Experimental platform for predictive maintenance of permanent magnet synchronous motors

Aditya Mahajan, Shrihari Vasudevan, Mark Calleija and Steven Scheding
Australian Centre for Field Robotics, The University of Sydney, NSW 2006, Australia
Email: {a.mahajan | s.vasudevan | m.calleija | s.scheding} @acfr.usyd.edu.au

***Abstract*— This paper describes the development of an experimental platform for predictive maintenance of permanent magnet synchronous motors. The platform can be used to simulate multiple faults and incorporates multiple sensory modalities. Key design choices are explained to assist rapid reproduction of such a platform towards research in predictive maintenance. Links to detailed specifications are also provided.**

I. Introdution

Conventional maintenance practices for machines have centered around planned maintenance and Condition Based Maintenance (CBM) [1], [2]. Planned maintenance refers to periodic, often manufacturer specified, maintenance to check for signs of abnormalities. CBM is typically performed when the need arises, when failure or a fault is imminent or when there is a noticeable decrease in performance. Inspection methodologies have typically been manual, fault specific and have relied on single sensor diagnosis.

Economic stresses and competitive markets have resulted in many industries turning towards maximizing cost-savings and developing more efficient operations. In terms of operating machines, the objectives have been to reduce maintenance costs, increase useful life of equipment and prevent catastrophic failures. This has resulted in a gradual shift in thinking towards a proactive approach towards monitoring equipment that mandates continuous monitoring using multiple sensory modalities and predictive maintenance [2]. Predictive Maintenance (PdM) seeks to anticipate the occurrence of faults significantly before they occur and thereby enable steps that maximize Remaining Useful Life (RUL) and optimize maintenance processes. PdM requires prognostics, a computer science and statistical analysis problem. At the present time, CBM and PdM are used analogously.

The diagnosis of faults in machines such as Permanent Magnet Synchronous Motors (PMSMs) has been studied before [3]. In the context of prognostics, the few data sets available (none for PMSMs) do not allow for low level control of experimental conditions. To address this gap, this paper presents the detailed experimental design of a platform for studying the problem of PdM of PMSMs. The paper will enable rapid development of similar platforms and also provide data sets to initiate research in this area.

II. Related Work

Condition based maintenance is widely used across industries to maintain all kinds of equipment - rolling element bearings, induction motors, machine tools, pumps, engines, railway infrastructure, HVAC machines, trucks, generators etc. Typical inspection techniques include vibration analysis, thermography, acoustic emission, wear/debris/corrosion monitoring, lubricating oil analysis and process measurements [1]. Most CBM systems include modules for data acquisition, data analysis (signal and image processing), diagnostics and maintenance scheduling. The information processing pipeline typically includes steps for data preprocessing, feature extraction, diagnosis, prognostics and maintenance planning. The prognostics problem is still unsolved and is currently being studied using model, physics or data driven approaches. The main perceived deficiencies in commercially available prognostics solutions are that PdM predominantly refers to "deviation from expectation suggesting a developing fault" and not "the equipment will fail at time X". The state-of-the-art still doesn't have mature algorithms and software products that can do advanced statistical analysis of individual systems and across different systems or sub-systems, involving an explosive amount of information. Software is thus still an issue. The platform presented in this paper addresses these issues by allowing for high and variable frequency data acquisition, the use of multiple sensors and the provision for a facility that enables repetitive testing under a wide range of operating conditions.

With the recent increase in focus on prognostics research, numerous public data sets have been made available for developing solutions. Many of these are hosted by the NASA Ames prognostics data repository[1]. These include the Milling Data Set [4], the Bearing Data Set [5], the Battery Data Set [6], the C-MAPSS Data Set [7], the IGBT Accelerated Aging Data Set [8]. A recent paper [9] compared these data sets and the Virkler Fatigue Crack Growth Data Set [10] to identify the suitability of the data sets for the development of data driven and physics driven approaches to prognostics. The paper suggests that while numerous data sets exist, many are not suited towards developing and testing different approaches either due to small sample sizes or due to lack of information for degradation model parameters. Many data sets are limited in the different operating conditions tested; many are limited in the scope of monitoring - few parameters that do not represent the whole system but only one specific component of it. Once a fault is detected, operating conditions may be altered to increase the RUL. Such actions would result in changing RUL estimates - this scenario does not appear to be covered in existing public data sets. Statistically representative testing and testing under a wide range of operating conditions would be a requirement for the development of robust solutions. Enabling this and testing in changing operating conditions requires an in-house

[1] http://ti.arc.nasa.gov/tech/dash/pcoe/prognostic-data-repository/

experimental platform that allows for such customization of conditions. Two recent theses that have inspired this work are those of Supangat [11] and Rajagopalan [3]. Both theses focus on the simulation and subsequent diagnosis of faults, for induction motors and PMSMs respectively. Like many other works, they inadequately delve into the detailed development of the experimental platform used, this presents a daunting challenge for the computer scientist interested in developing prognostics algorithms. This paper thus presents a detailed description of a platform for pursuing prognostics research. It considers multiple faults, multiple sensors and also addresses safety considerations. It also provides links to detailed specifications that would enable repetitive testing under a wide range of conditions and thus facilitate prognostics research.

