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Design and development of automated high temperature motor test facility

SAJI JACOB GEORGE[1], K S SREE RANJINI[2,*], C RAJAGOPALAN[1] and S MURUGAN[1]

[1]Robotics, Irradiation Experiments and Mechanical Maintenance Division (RIMMD), Indira Gandhi Centre for Atomic Research, Kalpakkam, India
[2]Homi Bhabha National Institute, Indira Gandhi Centre for Atomic Research, Kalpakkam, India
e-mail: jacobg@igcar.gov.in; sreeranjiniks53@gmail.com; crgopal@igcar.gov.in; murugan@igcar.gov.in

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Abstract. With increasing applications in high performance actuation systems as in aerospace and nuclear industries, demand for motors operating at an ambient temperature of 100°C and above has increased. Hence, it is highly necessary to validate the performance of motors at high temperature before their integration into complex critical systems. Most commercial test benches for motor available today, are designed for operation only at normal temperature. This paper describes the design, physical structure, operating principle and data acquisition system of automated test facility developed for testing stepper motors, brushed DC motors and brushless servo motors at room temperature as well as at elevated temperatures. To make the entire measurement system automated, a graphical user interface based on C# software is developed. Through the experiments on standard motors, quality of the design, performance of test bench and implementation of control modes are validated. The results obtained show a successful intercommunication between modules such as control, drive, measurement, data acquisition and display as per the required performance.

Keywords. High temperature motor test bench; data acquisition system; measurement; graphical user interface; automated testing.

1. Introduction

With advancements in power electronics, materials science and control technology, electrical actuators are effectively replacing conventional hydraulic components in aerospace, nuclear and other industrial applications [1]. A few critical applications demand high torque density along with operation under harsh environmental conditions such as high temperature and pressure. Temperature is one of the main factors that affect the electrical and magnetic loading of electrical machine. Electrical loading is mainly determined by the property of winding insulation to withstand the prescribed temperature rise over an ambient temperature whereas magnetic loading depends upon the magnetic flux density that can be produced by magnets without irreversible demagnetization, which again is a function of temperature. All electrical motors are characterized by an ambient temperature and allowable temperature rise. Most manufacturers do not recommend the operation of motor beyond the specified temperature as it adversely affects the performance of machine and reduces its lifetime. However, in applications where the ambient itself is characterized by high temperature, thermal management inside motor can be done either by effective design of cooling system or by using high temperature materials in the design. Inspection of critical components of a nuclear reactor using a semi-automated vehicle is such an application characterized by an ambient temperature of 150°C [2]. High ambient temperature makes manual inspection of the plant infeasible. Any inspection under these circumstances can be carried out only by customized remote inspection techniques coupled with semi-automated vehicles. A compact, high temperature traction motor is required to drive the vehicle in the limited space. Operating conventional motors at this high ambient temperature can result in partial or complete demagnetization of permanent magnets and deterioration of insulation, which further leads to thermal runaway and stalling of motors [3]. Stalling of motors can cause the risk of vehicle getting jammed in the annular space, which is highly undesirable. Hence it is very necessary that the traction motor must be capable of withstanding high temperatures and providing required torque while meeting the space constraints of the vehicle. Many research groups have come up with novel motor configurations incorporating materials withstanding high temperature [4], phase change materials [5] and with enhanced thermal management strategy [6] . The temperature rise and torque capability of motors can be studied with the help of Computational Fluid

*For correspondence
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Dynamics (CFD) or with the help of Finite Element Analysis (FEA) coupled with lumped parameter thermal analysis software. However, the results produced by software simulations are usually optimistic and must be backed up by experimental results for confirmation, before their use for real time applications. Electric motor test bench is an off-site test facility used for evaluating the performance of motors. Most of these test benches available in the market do not have a facility to test the performance of the motor at different ambient temperatures [7, 8]. Hence, a proposal for an innovative design and development of high temperature test bench suited for testing different types of motors at elevated temperature is presented. The proposed system is capable of evaluation of steady state and dynamic performances of system. Test bench can be used to test latest technology in control algorithms for electrical machine drives and analyse their transient behaviour. Test bench can be also used for accelerated life test where the motor is operated at high temperature, thereby subjecting to severe thermo-mechanical stress. This on-line monitoring/data analysis gives valuable information regarding the calculation of reliability and possible failure modes. This paper describes a new test facility designed and fabricated for testing electric motors specifically for ambient temperatures up to 250°C. It is primarily intended for testing motors for high temperature robotic applications and to get the performance parameters such as torque, speed and temperature in different parts of motors. The performance data acquired through special sensors are conditioned with the help of a stand-alone data acquisition system and graphical user interface (GUI) is realized through C# software, which simultaneously collect all the data from the test bench, calculate and display the result.

