Available online at www.elixirpublishers.com (Elixir International Journal)

Electrical Engineering

Elixir Elec. Engg. 71 (2014) 24980-24985

ISSN: 2229-712X

Identify and describe the types of standardized tests for construction and operation of the BLDC motor

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ARTICLE INFO

Article history:

Received: 15 February 2014;

Received in revised form:

6 June 2014;

Accepted: 14 June 2014;

Keywords

BLDC motor,

Measurement,

Parameter.

ABSTRACT

Brushless Direct Current (BLDC) motors are one of the motor types rapidly gaining popularity. BLDC motors are used in industries such as Appliances, Automotive, Aerospace, Consumer, Medical, Industrial Automation Equipment and Instrumentation. As the name implies, BLDC motors do not use brushes for commutation; Instead, they are electronically commutated. This paper is focused on the various methods of testing and various tests both during construction and after construction is done on BLDC motors. These tests include: measurement of coil resistance, measurement of air gap, vibration testing, magnetic saturation, temperature experiments and etc. For a large number of experiments, The proposed method has been described for the size and various types of BLDC motors that in different conditions the motor is encountered.

Introduction

There are no generalized data on the motor performance maps in the literature. The only data available are the separate results for different motors obtained from test beds run under constant loading conditions. Accordingly, one of the goals of this paper is to generalize the data in a form of generalized motor performance maps which could cover the whole family of the specific motor of different rated power under dynamic load operation.

In practice, motors operate in the factories with a changing environment such as different room temperatures, load and velocity profiles, and the type of tasks. As a result, the motor loading happens to be non-stationary and stochastic variables. However, the influence of load variation on motor performance has not received proper attention from engineers. That is, the motor catalogs and brochures are not presenting enough information about the response to non- linear, periodic loadings [1]. Therefore, the first goal of this paper will be development of the test protocols to generate the motor performance maps under variable loadings. Additionally, the parasitic motor characteristic like torque ripple will be identified in different operating ranges. Finally, in order to cover completely the operational range of the specific motor, the test regime for the response time will be presented. All of the test regimes established in this paper are based on the performance criteria developed in [2].

BLDC motor standards fall into two categories, viz., standards for performance and standards for test. For test, IEEE Std 113 applies. For performance, the applicable U.S. standard is NEMA MG1–1993, Revision 4. In NEMA MG1, DC motors are divided in two categories by size: those with outputs of up to and including 1.25 hp per r/min and those with higher outputs. Because of their smaller size, motors in the former category (the medium BLDC motors) have their size and mounting dimensions standardized, and their performance is defined more precisely. Motors in the latter category (the large BLDC motors) do not have standardized dimensions and the performance is more generalized. This is so because larger motors are not mass produced and are usually designed to fit the needs of specific applications [3].

Equivalent Circuit and General Equations for a BLDC Motor

The per phase equivalent circuit for a BLDC motor is shown in Figure 1 as following, where λ_m is the flux linkage of stator winding per phase due to the permanent magnet [4, 5].

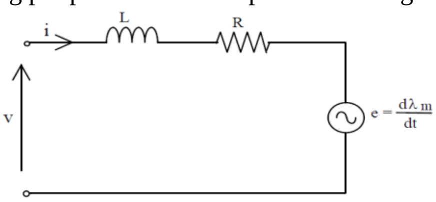

Figure 1: Dynamic per phase equivalent circuit of brushless dc motors

For steady state conditions, assuming v and e are sinusoidal at frequency ω, the equivalent circuit becomes the one shown in Figure 2, where $X=\omega L$, and V, I, E, and λ_m are phasors with rms amplitudes.