III. Experimental Platform

The experimental platform was designed for easy setup and data acquisition for CBM. From an operational standpoint, PMSMs have several advantages over rotary machines like pumps or engines. Our primary concern is operator safety, followed by diversity of fault simulation and ease-of-use. The working fluid for pumps or engine exhaust may pose operational difficulties [12] and obvious safety concerns arise when a combustion engine is operated until failure. PMSMs fall into the broadest spectrum in terms of fault characteristics for electric machines. The operation and fault modes of PMSMs and AC induction motors are very similar. Additionally, this setup may be used for CBM of brushed DC motors with minor modifications.

The complete setup (Fig 1) is intended to facilitate ease-of-use and therefore designed with off-the-shelf components with minimal customisation. Brands and part numbers are not listed in this paper, but details on specific components are available in [13]. The only customised part is the Printed Circuit Board (PCB) (see Section III-B). The function of this component is to provide electrical isolation from high voltage signals as well as amplification of low voltage signals.

A. Core Equipment

The PMSM was regarded as a disposable component in this study. To preserve the realism of fault simulation, the motor was irreversibly degraded to failure. This practice required a new motor for every experiment. Motor selection was governed by the need for:

- Ease of operation and replacability
- Access to internal structure
- Operational safety (current, power limits)
- Repeatability of experiments through low purchase cost

As a result, a PMSM with the following specifications was sourced from a hobby specialist store. Designated as the ‘primary’ motor, it was used for all experiments with the exception of the stator fault.

- Electrical, Maximum for Continuous Operation (MCO): 15V, 17A, 250W
- Mechanical: 3 phase, 2 poles, 17.5 turns, Y-type
- Size: 52mm x 36mm dia.
- Sensors: Hall-effect sensors included

TABLE I
Inferred motor parameters and their means of calculation.

Inferred parameters	Means of calculation
Rotational velocity	Switching Frequency of Hall sensors
Efficiency	Motor torque and rotational velocity
Winding current	Voltage drop across precision resistors
Winding resistance	Winding voltage and current

Another PMSM, the ‘secondary’ motor, was used for stator fault experiments. The key difference is that the ‘secondary’ motor has a lower amperage rating than the ‘primary’. This allows for accelerated degradation of stator windings by overcurrent (see Section IV-B) with the same controller. The motor specifications are given below.

- Electrical, MCO: 48V, 4A, 200W
- Sensors: Hall-effect sensors included

The Electronic Speed Controller (ESC) was selected on similar principles and compatibility with the motor was a critical parameter in the selection process. Typically, it is best to have a controller that can deliver higher voltage and current than the motor requirement, ensuring that the ESC is capable of making the motor fail without exceeding its own limits. The ESC (specifications below) was sourced from a manufacturer of precision motor drives. The ESC provides trapezoidal commutation with feedback from Hall-effect sensors but can be configured for sinusoidal commutation with the inclusion of a rotary encoder.

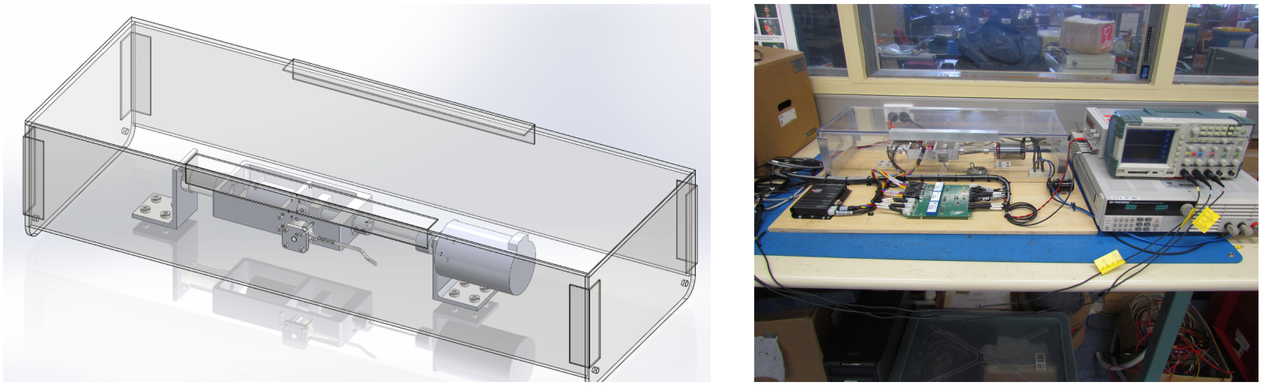
- Electrical, MCO: 70V, 10A, 700W
- Commutation: Trapezoidal or sinusoidal with feedback from Hall-effect sensors
- Interface: USB 2.0, RS232 or CAN

