TEMPERATURE EFFECTS ON TORQUE PRODUCTION AND EFFICIENCY OF MOTORS WITH NdFeB

CARMEN LUNGOCI, DAN STOIA

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Recent developments in the high energy magnets fields determined a widespread interest for the permanent magnet (PM) motors designers. The requirements regarding the high specific energy for the motor are satisfied by the NdFeB magnets, which are the most utilizable, due their easier manufacturing and relative law price. Unfortunately, at the temperature range (above 150^{o}C) of the PM motors operating regimes, it is produced a reversible demagnetization of the Neodymium magnets, which determines negative effects on the torque capability. The paper deals with the temperature effects on the torque production and on the efficiency of the PM motors using Neodymium magnets. The main parameters of the magnets and of the motor which are influenced by the temperature are presented.

1. **INTRODUCTION**

Known as third generation of Rare Earth magnets, Neodymium Iron Boron (NdFeB) magnets are the most powerful and advanced commercialized permanent magnet today. Since they are made from Neodymium, one of the most plentiful rare earth elements, and inexpensive iron, NdFeB magnets offer the best value in cost and performance [1].

NdFeB magnets are available in the PM motors construction due to their high energy and their high values of the coercive field intensity and remanente flux density. In this way the motor can be designed at smaller values from the dimensional point of view and it can operate in heavy loads conditions. The disadvantage of this type of magnets is the sensibility at the relative small values of the temperature, which determines negative effects on the magnet and motor parameters [2, 3].

In the normal range of operating temperature, as the temperature is increased, the residual flux density and intrinsic coercive field intensity of the magnet will come down. When the temperature is reduced, the flux density and the coercive field intensity will return to the original value. This variation in the residual flux

"Transilvania" University of Braşov, Electrical Engineering Department, Politehnicii no.1 Street, Braşov, Romania, lungoci@unitbv.ro

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density of the magnet, along with the variation in the armature resistance of the motor with temperature, influences the torque capability and the PM motor efficiency [4].

Regarding the influence of the temperature on magnet parameters many researches have been done, but the impact on the PM motor behaviour is still studied [5].

In this paper, there are presented main parameters and the demagnetization curves of the magnet which are influenced by the variation of the temperature. The behaviour of a PM motor which uses the NdFeB magnet at an operating temperature range of 20 ^{o}C to 140 ^{o}C is studied, from the point of view of back emf, torque capability and efficiency.

An approximate analysis technique is used, which gives inside into the effect of various motor parameters on the maximum torque capability. Later on, an accurate method is used to analyze the effect of saturation of the PM motor.

At the end, conclusions are done, proving that the maximum torque capability of PM motors using NdFeB magnets can vary over a wide range, with a great impact on the functionality of the systems which contains PM motors.

2. **TEMPERATURE EFFECTS**

For PM motors with linear demagnetization curve, *i.e.* NdFeB magnets, the coercive field intensity at room temperature can be calculated as:

$$H_c = \frac{B_r}{\mu_0 \cdot \mu_{rrev}}, \tag{1}$$

where μ_{rrev} is recoil magnetic permeability.

The magnetic flux density produced in the air gap δ by an NdFeB magnet with linear demagnetization curve and its height L_M placed in a magnetic circuit with large magnetic permeability and air gap length δ is approximately:

$$B_\delta \approx \frac{B_r}{1 + \mu_{rrev} \cdot \dfrac{\delta}{L_M}}. \tag{2}$$

The air gap field strength according to the equation due to practically linear demagnetization curves at room temperature:

$$B = B_r \cdot \left(1 - \frac{H}{H_c}\right), \tag{3}$$

$$H_\delta = H_c \cdot \left(1 - \frac{B_\delta}{B_r}\right). \tag{4}$$

The useful energy per magnet volume is:

$$w_g = \frac{B_\delta \cdot H_\delta}{2}. \tag{5}$$

The remanente magnetic flux density B_r and coercive field intensity H_c decrease as the magnet temperature increases, i.e:

$$B_r = B_{r20} \cdot \left[1 + \frac{\alpha_B}{100} \cdot (\theta_{PM} - 20)\right], \tag{6}$$

$$H_c = H_{c20} \cdot \left[1 + \frac{\alpha_H}{100} \cdot (\theta_{PM} - 20)\right], \tag{7}$$

where θ_{PM} is the temperature of PM, B_{r20} and H_{c20} are the remanente magnetic flux density and coercive field intensity at 20 ^{0}C and $\alpha_B < 0$ and $\alpha_H < 0$ are temperature coefficients for B_r and H_c in % / ^{0}C, respectively.