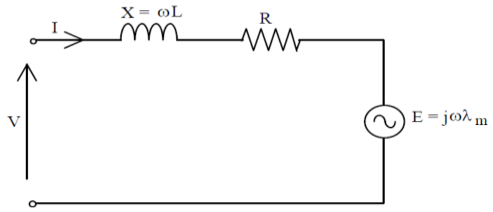

Figure 2: Steady state per phase equivalent circuit of brushless dc motors

The steady state circuit equation can be written as function (1).

$$V = E + (R + j\omega L)I \qquad (1)$$

For a maximum mechanical power at a given speed, I and E are in phase. This also gives maximum torque/ampere (minimum current/Nm). A brushless dc motor has position feedback from the rotor via Hall devices, optical devices, encoder etc. to keep a particular angle between V and E, since E is in phase with rotor position, and V is determined by the inverter supply to the motor. Assuming that $\omega L << R$, when I is in phase with E, V will also be in phase with E. Thus the circuit can be analyzed using magnitudes of E, V, and I as if it were a

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dc circuit.

But first note that when E and I are in phase, the motor mechanical power output (before friction, windage, and iron losses) i.e. the electromagnetic output power is formulated as function (2).

$$P_{em} = m|E||I| = m\omega|\lambda_m||I| \quad (2)$$

where m is the number of phases, |E|, |I|, and |□□m | are the amplitudes of phasor E, I, and □m, and the electromagnetic torque is formulated as function (3).

$$T_{em} = \frac{P_{em}}{\omega_r} = \frac{m\omega|\lambda_m||I|}{\omega_r} \quad (3)$$

where □r = 2□/p is the rotor speed in Rad/s, and p the number of poles.

$$T_{em} = \frac{mp}{2}|\lambda_m||I| \quad (4)$$

The actual shaft output torque is formulated as function (5).

$$T_{load} = T_{em} - T_{losses} \quad (5)$$

where T_{losses} is the total torque due to friction, windage, and iron losses. Dropping the amplitude (modulus) signs, we have

$$T_{em} = \frac{mp}{2}\lambda_m I \quad (6)$$

and in terms of rotor speed

$$E = \frac{p}{2}\omega_r \lambda_m \quad (7)$$

Measurement of the BLDC Motor Parameters

The Nonlinear Test Bed for Actuators shown in Figure 3 will incorporate a large number of variables to be used during the tests [6].

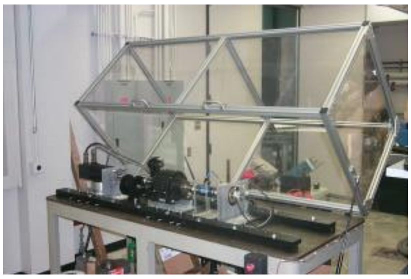

Figure 3: Nonlinear Test Bed for BLDC Motor

Variables will be determined at various locations in the system. Some of the parameters that will be useful to read out from the test bed are position, velocity, torque, temperature, voltage, current, and magnetic flux density. This set of data can be combined to represent specific performance criteria for the actuator. Depending on performance envelope, we can evaluate the output performance of the actuator in the specific range of criteria. Most of the parameters demand to select highly qualified sensors. Table 1 lists several dominant parameters and required sensors to test an actuator.

Table 1: Select appropriate sensors to measure parameters of the experiment

Test Parameters	**Sensor Selection**
Position, Velocity	Encoder
Torque	Torque sensor
Current, voltage	Current sensor
Temperature	Thermister
Magnetic flux density	Hall effect sensor

An encoder or a potentiometer can measure position. In industry, people use encoders because it is possible to have more precise resolution. Velocity and acceleration can be obtained from the differentiation of position in the sensor. Also, the resolution of more than 22 bits is the critical value of selection in torque sensor because an even small amount of torque changes are recorded during the test. Magnetic flux density is also important to evaluate the performance of a motor because the maximum value of this quantity is the criteria to evaluate torque saturation. Usually, the Hall effect sensor is used to measure the magnetic signature [7]. In addition, thermocouples are used to measure the temperature inside the test motor but the difficult problem is how to implement the temperature sensor inside of the motor. A microphone might also be useful to measure the acoustic sound from the motor during operation.

These are the motor parameters that are needed:

Motor voltage constant K_e (volts-sec/rad)
Motor torque constant K_T (lb-in/amp)
Motor resistance R_a (ohms)
Motor inductance L_a (Henries)
Motor inertia J_m (lb-in-sec^2)
Load inertia reflected to the motor armature shaft J_{load} (lb-in-sec^2)
Total inertia=Jm+Jload J_{total}(lb-in-sec^2)

Note that the above values are stated for a single winding with dc motors, and are the phase values for a BLDC motor. Brushless dc motors (BLDC) are 3 phase synchronous motors used in a configuration to be treated as dc drives.