An additional PMSM, connected to a programmable resistor (via an AC-DC rectifier) is used as a generator to provide a resistive torque load during operation. The load serves to limit the speed of the PMSM under test for safety reasons [14] and can dissipate power in a controlled manner. The brushless generator is rated significantly higher than the monitored PMSM to decrease the likelihood of generator electrical failure. The specifications for the generator and programmable resistor are given below:

- Generator electrical, MCO: 41V, 128A, 5280W
- Generator mechanical: 3 phase, 4 poles, Y-type
- Resistor dissipation, MCO: 2400W
- Resistor interface: USB-to-Serial

B. Sensor Suite

A unique feature of the platform is the ability to take synchronous measurements in multiple sensor modalities. This is achieved via sensors that measure output torque, radial bearing load, vibration, acoustic emissions, winding voltage and temperature. Other data is inferred from indirect measurements as indicated in Table I. Detailed on how these parameters are inferred are provided in [13].



(a) 3D CAD model made prior to construction. (b) Assembled apparatus for condition monitoring.

Fig. 1. The experimental platform, showing motor assembly inside a clear safety cover.

The raw sensor signals are not suitable for direct input to a Data Acquisition (DAQ) system (except the microphone and accelerometer) due to the low-voltage nature of the torque, radial load & temperature signals as well as the high-voltage nature of the direct measurements from motor windings.

A custom-made PCB is used to solve these problems. It has several functions as listed below:

- Signal amplification for torque and radial load sensors.
- Amplification for thermocouple signal.
- Voltage tap-off for each winding (isolated by DAQ).
- Isolation and amplification of voltage across precision resistors in each winding.
- Direct signal tap-off for Hall-effect sensors.

For detailed design of the PCB, please see [13].

C. Data Acquisition System

The goal of this platform is to facilitate ease-of-use, allowing the user to focus maximum effort on data analysis as opposed to signal conditioning and data acquisition. An ideal DAQ system should offer:

- Synchronous channel sampling at high sampling rates
- High-volatge isolation
- Noise rejection
- Expansion capacity - to include future sensors

The chosen DAQ system has the capacity to achieve all of the above with limited noise rejection and expansion capacity. The 'chassis' is programmed using proprietary software and includes modules capable of measuring:

- High-voltage signals with electrical isolation.
- Low-voltage analog/digital signals with independent sensing ranges.
- Direct input from microphone and accelerometer.
- High and variable sample rates.

D. Safety Considerations

Safety benefits resulting from PdM are noted [14], [15], [16] but many authors do not establish strict and safe procedures for start-up, operation and shut-down of equipment used for condition monitoring. This is of particular importance when the apparatus is *designed to cause catastrophic failure!* Key hazards pertaining to this platform include:

- Projectiles/debris from rotating machinery.
- Electrical shorts from exposed leads or windings.
- Burns due to heating of parts.
- Excess noise, vibration, particulates or fumes.

The steps taken to mitigate these risks are listed below. On the administrative side:

- Risks highlighted in Project Risk Assessment (PRA).
- Established Safe Operating Procedures (SOP) for apparatus start-up, operation and shut-down of equipment.
- Established requirements for Personal Protective Equipment (PPE).

On the technical side:

- Isolation boundary for high-voltage signals.
- 'Safety cover' (see Fig 1) made from highly durable polycarbonate polymer to contain debris.
- Multiple anchor points for for critical components.
- High-strength adhesive on all critical bolts and joints.

IV. Simulation of Faults

For the purpose of this paper, fault simulation was governed by two requirements:

- Gradual and online (non-stop) component deterioration.
- Accelerated rate of deterioration for repeated trials.

The key to a successful setup is to measure characteristic warning signs that intensify over time. In addition to this, non-invasive measurement techniques allow for quick motor replacement without unnecessary sensor reconfiguration as well as easy application to other (larger & complex) systems.

A. Bearing Fault

Bearing faults are the most common form of failure for electric motors [11]. These faults occur in all forms of rotating machinery and are typically caused by excessive or uneven stress. Degradation of the bearing elements may lead to increased friction, noise and vibration. Catalysts for this process include foreign contaminants (dust & moisture), loss of lubrication or heat. The wear causes more particulates and heat in the bearing, which leads to more degradation and the process cumulatively worsens over time. Bearing faults may also be caused by rapid voltage switching which cause uneven torque distribution over each rotation cycle [15]. Bearing faults can be detected by monitoring:

- Stator current profile and
- Vibro-acoustic emissions [11].

Bearing wear was induced by applying a measured radial load on the motor shaft with the objective of causing continuous, accelerated wear from uneven stresses on the raceways while minimising wear of other motor components. Figure 2 shows the discrepancy between the current profiles of each motor phase before and after the fault was induced.

B. Stator Fault

Stator winding insulation is a major cause of failure in electric machines. Winding insulation typically deteriorates as a result of thermal, electrical, mechanical or environmental stresses [17], [18], [19], [20]. Winding insulation degradation is typically constant over time [17] and hence predictable if measured regularly over the course of operation.