The effect of the temperature on the demagnetization characteristics of a typical NdFeB magnet is shown in the Fig. 1.

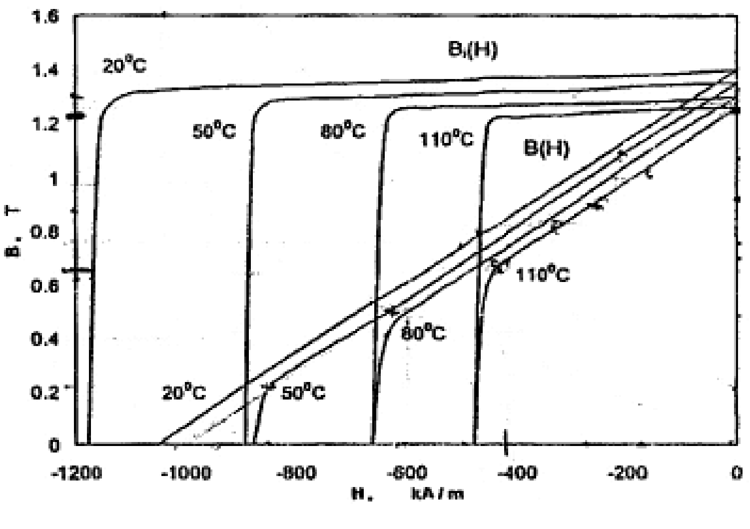

Fig. 1 – Demagnetization characteristics of NdFeB magnets at various temperatures [2].

At $\theta_{PM} > 20$ °C the demagnetization curve is nonlinear. At $\theta = 120$ °C, its linear part is only between 0.6 T and Br parallel to the demagnetization curve at 20 °C. Thus, the relative recoil magnetic permeability μ_{rrev} and air gap magnetic field strength Hg at 100 °C are approximately as those at room temperature.

A material which has a straight demagnetization characteristic at room temperature may develop a knee in the second quadrant (point K) at higher temperatures (characteristics of Nd-Fe-B magnets). The coercive field intensity also varies with temperature, but this is not as important as the variation of the beginning of recoil line. The location of this point is at the intersection of the demagnetization curve with a straight line representing the reluctance of the external magnetic circuit (open space). In table 1 are showed the values of the flux magnet and coercive field intensity in the point K, for some values of the temperature.

Table 1

K points coordinates at different temperatures

50 °C	B_k = 0.2 T	H_k = 810 kA/m
80 °C	B_k = 0.45 T	H_k = 600 kA/m
120 °C	B_k = 0.62 T	H_k = 400 kA/m

The equation of the recoil line is the same as that for the demagnetization line. In most designs the range of variation on the torque constant which can be tolerated is quite small, of the order a few percent. Limits are therefore set on the motor temperature and on the phase currents to keep the operation within this safe range.

The residual flux density B_r and air gap flux density respectively decreases with temperature and this decrease is reversible. If the operating point moves down to the non linear part of the curve, it will result an irreversible demagnetization. The machine design should be done to make sure that the magnet operates only on linear part of the curve. The flux density measurements done on the NdFeB magnet given in the Fig. 2 agrees with the specified values, though at higher temperature (>100 °C) the error is about 4 % (assumed that α_B is constant at all range of temperature).

From the Fig. 2 it can be seen that though at higher temperature B_r comes down at a faster rate, the B_r comes back to original value when cooled down.