1. Operating Conditions for a BLDC Motor

The usual or normal site operating conditions include the following:

- An ambient temperature in the range of 0°C to 40°C.
- An altitude not exceeding 1000 m.
- A location such that there is no serious interference with motor ventilation.
- Installation on a rigid mounting surface.

Test Regime for BLDC Motor

Speed-Torque Test

The speed-torque test provides a curve of the speed and the test motor torque (Figure 4) [8].

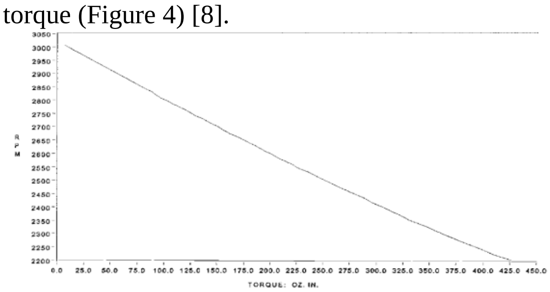

Figure 4: BLDC Motor Speed-Torque Curve

Couple the shaft of the test motor to the dynamometer and attach the motor terminals to a programmable power supply. Set the supply voltage limit at the rated motor voltage and the current limit to the rated peak current. Acquire voltage and current from the programmable power supply and speed and torque from the dynamometer controller.

By using the dynamometer controller to take the motor from idle to a predetermined maximum torque and back to idle speed at a controlled rate, inertial effects will nearly disappear simply by interpolating for the same speed points and averaging the two sets of data. Points from the resulting curves will then compare very well with static measurements made at the same performance point. In most cases, a BLDC motor curve will not include the locked point, since a test at stall will often risk demagnetizing the motor and/or damaging the commutator.

Speed-Torque Curve with Dynamic Loadings

Generally, the torque-speed curve is obtained by increasing torque with a fixed value of speed in current mode. However, this torque-speed plot does not show whether it takes the deteriorated effect in several different kinds of loads such as sinusoidal, ramp, arbitrary nonlinear periodic loads. Given one of these loading types, several tests will be performed with different magnitudes and frequencies. The whole loading period will be at least one minute for each test in order to see the trajectory with different torque profiles. The generated torque will be recorded as a state at each time to compare the value of the measured state with the monitored state values obtained from a Condition Based Maintenance system in real time. In all of the tests with different dynamic loadings, it should be noticed that both amplifier and motion controller influence the performance of the test motor. The example of the test procedure for the first criterion is represented in Figure 5. The amplifiers for the test motor and the load motor use current feedback. The motion of the load motor hinders and disturbs the motion of the test motor. Thus, the side effect generated between these two torque- generators cause the output shaft torque. Increasing or decreasing speed in the test motor can change the output torque measured from the torque sensor. Also, varying the magnitude and frequency of the load torque in the load motor can affect to the output torque obtained between these two motors. The test motor and the load motor cannot run independently at the start of the running. Because they are connected by a clutch on operation, the position and velocity feedbacks have to be assigned in the test motor only. The load motor will have only a torque feedback control loop. The test motor will start to run at the highest speed that the test motor can generate. The torque-speed curve will be obtained by reducing the speed, and in each speed region, the electrical torque command from the load motor will be increased until it arrives the highest value of the torque without changing the speed. The nonlinear periodic loading will be developed by four bar linkages, and the sinusoidal and ramp loadings will be performed by programmed torque from the load motor. In order to measure the loading torque, the test bed has a torque sensor which can measure up to 40 Nm. Each test will be repeated at least 20 times to allow for statistical analysis. The data obtained from all of the tests will be ana lyzed by generating the mean and standard error values with the proper assumption of normal distribution. As an initial set of torque-speed curve with respect to several different types of loadings, at least 20 performance maps for this criterion will be obtained. Ten maps are considered with 10 different levels of torque magnitudes in sinusoidal input loadings. Also, 10 additional maps will be obtained from arbitrary generated nonlinear periodic torque loadings in the load motor [9].