The primary means of inducing insulation faults is 'overcurrent'. This is gradual (but accelerated) insulation degradation resulting from heat generated due to excess current flow. Stator electrical faults are summarised into 4 categories :

- Open-circuit faults [19].
- Turn-to-turn faults, which lead to
- Phase-to-phase faults, which lead to
- Phase-to-ground faults.

As seen in Section III-A, the controller cannot provide sufficient current to achieve this. Higher-amperage controllers are available, but a lower-amperage motor is preferred in the interests of safety (see Section III-D). The lower rated 'secondary motor' was used for stator-related faults.

Shorted turns can increase winding temperatures rapidly [21] and so preventive action must be taken in the order of milliseconds. At first glance, temperature measurements may seem to be a good fault indicator, but the comparatively slow response time of temperature probes, coupled with the almost instantaneous nature of the fault makes this difficult. Relying on measurements after fault occurrence also invalidates the 'prognostic' nature of this study.

The focus of identifying this fault was hence shifted to measuring insulation resistance as opposed to winding temperature. Insulation resistance is measured through 'current leakage' [22]. This leakage is the loss of current through the winding insulation, from the windings to the grounded motor housing, measured as a discrepancy in the sum of individual winding currents, I_ϕ, as shown in Equation 1. The nature of this technique provides additional benefits [19] as measurements do not require specialised sensors.

$$\text{Ideally:} \sum I_\phi = 0; \quad \text{Actually:} \sum I_\phi = I_{Leak} \tag{1}$$

C. Rotor Fault

In a PMSM, the rotor consists of a magnet with one or more pole pairs. Rotor faults are generally categorised into mechanical faults (e.g. eccentricity) and magnet-related faults. Mechanical faults require significant modification of motor components [3] whereas magnet-related faults require changes to the magnet only. Magnetic faults also tend to be more time-based and may be of use in prognostic analysis. For this reason, magnet faults were considered for this study. A simple means of determining the deterioration of magnetic strength is to measure the motor torque constant, K.

Demagnetisation is achieved by chipping or cracking the magnet [3]. Magnetic strength also decreases with vibration/knocking or high temperature. The difficulty of replicating these processes lies in ensuring time-based continuity and specific fault simulation. Chipping or knocking the magnet is unfeasible as this will cause a discontinuity in magnetic strength with respect to time; there is no gradual fault development and the motor has to be disassembled every time. On the other hand, high temperature exposure is more likely to induce a stator insulation fault (see Section IV-B) prior to demagnetisation. While these methods can be explored in future studies, it was decied to allow the magnet to degrade on its own (degradation expected over continuous long-term operation) and to measure this through the relationships illustrated in Equation 2.

$$E_{RMS} = K \times \omega; \qquad T = K \times I_{RMS} \tag{2}$$

D. Gear Fault

Gear faults are an external means of component degradation and are applicable to forms of rotating machinery where changes in speed and torque take place. The simulation of these faults may not directly be connected to PMSMs but the effects of a gear fault may be observed by measuring affected motor parameters. Faults such as cracking, pitting, scoring or plastic deformation caused by misalignment, loss of lubrication or excess wear [23] may eventually lead to catastrophic failure. CBM techniques may be used to forecast such failures. Some techniques considered for gear related failures are:

- Vibro-acousitc monitoring.
- Variations in motor torque output.

V. Discussion

This paper presents an experimental platform designed for PdM of PMSMs. This apparatus facilitates the simulation of several faults under variety of operating conditions. The focus of this design has been to allow easy operation and synchronous data acquisition from multiple sensors. The platform has also been assessed from a safety standpoint and steps heve been taken to mitigate hazards. Detailed specifications for the equipment used (such as part numbers and connectivity diagrams) are provided in [13]. A set of preliminary data is available (here).

Avenues of future work exist in simulation of eccentricity and more manufacturing-related faults. This will be possible once constraints on motor power (and hence size) are reduced, allowing for better access to the PMSM internal structure. Potential work also exists in:

- Fault simulation - such as extended exposure to extreme temperature and moisture.
- Fault measurement - like the use of magnetometers for demagnetisation or multiple thermocouples for a detailed thermal profile.