2. Structure of test bench

The design of test bench is carried out keeping special attention on individual modules to withstand high temperature conditions. The developed test bench consists of a high temperature oven with stainless steel frame, fixtures for holding the motor under test, torque sensor and a braking mechanism. A work table with provisions for holding the drives, power supplies, accessories like panel meters for the measurement, personal computer (PC) with control software and GUI for display of the motor parameters is also provided. A block diagram of the high temperature test set-up is shown in figure 1. The main components of test bench include (i) high temperature oven, (ii) torque sensor, (iii) braking system (iv) control panel and (v) software.

2.1 *High temperature oven*

A programmable, temperature-controlled oven for carrying the characteristic tests of motor at high temperatures up to

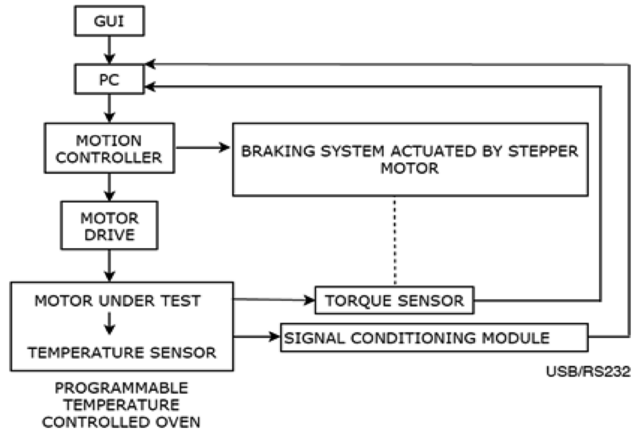

Figure 1. Block diagram of test bench.

250°C is the main component of this test bench. It has a capacity of 216 l. Inner dimensions of the oven are $600 \times 600 \times 600\,\mathrm{mm}^3$ and outer dimensions are $900 \times 900 \times 900\,\mathrm{mm}^3$. The inner chamber is made of stainless steel while the outer chamber is made of mild steel. A ceramic blanket insulation is placed between the walls, covering top, sides and bottom. This insulation helps in preventing the loss of heat and thus increases the efficiency of oven. Heating elements are located on sides of oven and a fan is provided on the oven top. The fan circulates air through air-guides located over the heating elements and around the chamber. This ensures uniform temperature distribution inside the oven. The temperature settings of oven are adjusted externally by a microprocessor-based PID controller. The accuracy and uniformity of oven is 1°C. Suitable penetrations (100-mm diameter) with leak-tight high temperature mineral insulation are provided for motor and sensor cables. An insulated door is provided for the oven with a safety latch and 180° opening hinges for easy mounting of the motors inside the oven. Front panel of the oven is provided with a double-layer glass window and lighting for viewing the motor under test. As a safety measure, an emergency stop button is also provided in the oven to shut down the heater if required. A K-type thermocouple is attached to the oven interior for temperature measurement and control. The test bench has provisions for fixing motors of various sizes and powers inside the oven. Suitable brackets of different sizes are fabricated to mount motors of different frame sizes (such as 28, 42, 50, 56, 60 and 86) in the test set-up. The oven with a suitable fixing mechanism and braking system is firmly mounted together on a common chassis during the testing. All components inside the oven are ensured to withstand the temperature of 250°C.

2.2 *Torque sensor*

Torque sensor is a very important component in the measurement system. For ISI application, torque–speed characteristic is a major parameter that needs to be measured at different temperatures. A commercially available dual-range Kistler-make torque sensor is used for torque and speed measurements in the test bench. The torque sensor has two ranges for torque measurement, 0–2 and 0–20 Nm, which can be selected based on the torque of the motor under test. The measurement is based on strain gauge technology. The torque and speed measurement accuracies are in the range of 0.25% and 0.01% of true value, respectively. The torque sensor is attached to the shaft of motor using two flexible (RADEX make) couplings, one inside the oven that can withstand temperatures up to 350°C, and another outside the oven that can operate up to 280°C. Since these couplings are provided on the motor output shaft, conductive heat reaching the torque sensor is fully attenuated. They can accommodate 10° of angular as well as radial misalignment and their homo-kinetic nature helps in delivering the same speed at input and output, making it ideal for the purpose. Moreover, the system is laser aligned to minimize the alignment errors. A picture of torque sensor is shown in figure 2.