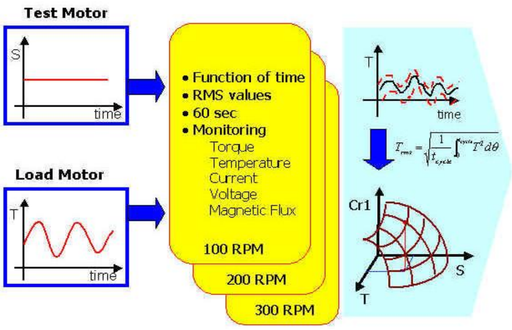

Figure 5: Torque Speed Curve with Dynamic Loading

Temperature Effect on Speed-Torque Curve

In all of the electrical machines, the electrical, magnetic and thermal processes are internally coupled together in some sense.The temperature distribution is affected by the properties of the conducting and magnetic materials and the performance of the electromagnetic force, which is generated from the reaction between stator and rotor. The most temperature sensitive parameters are the stator winding resistance and the iron core of the stator [10]. Over the operational temperature range of the motor, the resistance variation with the temperature will be obtained. Figure 6 shows the test motor stator and four spots are chosen for the measurements of the temperature inside the motor [9].

Figure 6: Stator of PMSM

There are four holes through the front cover face of the stator and four thermisters are attached on the stator windings and core by using epoxy. The temperature sensors are attached to the stator as shown in Figure 7 [9].

Figure 7: Stator with Thermisters

The winding wires have insulation so actually the sensors measure the temperature on the insulation of the wires. However, it is too hard to find the way to measure the actualtemperature of the wires, so in this test, when the temperature calculation is performed, the small additional weighting factor might be multiplied to the real measurement values with proper assumptions. This will need further research in the future. The same torque profiles are generated in the load motor while the test motor runs at a certain speed to produce the torque-speed curve. At this time, there is one more measurement parameter, which is temperature. The operating temperature of the test motor is considered between 25 °C (an ambient temperature) and 100°C . The temperature values measured in four different spots inside the test motor will be recorded with respect to given torque and speed values to generate 3D plots. The experimental results including the variation of the temperature will provide the complete set of the electromechanical performance maps. Therefore, the first three criteria will be obtained at the same test setting and time.

Torque Ripple

A Permanent Magnet Synchronous Motor (PMSM), which is the test motor, generates parasitic torque pulsations owing to variable magnetic reluctance, distortion of the stator flux linkage distribution, and deficiencies of feasible winding geometries. The torque ripple is particularly undesirable in some demanding motion control and it leads to speed oscillations which cause deterioration in the performance [11]. Continuous constant torque from the test motor generates in order to identify the ripple on the output torque curve. The torque ripple will be measured in the following equation (function (8)).

$$T_r = \frac{Peak-to-Peak\ Torque\ Ripple}{Average\ Output\ Torque} \times 100(\%) \quad (8)$$

If the load motor is used to generate the constant torque, the measurement data from the torque sensor cannot be identified which motor out of the test motor and the load motor develops more torque ripple. Therefore, the constant torque will be applied from the brake loading. The static brake generates a lot of heat so it is applied a very short time (i.e. one or two seconds). Also, the output signal from the torque sensor should be filtered using an active filter to eliminate measurement noise.

The output torque of a dc motor at low speeds appears constant, but closer examination reveals a cyclic component called torque ripple, as illustrated in Figure 8.

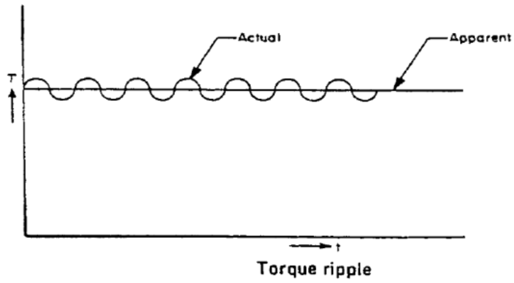

Figure 8: Torque Ripple Test

This torque ripple results from the switching action of the commutator, from the armature reluctance torque and sometimes from the bearings.

