Issues and Challenges in Robust Controller Design for Integrated External and Unconstrained Internal Disturbances: A Case Study

Prashanth N A
Dept of Electronics and Electronics
BMS Institute of Technology & Management
Bangalore, India

Prasanth Venkatareddy
Dept of Electronics and Electronics
Nitte Meenakshi Institute of Technology
Bangalore, India

Abstract: *Recent advances in the fields of high-energy magnets have established a wide value for the designers of permanent magnet (PM) motors. The most used magnets are NdFeB magnets, which meet the requirements for high specific energy for the motor due to their easy manufacture and relative low size. Unfortunately, a reversible demagnetization of the neodymium magnets is generated for temperatures ranging (above 120oC) of the permanent magnet motors operating regimes, which defines negative effects on the torque ability. This research explores the temperature effects of Neodymium magnets over torque and performance of these motors. In this paper, the important parameters of magnets and motors that are impacted by temperature are described.*

Keywords—PMDC, NdFeB (Neodymium)magnet, stall current, stall torque.

1. Introduction

Though the challenges for integrated approach remain common irrespective of motor drives, we present this work with PMDC as the drive under consideration. The demand in performance requirements of PMDC motor is high in applications where precision is on priority [1]. Especially in speed control loop, the mechanical vibrations, uncontrolled disturbances, and the plant uncertainties like parameter variations [2] play an important role to decide the motor performance. This chapter aims at gaining a better understanding of how motor's performance is impacted. There is no substitute for checking and validating the motor operational conditions, as the number of variables along with assumptions cause an impediment towards building a proper theoretical design framework. Hence the best way to understand motor output under real operating conditions is to simulate and track temperature variations from different parts of the motor via an appropriate data acquisition system. The motor performance with output torque and motor speed dependent applications [3] are governed by the values of torque constant (Kt), voltage constant (Ke) and motor armature winding resistance (Rarm).

Changes in temperature caused by load variations have a significant impact on winding resistance and magnetic flux density, as is well known. As the motor temperature increases, the winding temperature also increases depending on the temperature co-efficient of the winding material (i.e. Copper) [4]. The armature winding resistance is the main cause for generating heat inside the the motor due to increased inrush of current meeting the changes in Torque requirement. Due to this the angular velocity of the system decreases necessitating increased damping ratio.

To summarize, the choice of appropriate winding resistance plays a big role to contain increasing dampness that further causes decrease in efficiency of the system. The variation in value of coil inductance due to temperature changes results in high settling time and increasing motor acceleration.

The constant of motor torque and the constant of voltage are directly proportional to the permanent magnet's magnetic flux density. The overall flux density varies proportionally with respect to the magnet temperature, which further depends on the magnetic materials used [5]. If the temperature of magnet exceeds its rating, demagnetization effect alters the motors performance. This further causes motor performance to deteriorate through variation in back EMF constant (Ke) and motor torque constant (Kt). In PMDC motor, torque produced can be divided into two components such as torque due to Internal loss (TM) and load due to external loss (TL). Thus, the current in the motor can be expressed as (TL + TM) /KT.

When the voltage is applied to the PMDC motor at rest, the starting current is limited by the armature resistance will nil back EMF. Therefore, this initial current is required to produce large torque to start the motor on load. When the speed increases, the back EMF increases causing the motor current to limit to the necessary torque.

Hence the PMDC motor has following characteristics:

i. Motor torque is a linear function of motor current.

ii. Speed of the motor is a linear function of load torque when operated at a constant input voltage.

The incorrect estimation of the motor parameter values leads to instability and poor control; therefore, the precision of parameter estimation is a real problem. The primary design challenge for the system's parameter estimation is to modify the mathematical model, that completely defines the physical model to be used for predicting the system response. Few methods exist that estimate the motor parameters viz. recursive least squares algorithms, particle swarm optimization etc.

Designing the system continues to be a challenging task for desired speed under a given load at suitable temperature as a control objective [7]. Temperature effects due to armature current on magnetic field effect (B, H, impact on magnetic material) is discussed in the following section where the design complexities are presented which continues to remain a challenge when it comes to controller design integrating internal and external disturbances (assuming temperature is main independent variable).