2.3 *Braking system*

A disc-type braking system of Kateel make, model KA-H-180, is intended for applying load torque. The braking system is attached to the motor through high temperature bearings, torque sensor and flexible coupling. As the shaft rotates, heat generated is dissipated through high temperature bearings, and flexible couplings attached to both ends of torque sensor; hence, special thermal insulation is not required for the braking system. Brake pads are electrically actuated by a stepper motor and screw and nut mechanism. Actuation and release of brake are implemented with help of software.

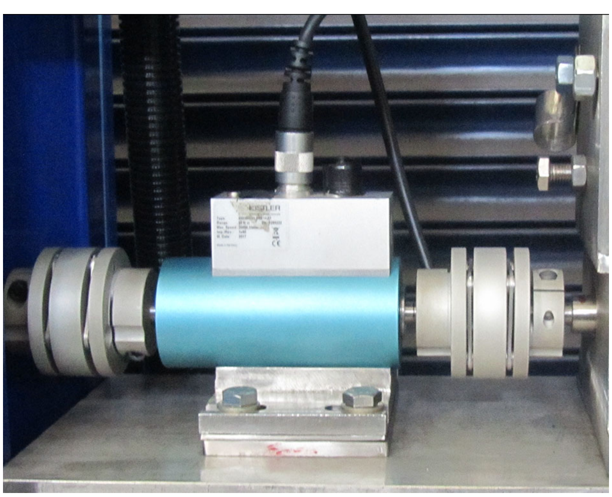

Figure 2. Torque sensor.

2.4 *Control panel*

Electrical control panel is designed for controlling each component or module of test bench. A picture of control panel is shown in figure 3. It includes a motion controller, drives, data acquisition system, power supplies and PC with GUI. An industrial PC with 16-GB RAM and 23” LED display is used as host. A standard Arcus-make 4-axis motion controller with high speed Ethernet interface to host the PC is selected for closed loop motion control. The specification of Arcus-make motion controller is tabulated in table 1. The motion controller in the control panel is a 4-axis controller suitable for DC, BLDC, and stepper and BLAC motors. The motion axis can be configured for any control technique. For each motor under test, drive of the corresponding motor is interfaced with the motion controller to perform the test. Power supply and isolation transformers are provided for powering the drives, which are to be used for the motor under test.

2.5 *Software*

A software-based GUI is developed in C# and loaded in the industrial PC, which communicates with the motion controller via Ethernet interface. The snapshot of GUI is shown in figure 4. The software issues various commands initiated by the user and communicates with motion controller to drive the motor. Performance of motor at high temperature without drastic decrease in torque is necessary for continuous movement of the vehicle in limited space. In order to verify the parameters given in the data sheet and to avoid malfunctioning of the critical system due to the failure of

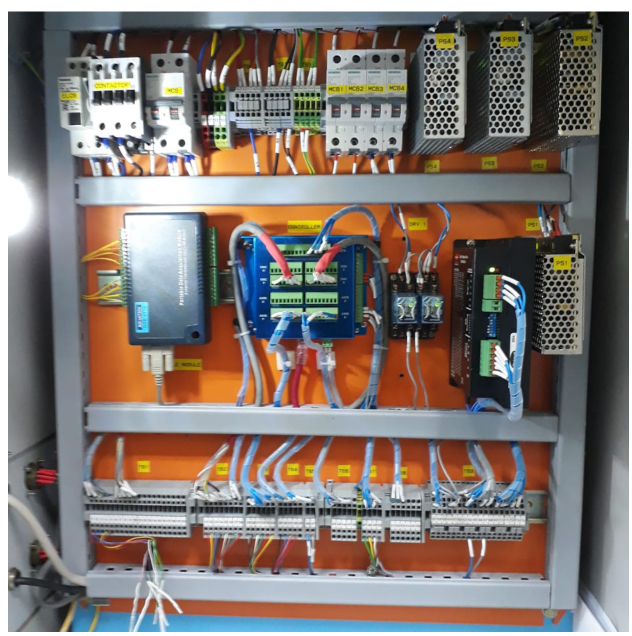

Figure 3. Control panel.