Torque ripple usually constitutes a very small percentage of the rated output torque and proves negligible for most uses. However, torque ripple may become critical in some applications, thereby requiring a means of measurement. The apparatus illustrated in Figure 9 can accurately measure torque ripple, as long as the moment of inertia of the measuring device remains much smaller than the motor moment of inertia (otherwise inertia filtering invalidates the ripple measurement).

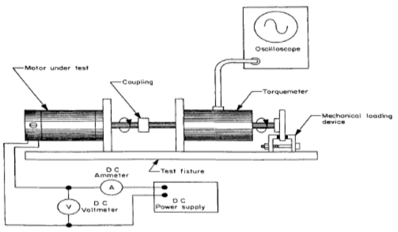

Figure 9: Torque Ripple Test Setup

Demagnetization Test

` The demagnetization test determines the amount of current the test motor can draw before reducing the K_e by 5 percent. Couple5 the shaft of the test motor to a dynamometer and attach the motor terminals to a dc power supply. Use an oscilloscope to monitor a current probe or current shunt on the positive output of the dc supply. Set the supply voltage limit to the rated motor voltage and the current limit well beyond the calculated demagnetization point. Using the oscilloscope to determine the current, quickly apply torque until reaching the desired current. Remove all torque immediately and repeat two more times. Recheck the K_e of the test motor after allowing the motor to fully return to room temperature, generally after about 30 to 60 min. A reduction in K_e greater than 5 percent means the test motor has demagnetized. Otherwise, repeat the test at a higher current (typically in 5 percent increments) [8].

Thermal Resistance Test

The thermal resistance test determines the temperature (°C) rise per watt loss of the test motor. Place the test motor into a stand and lock the shaft. For brush dc motors, route wires from the commutator and under the bearings to the outside for the winding resistance measurement, to avoid errors introduced by the brushes and the contact drop. Measure the cold winding resistance with the multimeter and record the ambient temperature. Attach a thermocouple to the shell to monitor the temperature rise. Attach the motor terminals to a programmable power supply. Slowly increase the voltage until reaching the rated current. Hold the rated current for 1 h after the shell temperature levels. Quickly detach the motor terminals and take the hot winding resistance with the multimeter. Record the ambient temperature. Repeat the test for the rated running condition, preferably with a different motor for brush dc tests to avoid the possible effects of a burned commutator. The thermal resistance constant equals approximately [8]:

$$R_{th} = \frac{\left(R_{hot}/R_{cold}\right) - 1 + \left(amb_{hot} - amb_{cold}\right)}{winding\ \ const \times voltage_{hot} \times current_{hot}} \qquad (9)$$

Use a winding constant for copper of 0.00393.

where

R_{th} = thermal resistance.

R_{hot} = hot winding resistance.

R_{cold} = cold winding resistance.

amb_{cold} = cold ambient temperature.

amb_{hot} = hot ambient temperature.

$voltage_{hot}$ = hot winding voltage.

$current_{hot}$ = hot winding current.

Acceleration Test

Determining torque and speed capacity curve to cover the majority of the potential operating situations is not easy and time consuming. IEEE Standard 115 [12] lists several methods that can be employed to measure torque and current. One of the methods for measuring them is the acceleration test. Measurements taken by this method generate values for stator current, applied voltage, input powers, and input torque. By measuring the position from the encoder, the acceleration will be derived at the instant time of the differential changes in rotor speed. The acceleration tests are conducted at different values of loading torque and speed to build a valuable and meaningful motor performance map. A high acceleration capability requires a high maximum torque combined with a constant polar moment of inertia, J_m of the motor and is expressed as function (10).