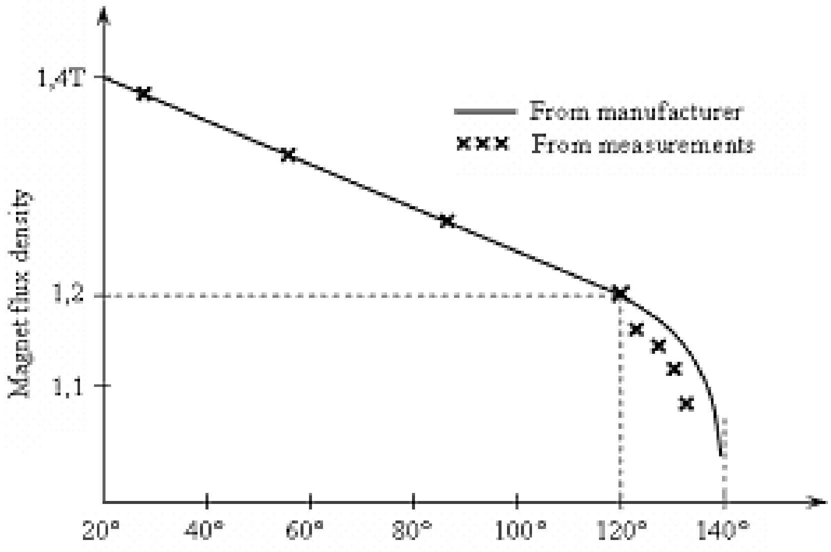

Fig. 2 – Measured magnet residual flux density.

The coefficient of utilization of the PM is defined as:

$$\xi = \frac{E_f \cdot i_{ak}}{E_r \cdot i_{ac}}. \tag{8}$$

i_{ak} is the current corresponding to the magneto motor force, and is the highest possible armature current which takes place at reversal, *i.e.*, $i_{ak} = i_{arev}$. The EMF E_r corresponds to B_r, and armature current i_{ac} corresponds to H_c.

In the Table 2 are shown the values of this coefficient for some temperature values:

Table 2

Coefficient of utilization ξ at different temperatures

20 ºC	0.7
50 ºC	0.531
80 ºC	0.457
120 ºC	0.49

The coefficient of utilization is inverse proportional with the volume of the permanent magnet.

3. FUNDAMENTAL EQUATIONS OF D.C. BRUSHLESS MOTOR

PM d.c. brushless motors use direct feedback of the rotor angular position, so that the input armature current can be switched, among the motor phases, in exact synchronism with the rotor motion. This concept is known as electronic commutation.

For a three-phase bridge inverter with six solid state switches and Y – connected motor, two phase windings are always connected in series during conduction period, e.g., for phases A and B.

$$v_1 = (e_{f\,A} - e_{f\,B}) + 2 \cdot R_1 \cdot i_a + 2 \cdot L_s \cdot \frac{\mathrm{d}\, i_a}{\mathrm{d}\, t}, \tag{9}$$

where $e_{f\,A} - e_{f\,B}$ is the line-to-line back-emf, e_{L-L}.

i_a is the armature instantaneous current, R_1 is the armature resistance per phase and L_s is the synchronous inductance per phase.

For d.c. current excitation, the voltage equation in steady state condition of a d.c. brushless motor is:

$$V_{dc} = e_{L-L} + 2 \cdot R_1 \cdot i_a^{(sq)}, \tag{10}$$

where $2R_1$ is the sum of two-phase resistances in series, and e_{L-L} is the sum of the two phase back-emf in series, V_{dc} is the d.c. input voltage supplying the inverter and $i_a^{(sq)}$ is the flat-topped value of the square-wave current equal to the inverter input current.

The back-emf contributing to the electromagnetic power is:

$$e_{L-L} = K_{edc} \cdot \Phi_f^{(sq)} \cdot n = K_{Edc} \cdot n, \tag{11}$$

where $K_{edc} = 8 \cdot p \cdot N_1$ and $K_{Edc} = K_{edc} \cdot \Phi_f^{(sq)}$.

In these relations Φ_f is the field excitation magnetic flux, N_1 is the turns in series per phase, p is the number of pole pairs and n represents the speed, in rpm.

With rated speed as the base speed, the per unit air gap torque at rated speed is (see equation 9):

$$T_\delta = e_{L-L} \cdot i_a^{(sq)} = \frac{e_{L-L}}{2 \cdot R_1} \cdot (V_{dc} - e_{L-L}). \tag{12}$$

Neglecting the saturation effects of the magnetic circuit of the machine and assuming that the temperature coefficient of B_r is constant over the entire temperature range, the back EME is proportional to the residual flux density of the magnet and can be written as follows:

$$e_{L-L} = \frac{B_{r20}}{1+\mu_{rrev}\cdot\dfrac{\delta}{L_M}}\cdot\left[1+\frac{\alpha_B}{100}\cdot(\theta_{PM}-20^{o})\right]. \tag{13}$$

On the other hand, the resistance formula of the motor armature winding temperature change is:

$$R_1 = R_{1(20^0)}\cdot[1+\Psi\cdot(\theta_w - 20^{o})], \tag{14}$$

where Ψ is the resistance temperature coefficient.