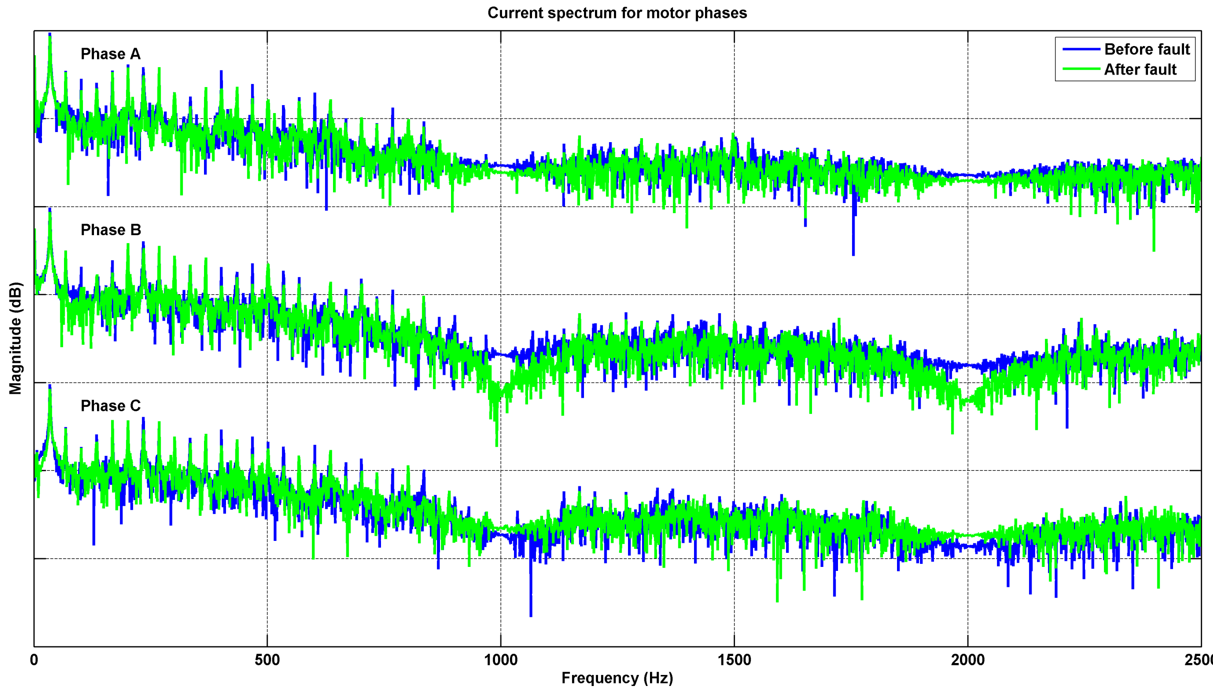


Fig. 2. The spectrum of phase current as measured before (blue) and after (green) the bearing fault was induced). Motor @ 2000 RPM, DAQ @ 5kHz.

ACKNOWLEDGMENT

This work has been supported by the Rio Tinto Centre for Mine Automation and the Australian Centre for Field Robotics (ACFR). The authors are grateful to Javier Martinez, other ACFR technical staff, Michael Turk and Steve Abrams of Rio Tinto for their assistance and advice in realizing this work.

REFERENCES

[1] A. Davies, *Handbook of condition monitoring: techniques and methodology*. Springer, 1997.
[2] R. K. Mobley, *An introduction to predictive maintenance*, 2nd ed. Elsevier, 2002.
[3] S. Rajagopalan, J. M. Aller, J. A. Restrepo, T. G. Habetler, and R. G. Harley, "Detection of Rotor Faults in Brushless DC Motors Operating Under Nonstationary Conditions," *IEEE Transactions on Industry Applications*, vol. 42, no. 6, pp. 1464–1477, 2006.
[4] A. Agogino and K. Goebel, "Mill Data Set," BEST Lab, University of California, Berkeley, Tech. Rep., 2007.
[5] J. Lee, H. Qiu, G. Yu, J. Lin, and Rexnord Technical Services, "Bearing Data Set," IMS Center, University of Cincinnati, Tech. Rep., 2007.
[6] B. Saha and K. Goebel, "Battery Data Set," NASA Ames, Moffett Field, CA, USA, Tech. Rep., 2007.
[7] A. Saxena and K. Goebel, "C-MAPSS Data Set," NASA Ames, Moffett Field, CA, USA, Tech. Rep., 2008.
[8] J. Celaya, P. Wysocki, and K. Goebel, "IGBT accelerated aging data set," NASA Ames, Moffett Field, CA, USA, Tech. Rep., 2009.
[9] O. F. Eker, F. Camci, and I. K. Jennions, "Major Challenges in Prognostics: Study on Benchmarking Prognostics Datasets," in *in proc. of European Conference of Prognostics and Health Management Society*, 2012.
[10] D. A. Virkler, B. M. Hillberry, and P. K. Goel, "The Statistical Nature of Fatigue Crack Propagation," *Journal of Engineering Materials and Technology*, vol. 101(2), pp. 148—-153, 1979.
[11] R. Supangat, "On-line Condition Monitoring and Detection of Stator and Rotor Faults in Induction Motors," Ph.D. dissertation, University of Adelaide, Adelaide and Australia, 2008.
[12] K. McKee, G. Forbes, M. Mazhar, R. Entwistle, and I. Howard, "A review of major centrifugal pump failure modes with application to the water supply and sewerage industries," in *ICOMS Asset Management Conference 2011*. Gold Coast Convention and Exhibition Centre and Queensland: Asset Management Council Limited, 2011.
[13] A. Mahajan, S. Vasudevan, M. Calleija, and S. Scheding, "Experimental platform for predictive maintenance of permanent magnet synchronous motors," Australian Centre for Field Robtics, The University of Sydney, Tech. Rep., 2013.
[14] A. Hughes, "Conventional D.C. Motors," in *Electric motors and Drives*. Elsevier, 2006, ch. 3.
[15] J. Yang, J. Cho, S. B. Lee, J.-Y. Yoo, and H. D. Kim, "An Advanced Stator Winding Insulation Quality Assessment Technique for Inverter-Fed Machines," *IEEE Transactions on Industry Applications*, vol. 44, no. 2, pp. 555–564, 2008.
[16] O. E. Dragomir, R. Gouriveau, F. Dragomir, E. Minca, and N. Zerhouni, "Review of Prognostic Problem in Condition-Based Maintenance," in *European Control Conference, ECC'09*, Budapest, Hungary, 2009.
[17] L. Y. Wagner, "Electric Motor Failure Modes: New Methods for Low Resistance Protection," Cleveland and Ohio, 1996. [Online]. Available: http://www.phillipselectric.com/pdf/techtalk1.pdf
[18] S. B. Lee and T. G. Habetler, "An online stator winding resistance estimation technique for temperature monitoring of line-connected induction machines," *IEEE Transactions on Industry Applications*, vol. 39, no. 3, pp. 685–694, 2003.
[19] S. Grubic, J. M. Aller, B. Lu, and T. G. Habetler, "A Survey on Testing and Monitoring Methods for Stator Insulation Systems of Low-Voltage Induction Machines Focusing on Turn Insulation Problems," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 12, pp. 4127–4136, 2008.
[20] J. Yang, S. B. Lee, J.-Y. Yoo, S. Lee, Y. Oh, and C. Choi, "A Stator Winding Insulation Condition Monitoring Technique for Inverter-fed Machines," in *37th IEEE Power Electronics Specialists Conference*, 2006, pp. 1–7.
[21] J. A. Haylock, B. C. Mecrow, A. G. Jack, and D. J. Atkinson, "Operation of fault tolerant machines with winding failures," in *1997 IEEE International Electric Machines and Drives Conference Record*. IEEE, 1997, pp. MC3/10.1—-MC3/10.3.
[22] K. Younsi and G. Kliman, "An on-line technique for monitoring the insulation condition of AC machine stator windings," in *IEEE International Conference on Electric Machines and Drives, 2005.* IEEE, 2005, pp. 286–294. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1531354
[23] S. Rajagopalan, "Detection of rotor and load faults in brushless DC motors operating under stationary and non-stationary conditions," Ph.D. dissertation, Georgia Institute of Technology, 2006. [Online]. Available: http://ezproxy.library.usyd.edu.au/login?url=http://search.proquest.com/docview/305333782?accountid=14757