Table 1. Specification of motion controller.

No of axes	4, user selectable
Serial interface	USB/RS485/Ethernet
Motor type	DC, BLDC, stepper and BLAC
Feedback type	Analogue, encoder
Absolute position range	231 counts
Velocity range (servo)	1–20,000,000 counts/s
Velocity range (stepper)	1–4,00,000 counts/s
Servo control loop modes	PID, PIV
PID gains	0–32,767
PID update rate	Less than 80 us (single axis)
Stepper output rate	4 MHz (full-, half-, micro-stepping)
Stepper output mode	Step/direction or CW/CCW
Velocity profile	Trapezoidal or S curve
Coordinated motion support	Yes
Analogue output	10 V(16 bit)
Programmable torque limit	10 V
Encoder input rate	20 MHz
Encoder	Incremental, differential, quadrature
Forward, reverse, home inputs	12 (4 × 3 per axis)
Trigger inputs	4 (1 per axis)
Output enable	4 (1 per axis)
Digital I/O	4-port, 8-bit, bit-configurable
PWM output	4-channel, 50 kHz
Power supply	12–36 V DC

motors, the performance of motor is verified at different temperatures. During the testing, real time values of torque, speed, position and temperature are acquired by the data acquisition system and read by the software at sampling rate of 300 data samples/s, displayed and printed in tabular formats at the user interface. The software also has the ability to test variety of motors in different configurations and to modify PID controller setting during various tests. Soft controls for enabling/disabling drive, start, homing, stop, speed selection, jogging and directions for each motor are also provided in the software. Stepper control tab in the software also has the option to select the type of stepping sequence. The status of operation and healthy communication between PC and motion controller is indicated in the GUI for an error-free operation. The overall set-up is shown is figure 5.

3. Testing of stepper motor for inspection devices

This section describes the various tests performed on typical high temperature motors to be used for inspection of nuclear reactors. As mentioned earlier, the traction motors for semi-automated device are rated for high temperature as per requirement specifications. The electrical actuators driving the robotic device must satisfy the requirements of torque greater than or equal to 0.2 Nm at an operating temperature of 150°C. Arun Microelectronics Limited (AML)-make high temperature, two-phase, 1.8° stepper motor is selected as the equipment under test. Torque–speed characteristic is one of the major criteria that needs to be satisfied for high temperature motors. Motor performance at high temperature without drastic decrease in torque is necessary for continuous movement of the vehicle in limited space. In order to verify the parameters given in the data sheet and also to avoid malfunctioning of the critical system due to the failure of motors, the performance of the motor is verified at different temperatures. The name plate details of stepper motor are shown in table 2.

