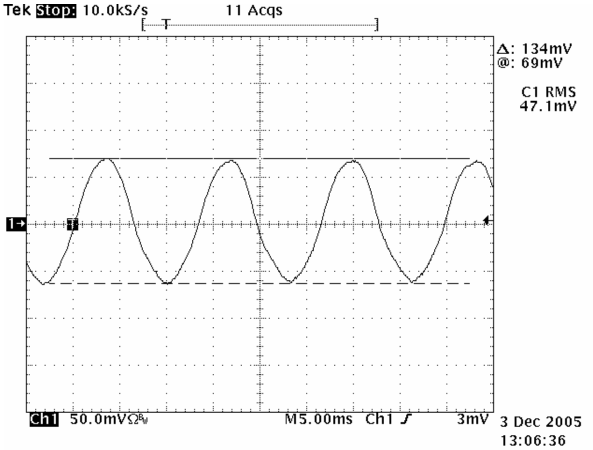

Figure 9. Controller Phase Current – Full Speed Operation

The Phase current is plotted over several speeds in Figure 10.

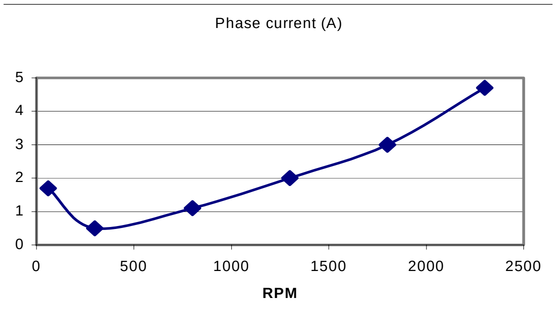

Figure 10 Startup and Speed Ramp

In practice, this controller can provide 100% continuous torque at rated speed and 200% for 50% rated speed and 400% intermittent overload torque at 5% of rated speed for starting purposes.

Hardware Description and Device Construction

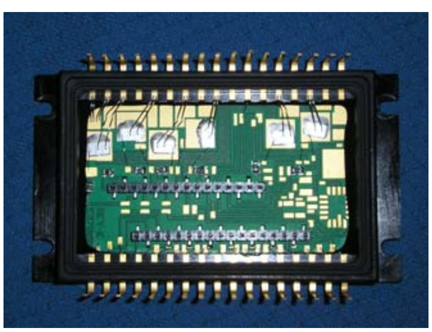

Figure 11 Insulated Metal Substrate

The IRMCT3UF1 Integrated Motion Controller is built and tested in separate stages to increase reliability and overall yield for the finished controller. The first stage of assembly is the IMS, shown in Figure 11 above. A thermal clad Insulated Metal Substrate (IMS) is used as substrate and base-plate. IMS substrates are more mechanically robust than thick-film ceramics or direct bond copper construction and provide a cost effective solution for the desired temperature range. If extended temperature operation is expected, an AlN DBC substrate can be used instead. IR's Low Rds-on, fast switching IRF4710 Mosfets are soldered directly onto the substrate. A special coating is used to protect the die from humidity and contamination. Additional components on the IMS assembly include gate resistors for the Mosfets, an NTC thermistor to monitor the substrate temperature, and the connectors for the Control Board. Attaching bare die to the IMS creates good thermal conductivity from the die to the heatsink and also allows future Mosfet substitutions, as customer applications require it. Once the Mosfets, resistors and connectors have been soldered to the IMS, the unit is wirebonded and tested. All passing units are then potted with a protective gel coat.

Figure 12 Control and Gate Drive Circuitry

Control and gate drive components are contained on a separate board also assembled and tested individually as shown in Figure 12 above. The control section consists of the iMotion$_{tm}$ control ASIC along with communications, current sensing and fault monitoring hardware. New high speed IR2011 high/low side MOSFET gate drivers are used which have efficient boot-strap power supply, undervoltage lockout and close channel-matched propagation delay (20ns max) for high speed switching.

Boards are first screen printed panels of 6 and then all devices are attached. Using custom test hardware, each board is individually tested for full functionality before being sent for conformal coating. The next step is to marry the control board to the IMS. The control board has through-holes matching the connector on the IMS. The board is dropped into place and soldered down. The completed hybrid is again tested for functionality, this time on a motor load, before sealing, case-marking and lead forming.

IR also offers customer specific application boards, shown in Figure 13 below, for a complete integrated motion control solution (as per Figure 3). Customer boards are assembled and tested individually for their particular functional requirement. All passing boards are conformally coated and controllers are attached to complete the assembly. The advantages of using a custom application board include reduced input and output connections, only one input supply (local supplies are derived from the bus), and a smaller total area for the complete solution. Typical I/O connections for an application board would include Bus voltage, On/Off, Speed Command, Fault and Fault Clear, and RS-232 communications.

Figure 13 Application Board

The Controller is being manufactured on IR's High Rel Manufacturing (Mil-PRF 38534 certified) line resulting in more stable hardware and ensuring better yields and fewer field failures. Designs are qualified and screened to Class H requirements to ensure each controller will operate for the required number of cycles and over the specified environment.

Controller costs are contained by using commercial parts where they do not adversely affect the system reliability. IR's iMotion$_{tm}$ chipset is rated to at least –40 to +85C operation. In cases requiring extended temperature or radiation exposure, Radiation Hardened or specially packaged components are available to create a more environmentally resilient controller

Summary

A new Low Voltage addition has been made to IR's sensorless speed controller family for High Rel applications requiring high performance in a small footprint. This controller has been introduced for motors working with a 28-48V DC bus. It uses IR's iMotion$_{tm}$ chipset, with enhancements in critical areas including fast development time, small size/weight, low noise and efficiency.
Future controllers are planned for other bus voltages and current levels to support other electric platform motor control needs.

References

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(4) Second Dependable Software Technology Exchange – June 1994 - A report prepared for the SEI (software engineering institute) Joint Program Office HQ ESC/AXS, 5 Eglin Street Hanscom AFB, MA 01731-2116, Copyright© 1994 by Carnegie Mellon University

(5) 5th Annual Electric Platforms Conference, Washington DC, April 18-20, 2005