Appendix

This appendix provides an outline for the experimental setup and equipment required for this study. Every experiment is designed to measure data from the PMSM when under a specific fault condition. All the experiments are based around a basic setup which is illustrated in figure 3. This is the top level of the most generic experimental setup and individual experiments may have different components and configurations.

The following is a list of the major components used in this study:

- Brushless motors
- Motor controller
- Power supply
- Brushless DC generator
- Electronic load
- Bridge rectifier & capacitor
- NI - PXIe chassis
- NI - PXIe ExpressCard for PC
- NI - Accelerometer & microphone module
- NI - Isolated voltage input module & connector
- NI - Analog/digital voltage input module & cable
- Labfacility K-Type Thermocouple
- Triaxial ceramic shear accelerometer
- General purpose array microphone & cable
- Reaction torque sensor
- Tension & compression load cell
- Winding resistor
- Printed Circuit Board (PCB)
- Flexible coupling
- Miscellaneous

A. Brushless motors

The selected PMSM is manufactured by Turnigy Track-Star and supplied by HobbyKing. The 17.5 turn sensored brushless motor has an estimated kv of 1870. This motor contains in-built Hall-effect sensors and requires a separate Electronic Speed COntroller (ESC) for operation. The sensor outputs are in the form of a standard 6-pin connector that is compatible for most controllers. The 'secondary' PMSM is manufactured by Maxon Motors and specifications for this machine are propreitary. The kay features of this motor are: low maximum amperage and in-built Hall-effect sensors

B. Motor controller

The chosen ESC is the EPOS2 70/10 controller supplied by Maxon Motors. It has a built-in speed controller and accepts inputs from Hall sensors. The voltage/current variations supplied by the ESC and resulting back EMF can have a trapezoidal or sinusoidal profile. The controller operates the motor by providing 3-phase current which is 120° out of phase and has a frequency proportional to the commanded speed.

C. Power supply

Power is supplied to the motor and controller via a regulated laboratory power supply from Jaycar Electronics (Part number: MP3094). The supply can provide voltage up to 16V at a maximum amperage of 40A.

D. Brushless DC generator

The PMSM to be tested will be operated under various loading conditions to investigate the relationship between winding current, back EMF and mechanical rotational speed. The primary load will be a torque generated as a resistance to motor rotation. This mechanical load will be applied by coupling a PMSM (1/5th sensorless brushless motor 730KV from HobbyKing) to the test motor. This PMSM, referred to as a 'generator', will convert mechanical energy into electrical energy. The electrical energy will be dissipated using a programmable E-Load.