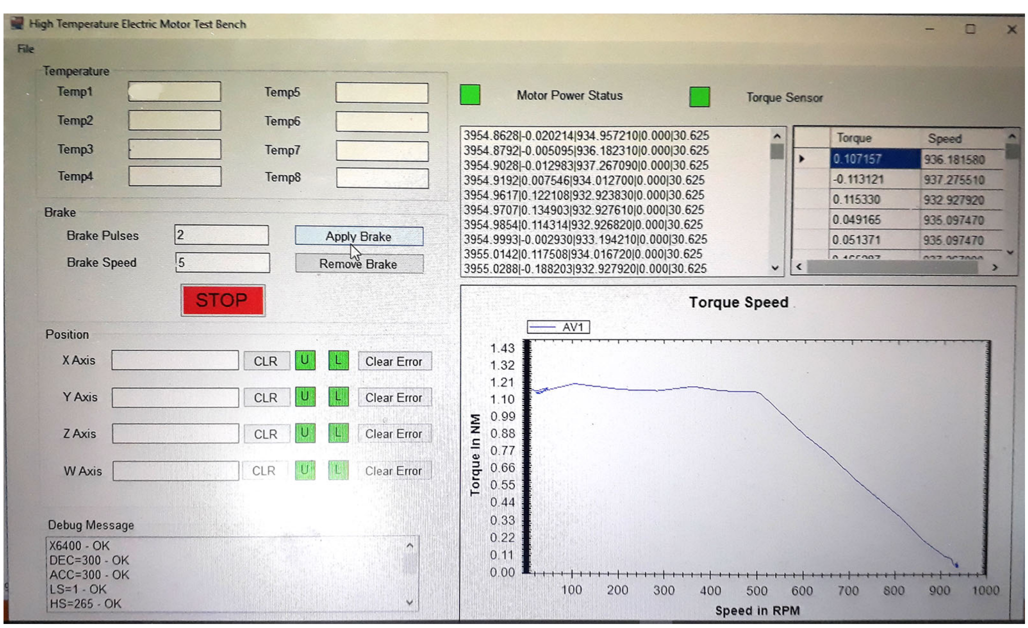

Figure 4. Snapshot of GUI.

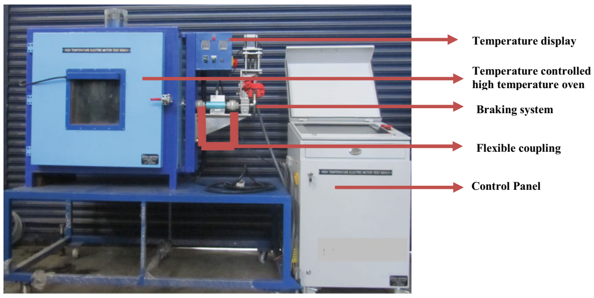

Figure 5. High temperature motor test bench.

Table 2. Specifications of stepper motor.

Holding torque (mNm)	450
Detent torque (mNm)	20
Rotor inertia (gcm^2)	102
Mass (g)	610
Current/phase (A)	1
Resistance/phase at 20°C (mho)	8.5

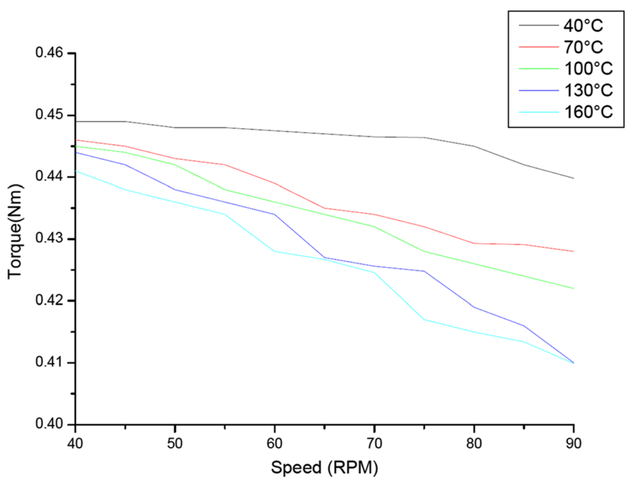

Figure 6. Torque–speed characteristics of stepper motor at different temperatures.

The motor was mounted inside the oven and tested at different temperatures of 40, 70, 100, 130 and 160°C at different speeds in the range of 40–90 rpm. A DC voltage of 25 V and rated current of 1 A are provided for motor testing. The winding temperature is also noted from the thermocouple attached to the stator winding of motor. Torque as functions of speed and temperature is obtained. It is found that with increase in temperature from 40 to 160°C, there is a decrease of 2.22% in torque output of the machine at speed of 20–50 rpm whereas there is a decrease of 7% in torque at higher speed of 50–90 rpm. The torque delivered by motor at 160°C and 65 rpm was found to be 0.425 Nm, which is acceptable for the application. Thus, the experimental results validate the performance of motor and confirm the selection of AML high temperature stepper motor for this application. The torque–speed characteristics of AML-make stepper motor are shown in figure 6.

4. Conclusions

This paper presents a high temperature motor test facility developed for verifying the performance of motors at different temperatures. High temperature motors are used mostly in critical applications; hence, it is necessary to verify their performance before integration into systems. A test bench is also designed with all key features essential for validation of performance of the motor. The test bench provides a single platform for testing of motors at high temperature with easy access with the help of GUI developed using C# software. The stored data can be used for further analysis and comparison of simulated results and actual results of indigenously designed motor configurations. A high temperature stepper motor is tested in this experimental test facility and the performance is validated. The test bench can be also used for research purposes to test the validity of novel motor configurations.

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