$$\alpha = \frac{d^2\theta}{dt^2} = \frac{1}{J}\left(T_e - F_b\frac{d\theta}{dt} - T_m\right) \qquad (10)$$

where a is the acceleration, θ is the angular position, T_e is the electrically generated torque, F_b is the friction coefficient, and T_m is the load torque. The major problem with the acceleration test is obtaining sufficient data points as motor speed approaches synchronous speed to be able to define the actual shape of the curve in a certain period of the testing. The optimum speed that produces a larger incremental acceleration in each time step should be found from this test by changing the level and frequency of the loading torques [13]. Another factor that affects the outcome of the acceleration test is the value used for the inertia. The moment of the inertia of the machines can be determined accurately from the results of the friction test for the mechanical frictions of motors, break, clutch and couplings. Finally, the acceleration capability of a permanent magnet motor is limited by the demagnetization of the magnets. It can result from high temperature of the magnets and the winding insulation. The temperature increases the resistance of the winding wires and the increased resistance affects on the applied current to the motor. For example, at a temperature around 100 ^{o}C, acceleration might be deteriorated as the torque generated by a reduced magnetic flux due to higher temperature [9].

Vibration

Motor vibration caused by mechanical or electromagnetic dissymmetry should be measured using a low ripple source of direct current such as a generator. Such measurements are usually made at no load and at rated speed using a half-key in the shaft extension. The frequency of vibration is related to the speed of rotation. On rectified power, in addition to vibration caused by mechanical or electromagnetic dissymmetry, vibrations may be experienced related to the amplitude and frequency of the ripple components of armature and field current. Tests should be conducted at various loads over the entire speed range of the machine including speed control by armature voltage where applicable. To differentiate between vibration due to current ripple and that due to slot ripple or other factors, the vibration frequencies should be examined as the speed of rotation is changed slowly. Natural frequencies of machine mechanical parts may be excited by power supply frequencies, harmonics, or sub-harmonics acting independently or reinforced by slot ripple. Also, measurements can be made with varying degrees of current ripple as accomplished by the use of a smoothing reactor or by using a low ripple power supply, such as a dc generator. Vibration velocity is the recommended measurement quantity. Radially- and axially-directed vibration measurements should be made at the machine bearing housing. If the bearing housings are not accessible the readings should be taken at the housing support as near the housing as possible. Mounting conditions will affect the vibration of the machine. Machines provided with self-supporting bases, or of the end-shield type construction, may be mounted in such a manner as to make them independent of mounting conditions. On large machines this becomes impractical and experience has shown it to be unnecessary. To obtain measurements that are as nearly as possible independent from mounting conditions, the machine should be placed on flexible pads or springs. These should compress by the weight of the machine alone, in amounts not less than the values shown below (Table 2) [14].

Table 2: Minimal Amount of Compression Layers to Suit the Motor Speed

Speed (r/min)	Minimum Compression	
	(mm)	(in)
7200	0.4	1/64
3600	1.5	1/16
1800	6	1/4
1200	15	9/16
900	25	1
720	40	$1^{9/16}$
600	55	$2^{1/4}$

` The value for minimum compression at other speeds may be determined from the equation (11).

$$c = \left(\frac{k}{\upsilon}\right)^2 \qquad (11)$$

Where

$$k = 4500 \text{ for } c \ \text{(millimeters)}$$
$$900 \text{ for } c \ \text{(inches)}$$
$$\upsilon = \text{ speed (r/min)}$$

The pads or springs should be selected *so* that the compression is not more than one-half of the unloaded thickness.

Air Gap Measurements

The measurement of the air gaps should include a check of correct installation of main poles, test of possible deformation of bearing or bearing support, inspection for sufficient clearance before testing, and proper assembly of rotor with respect to stator. Dissymmetry in main- or commutating-field pole air gaps may cause difficulties such as excessive voltage ripple or overheating of equalizers. Measure the minimum air gap beneath the center (approximately) of each main pole and each commutating-field pole piece using a suitable feeler gage or tapered gage to determine the gap to at least the nearest 0.100 mm (0.005 in) for integral-horsepower motors and to the nearest 0.050 mm (0.002 in) for fractional-horsepower motors. All measurements should be made between iron surfaces of the pole pieces and the rotor. In normal practice, a common point on the rotor is selected and the point is rotated to each pole in turn as measurements are made. Where apertures are not provided, the uniformity of the air gap can be determined by ascertaining that the rotor turns freely in the assembled machine when wound with a wire spaced spirally around the rotor periphery. For this test the diameter of the wire should be at least 70% of half the difference between the diametric distance of the main pole faces and the outside diameter of the rotor [8].