E. Electronic load

The E-Load is a programmable resistor (BK Precision 8154 Electronic Load) and is designed for controlled dissipation of electrical energy. This part of the system will connect to the generator via a bridge rectifier/capacitor assembly. The E-Load will be controlled through software that is linked up with the Data Acquisition (DAQ) software. The advantage of a programmable resistance is that fluctuating, sinusoidal or ramp profiles can be applied. The potential to observe the motor performance when loaded at specific frequencies is highly valuable for this work.

F. Bridge rectifier & capacitor

The bridge rectifier and capacitors allow for conversion of the 3-phase AC from the generator into DC voltage that can be dissipated by the E-Load. The rectifier is placed in series between the generator and E-Load. Following this, the capacitor is placed in parallel in between the rectifier and E-Load to reduce voltage ripple.

G. NI - PXIe chassis

The role of the DAQ system is to measure different characteristics of the motor. Sensors will be connected to modules and a chassis supplied by National Instruments. Sensing will be accomplished through several specialised sensors. The core of the DAQ system is the NI PXIe-1071 Chassis and connecting modules. The software components, hardware drivers and signal processing tools are available through teh LabVIEW graphical programing suite.

H. NI - PXIe-ExpressCard for PC

The PXIe-ExpressCard 8360 facilitates the interface between LabVIEW on a PC and the hardware connected via the PXIe Chassis. This card occupies one of the four module slots on teh PXIe Chasis.

I. NI - Accelerometer & microphone module

The NI PXI-4462 dynamic signal acquisition and generation module connects the accelerometer and microphone to the NI PXIe-Chassis.

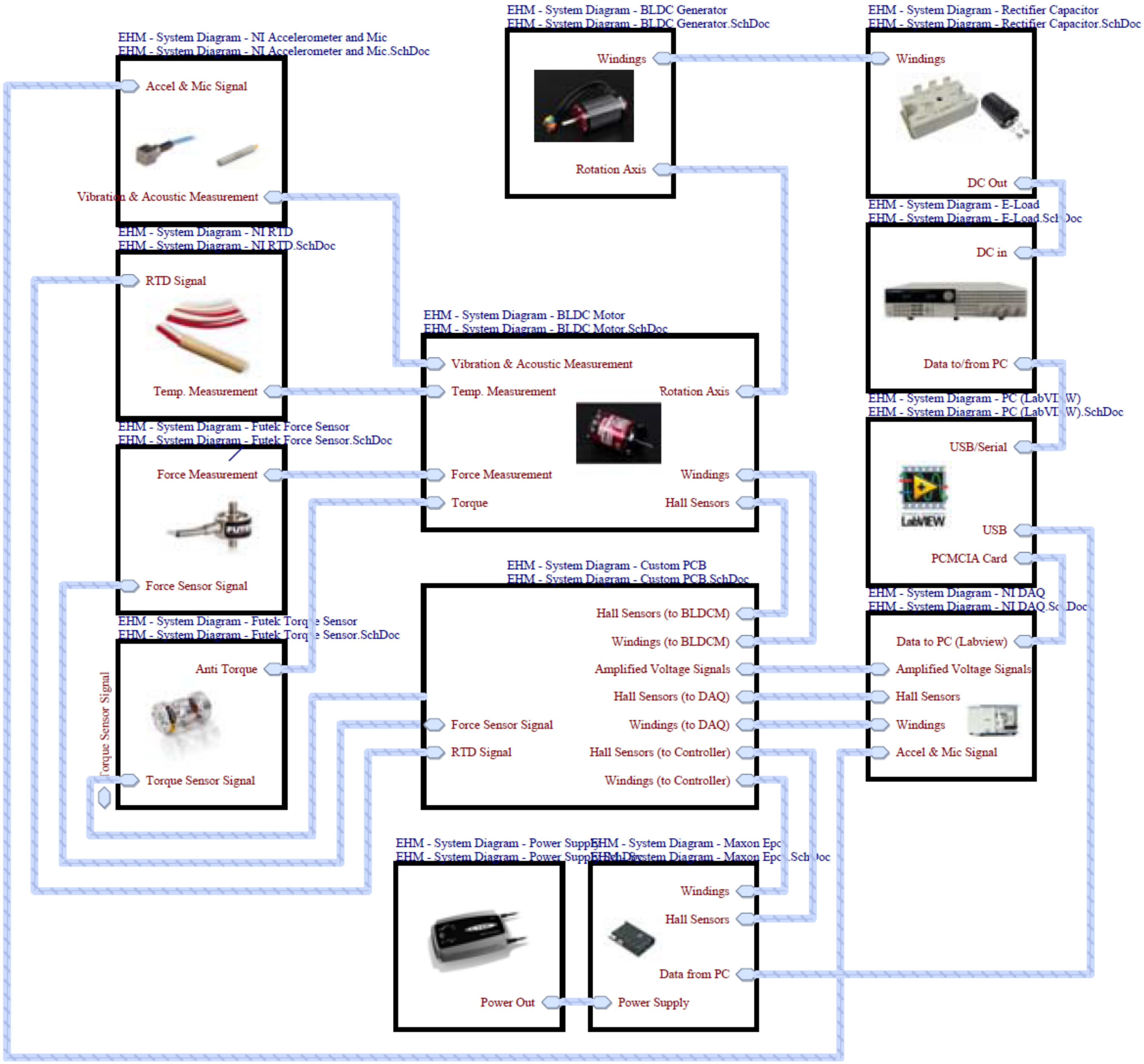


Fig. 3. This flowchart shows the basic connections between equipment.