2. Temperature effects on Magnetic Field and Armature current

The underlying principle is the increasing load variations leads to increase in temperature of motor which impacts the operating magnetic field. The hysteresis of BH curve is sensitive to demagnetization effect with increased temperature is shown in figure.1

The following equations represents temperature vs B and H [5]

$$B_r = B_{r20} \cdot \left[1 + \frac{\alpha_B}{100} \cdot (\theta_{PM} - 20)\right] \quad \ldots\ldots. \ (1)$$

$$H_c = H_{r20} \cdot \left[1 + \frac{\alpha_H}{100} \cdot (\theta_{PM} - 20)\right] \quad \ldots\ldots. \ (2)$$

here θ_{PM} is the permanent magnet temperature, B_{r20} is the flux density and H_{r20} is coercive field intensity at 20 °C and $\alpha_B < 0$ and $\alpha_H < 0$ are corresponding coefficients of temperature. NdFeB magnets of PMDC motors have high energy, high coercive field intensity (Hc). and residuary flux density (Br). The residual flux density of this magnet decreases due to increase in temperature and other way round it obtains its original value when this temperature is reduced. This residual flux density variation along with the variation of armature resistance due to temperature have great influence on the torque and PMDC motor efficiency. The motor should be designed to operate on nonlinear portion of the curve only. The permanent magnetic flux density and coercive field strength decrease with rising temperature in Magnet.

In [3] the design of controller for external disturbances assuming limited or no variations in operating temperature. Example motor internal parameters are assumed to exhibit limited variations with limited or no variations in temperature. However, variations beyond constrained limited temperature changes demands simultaneous robustness in controller design with external and internal disturbances of the motor. An integrated approach thus needs to overcome both the external and internal disturbances in a consistence way accommodating wide range of operating temperature.

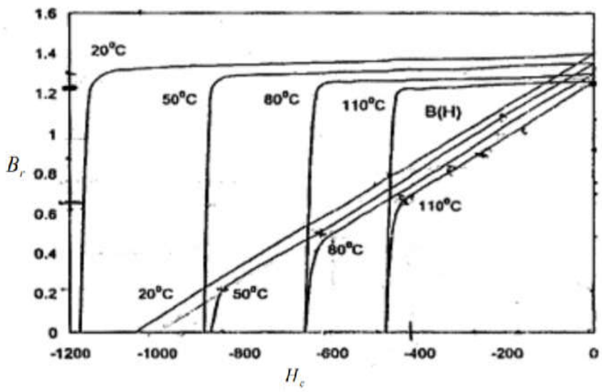

Figure 1 characteristics of Demagnetization in NdFeB (Neodymium Iron Boron) magnets at different temperatures

As load variations demand variation in operating torque, the facilitating armature current need to meet required torque proportionally. With increased current thermal losses are bound to increase. As load torque increases temperature effects cause the torque and Current relationship to remain unbounded or saturated. Such situation invites motor to restart again.

The Torque vs Temperature curve in figure 2 presents the unboundedness in the situation. The decaying exponential corresponds to effective torque available, alternately rising exponential corresponds to excess torque to be applied for consistency in meeting desired torque.

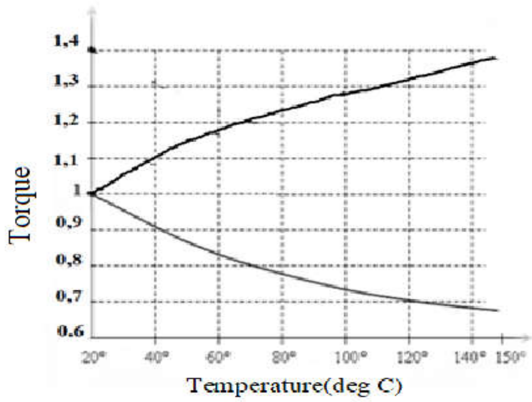

Figure 2 Applied torque against Required Torque Vs Temperature capability of PMDC motor

Any rise in armature current leads to increase copper loss (I2R losses). Copper loss directly contribution to thermal dissipation inducing rise in temperature. Further motor torque is directly proportional to armature current. With increased requirement of motor torque, the corresponding armature current has to rise meeting

- Desired motor torque
- Simultaneously incurring copper loss (I2R losses)

Unless load variation is not constrained this situation remains untenable on the contrary internal parameters need to be confined over the limited range of variation to avoid further rise in temperature. Temperature being the important parameter in disturbance rejection an integral approach for simultaneous external and internal variations remains beyond the bounds of controller design. However, constraining either external or internal variations as always been a problem of research interest.