Response Time

` As one example of the transient response tests, the response time will be measured at several torque and speed levels. The input source will be a step input to clearly identify the changes of the input. Figure 10 shows the torque response for a step change of the reference torque from –2 to 2 Nm when the rotor is blocked. It is seen that the torque response is as fast as predicted earlier and there is no overshoot. Also, there is the torque ripple with signal noise. From this figure, the response time can clearly be identified as 3.2ms. This criterion test will generate performance maps for a number of torque and speed values. During the test, there must be a limit torque that never reaches to the desired value. The response time is limited by the mechanical inertia and the performance of the motion controller. These values are fixed at first and never changed, so the inertia should be carefully calculated to obtain an exact value and it is recommended to install the best performance of the motion controller. This test will be repeated with both increased and decreased cases in several times. The speed response time will be obtained from no load test. Also, The torque response time data will be generated from the test set-up with locked rotor using the brake [9].

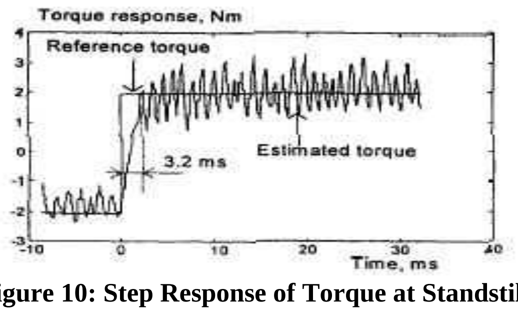

Figure 10: Step Response of Torque at Standstill

Safe Operating Area Curve Test

The safe operating area curve (SOAC) determines the boundaries of safe operation. Use the running thermal resistance constant to estimate the winding temperature and maintain safe operating temperatures (usually below 85°C plus ambient). Place the test motor into a stand and couple the test motor to the dynamometer. Attach a thermocouple to the shell to monitor the temperature rise. Attach the motor terminals to a programmable power supply. Set the supply voltage limit at the rated motor voltage, and the current limit to the rated peak current. Start the current at the rated continuous motor current with the appropriate torque on the dynamometer. Adjust the voltage on the power supply to obtain the desired shell temperature when level. Acquire the speed and torque from the dynamometer controller, and the voltage and current from the power supply. Adjust the torque as needed to keep the winding temperature at

85°C plus ambient. Repeat the test at the next desired level. Acquire data at different speeds and torques to plot the SOAC. The winding temperature rise equals approximately:

$$Temp_{winding} = R_{th} \quad (\text{watts lost})$$

$$Temp_{winding} = R_{th} \times \left(\frac{voltage \times current - speed \times torque}{1351.7} \right) \quad (12)$$

where torque is in ounce-inches. Record the cold winding resistance at the beginning of the test, the hot resistance at the end of the test, and the ambient temperature for each measurement [9].

Conclusion

This paper presents a work- in-progress that aims to develop the performance criteria test regimes for the nonlinear testing of an actuator. An actuator is a highly nonlinear device with redundant resources and that its performance can be improved by using a non-linear model and extensive sensory information. A collection of performance maps is our approach of representing the complexity of the actuator (both model and sensor) as well as metrics for measuring the actuator state. For performance envelopes, the parameters in each criterion are carefully investigated as to whether they are controllable and independent. Then, these are manipulated as common factors to get the unique performance envelope for the actuator. The test data developed from each test regime must be normalized and made homogeneous: for instance, it may be necessary that all criteria be described for values between 0 and 1, with 1 being the desirable value. Great difficulty appears when the bounds for the map are unknown. The test regimes developed in this paper apply only to the prime mover and specifically to BLDC motor. Further work involves developing more test regimes to generate performance maps that represent comp lete actuator behavior.

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Biographies

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