J. NI - Isolated voltage input module & connector

The NI PXIe-4300 high-voltage data acquisition module measures differential voltage across each of the motor phases. This module occupies one slot in the PXIe-Chassis. The PXIe-4300 module has a terminal block (NI TB-4300B) to facilitate wire connections and strain relief.

K. NI - Analog/digital voltage input module & cable

The NI PXI-6123 analog & digital voltage input module measures inputs from a variety of sources and sensors. For analog inputs, the measurement ranges are ±10V,±5V,±2.5V & ±1.25V. This module occupies one slot in the PXIe-Chassis. The PXI-6123 module has a connecting cable (SH68-68-EP) and a shielded terminal block (SCB-68A) to facilitate wire connections. The cable is a shielded 68-conductor cable terminated with two 68-pin female 0.050 series D-type connectors.

L. Labfacility K-Type Thermocouple

The thrmocouple measures the temperature of the PMSM by producing a proportional voltage cross the wire leads. The placement of the thermocouple in relation to the motor must be kept unchanged across all experiments for consistent measurements.

M. Triaxial ceramic shear accelerometer & cable

A triaxial ceramic shear accelerometer manufactured by PCB Piezotronics will be used to measure vibration data. The accelerometer has 3 channels (one per axis) which connect to the appropriate module via BNC connectors.

The acelerometer signals can be directly read by LabVIEW without the need for additional signal conditioning.

N. General purpose array microphone & cable

An array microphone manufactured by GRAS Sound & Vibration will be used to measure acoustic emissions. The microphone connects to the NI PXI-4462 with a SMB110 cable and can be directly read by LabVIEW without the need for additional signal conditioning.

O. Reaction torque sensor

The Futek FSH00606 reaction torque sensor provides the only 'rigid' mechanical connection between the PMSM and the bench. The mechanical connection forces the sensor to apply a counter-torque (equal to the PMSM torque output) to maintain a fixed position. This torque is output as a voltage differential between the Green and White signal leads. All leads from the sensor are connected to the custom-built PCB for power supply and amplification.

P. Tension & compression load cell

The Futek FSH02703 tension & compression load cell measures radial force applied to the bearings This force is output as a voltage differential between the Green and White signal leads . All leads from the sensor are connected to the PCB for power supply and amplification.

Q. Winding resistor

The precision resistor in each winding is used to make current measurements in each of the motor phases. One resistor is used in series with each of the motor phases. The voltage drop across each resistor is measured and divided by the known resistance (0.005Ω) to derive the current.

R. PCB

The PCB contains electronics for signal amplification and tap-offs for data acquisition. The PCB has 4 primary functions:

- Tap-off hall sensor signals and send to DAQ.
- Power and measure voltage generated by the thermocouple.
- Provide power to the force & torque sensors, amplify signal range and send signals from each sensor to DAQ.
- Measure voltages of the motor windings and differential voltage across the winding resistors.

1) Hall sensor tap-offs: This part of the PCB is for measuring Hall sensor pulses. The inputs are 6 sensor leads from the PMSM and the outputs are 6 corresponding leads to the ESC. 4 of these signals are tapped off and fed to the DAQ. These are:

- Hall sensor #1 TTL 0-5VDC
- Hall sensor #2 TTL 0-5VDC
- Hall sensor #3 TTL 0-5VDC
- GND

Note: Pins 1-6 from the motor *DO NOT* correspond to pins 1-6 to the ESC (See PMSM and ESC specifications for details).

2) Signal amplification: The key components used in this phase of the setup are:

- Instrumentation amplifier: Analog Devices AD8226
- Precision reference: MAX6192CESA+
- Op-amp: Mouser TLV2371IDBVT
- Various resistors

3) Winding tap-offs: The precision resistor across each winding allows for current measurements. The differential voltage across each resistor must be amplified for the DAQ. Due to the sensitivity of the DAQ equipment, an isolation amplifier (Analog Devices AD210) with unity gain is placed between the resistor and instrumentation amplifier.

S. Flexible coupling

The flexible coupling (Part number: A 7C12-03311) is from Stock Drive Products, Sterling Instruments (SDP/SI). This component is responsible for transferring torsional force from the PMSM to the generator whilst limiting the transfer of axial and radial stresses. Additional information is given online (here)

T. Miscellaneous

Other components may include, but are not limited to:

- High quality, durable bearings (NSK 6000, sealed and unsealed)
- Mounting boards/saddles for motors and other components.
- Wires & wire connectors.
- Customised, experiment-specific loads: flywheel, bar with a hole off-centre, fan etc.