The function of armature resistance is determined by slope of torque capability obtained from the torque vs temperature characteristic. Higher the slope, smaller is the resistance value. The increase in this value of resistance decreases the motor's efficiency (an increase in I2R losses). If needed Torque is required to accelerate the load, the back emf decrease and more source current is required to provide essential torque. This back emf decrease thereby additional fall off in motor speed for required torque. Thus, torque capability of the motor depends on the temperature.

3. Temperature effects on various performances measures

The effects of temperature on different PMDC motor parameters have been studied by [4] and inferences on their work can be drawn from the figure 3.

Following observations are drawn for temperature effects on various performance measures and motor parameters.

Under Nominal temperature, to obtain high required torque, with correspondingly high current, I2R losses are high resulting with lower efficiency. At very low torques, despite high speed limited required mechanical power is supplied to overcome friction which scales linear with speed. This results in lower efficiency. Maximum efficiency should occur in between. Therefore, maximum efficiency operation occurs during high speed, lower torque so, current leading to minimal I2R losses. The PMDC motors are operated for most of the application in the region of maximum efficiency and maximum power for desirable conditions.

There are two effects due to increase of motor temperature:

- PM strength decreases – resulting in higher no-load speed.
- Winding resistance increases – which cause stall current low.

Both effects reduce the stall torque value.

During high speed and low torque operation (e.g. at or near the no-load condition) is dominated by friction and hence inefficient.

At very low speed and high current operation (e.g. near the stall condition) is dominated by heating of the coils through I2R losses and hence not efficient.

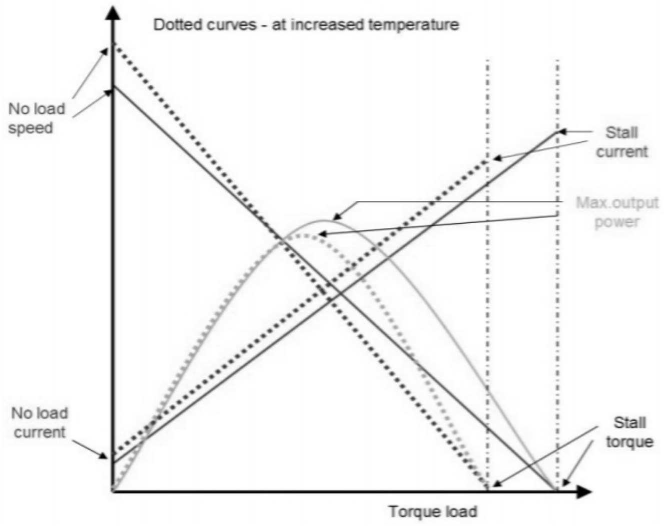

Figure 3. Composite PMDC motor's characteristics, representing relationship of efficiency, torque, current, speed, and power for voltage at Nominal temperature Vs increased Nominal temperature (curtsey: Carryer, Kenny et.al)

4. Conclusion

An unconstrained robust controller approach for simultaneous internal and external variations remains unresolvable due to impact of temperature on load variations and internal parameter variations. In robust controller design for PMDC motors the primary factor for design against variations is motor operating temperature. However, attempts have been made by researchers and also in this research to design robust controller by constraining either internal or external variations.

REFERENCES

[1] *Prasanth Venkatareddy, Subhash kulakrni, "Design of Robust H∞ Controller for a Realistic PMDC Motor with GA Based Performance Optimization," International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 1 (2018) pp. 385-393.*

[2] *Prasanth Venkatareddy, Subhash kulakrni," H∞ Controller Design of PID Gain Tuning based for Robust Control of PMDC Motor with Uncertain Parameters" Jour of Adv Research in Dynamical & Control Systems, ISSN 1943-023X ,Vol. 11, No. 5, 2019, 345*

[3] *Prasanth Venkatareddy, Subhash kulakrni," PID gain tuning for Robust Control of PMDC Motor with tracking and disturbance rejection through H∞" International Journal of Innovative Technology and Exploring Engineering (IJITEE) ISSN: 2278-3075, Volume-9 Issue-1, November 2019.*

[4] *J. David, Introduction to Magnetism and Magnetic Materials, Chapman and Hall, New York, 1991.*

[5] *I. Dudzikowski, S. Kubzdela, Thermal problems in permanent magnet commutator motors, 23rd Int Symp on Electro Machines SME'97, Poznan, Poland, pp. 133–138, 1997.*

[6] *J. R. Hendershoot Jr, THE Miller, Design of Brushless Permanent Magnet Motors, Clarendon Press, Oxford, 1994.*

[7] *W. H. Yeadan, Handbook of small electric motors, McGraw-Hill, 2001.*

[8] *D.C. Motors, Speed Controls, Servo Systems, Electro-Craft Handbook, 5-th ed., ElectroCraft Motion Control, Gallipolis, Ohio, 1980.*

[9] *Clemens müller, Ulrich schwarzer, Motor Handbook, Version: 2.1 Release Date: 12.03.2019.*

[10] *Hongfeng Li, Yanbo Shen," Thermal Analysis of the Permanent-Magnet Spherical Motor" IEEE transactions on energy conversion, 0885-8969.*

[11] *H. F. Li, C. L. Xia, and T. N. Shi, "Spherical harmonic analysis of a novel Halbach array PM spherical motor," in Proc. IEEE Int. Conf. Robot. Biomimetics, Dec. 2007, pp. 2085–2089.*

[12] *C. L. Xia, H. F. Li, and T. N. Shi, "3-D magnetic field and torque analysis of a novel Halbach array permanent-magnet spherical motor," IEEE Trans. Magn., vol. 44, no. 8, pp. 2016–2020, Aug. 2008.*

[13] *H. F. Li, C. L. Xia, and P. Song, "Magnetic field analysis of a Halbach array PM spherical motor," in Proc. IEEE Int. Conf. Autom. Logistics, Aug. 2007, pp. 2019–2023.*

[14] *C. L. Xia, P. Song, H. F. Li, B. Li and T. N. Shi, "Research on torque calculation method of permanent-magnet spherical motor based on the finite-element method," IEEE Trans. Magn., vol. 45, no. 4, pp. 2015–2022, Apr. 2009.*

[15] *L Yan, I M Chen, and K M Lee , "Modeling and iron-effect analysis on magnetic field and torque output of electromagnetic spherical actuators with iron stator," IEEE/ASME Trans. Mechatron., vol. 17, no. 6, pp. 1080–1087, Dec. 2012.*

[16] *J. G. Xin, C. L. Xia, H. F. Li, and T. N. Shi, "A novel orientation measurement using optical sensor for spherical motor," Science China, vol. 56, no. 6, pp. 1330–1339, Jun. 2013.*

[17] *S. Mezani, N. Takorabet, and B. Laporte, "A combined electromagnetic and thermal analysis of induction motors," IEEE Trans. Magn., vol. 41, no. 5, pp. 1572–1575, May 2005.*

[18] *A. Boglietti, A. Cavagnino, and D. Staton, "Evolution and modern approaches for thermal analysis of electrical machine," IEEE Trans. Ind. Electron., vol. 56, no. 3, pp. 871–882, Mar. 2009.*

[19] *S. Nategh, O. Wallmark, M. Leksell, and S. Zhao, "Thermal analysis of a PMaSRM using partial FEA and lumped parameter modeling," IEEE Trans. Energy Convers., vol. 27, no. 2, pp. 477–488, Jun. 2012.*

[20] *S. Nategh, Z. Huang, A. Krings, O. Wallmark, and M. Leksell, " Thermal modeling of directly cooled electric machines using lumped parameter and limited CFD analysis," IEEE Trans. Energy Convers., vol. 28, no. 4, pp. 979–990, Dec. 2013.*