From equations (11-13), the torque capabilities of three phases small power d.c. PM brushless are given in the Fig. 3.

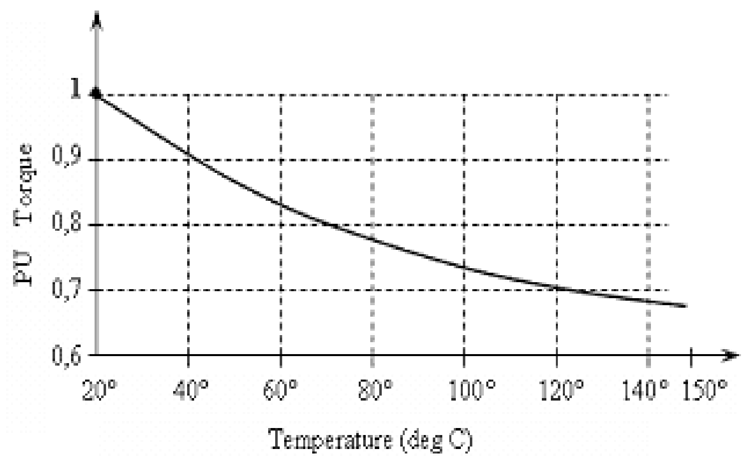

Fig. 3 – The torque capability of a PM motor neglecting saturation effects.

A tested motor with copper armature winding has the following ratings:

– rated base speed at 160 V d.c. is 1000 rpm;
– current at rated speed is 10 A;
– resistance (line-to-line) of hot machine is 0.8 Ω;
– temperature coefficient α_B of B_r at 20 to 100 °C is –0.130.

From the Fig. 3, the following conclusions may be made.

1. The slope of the torque capability of the torque versus temperature plot a strong function of armature resistance of the motor; higher resistance of the motor,

smaller is the slope of the torque-temperature plot and when resistance is less than some value the slope may be negative.

2. Neglecting mechanical and iron losses, as resistance increases the motor efficiency decreases (an increase in $i_a^2 \cdot R$ losses). If a given torque is required to accelerate a load, $e_{L\text{-}L}$ decrease and more current will be required to provide the same torque.

3. The decrease of the back emf would cause an additional fall off in speed of a motor caring rated load torque; the speed regulation constant of speed torque curve increase.

4. Because of the reduced torque capability, the frequency response of the motor is reduced; increase the mechanical time constant.

In the approximate below analysis, it is assumed that the magnetic circuit is linear and that the motor flux and the motor back EMF directly follows the magnet residual flux density. The magnetic saturation effects will make the relationship non linear.

In this case the air gap magnetic flux density is [3]:

$$B_\delta = \frac{B_r}{1 + (\mu_{rrev} \cdot \frac{\delta}{L_M}) \cdot K_{sat}}, \tag{15}$$

where the saturation factor is:

$$K_{sat} = 1 + \frac{\sum F_{fe}}{2 \cdot B_\delta \cdot \frac{L_M}{\mu_0}}, \tag{16}$$

in which $\sum F_{fe}$ is the sum of magnetic voltage drops per pole in the iron and $\mu_0 = 4 \cdot \pi \cdot 10^{-7}$ H/m.

Thus the torque capability of the motor depends of the temperature coefficient of B_r and the magnetic saturation as they determine the back EMF. With decreased magnet temperature, the residual flux density of the magnet will be increased, which creates magnetic saturation. It will result changes on the load line of the magnet. In addition, the inductance effect of the motor changes the rectangular current wave shape.

Another parameter which is of interest is the effect of temperature on motor efficiency. It is easy to conclude that the motor efficiency will come down as the temperature is increased. This is because the increase in resistance and the reduction in the back EMF, with increased temperature results in reduced efficiency of the motor. The efficiency corresponding to the torque point in Fig. 3 is given in Fig. 4.

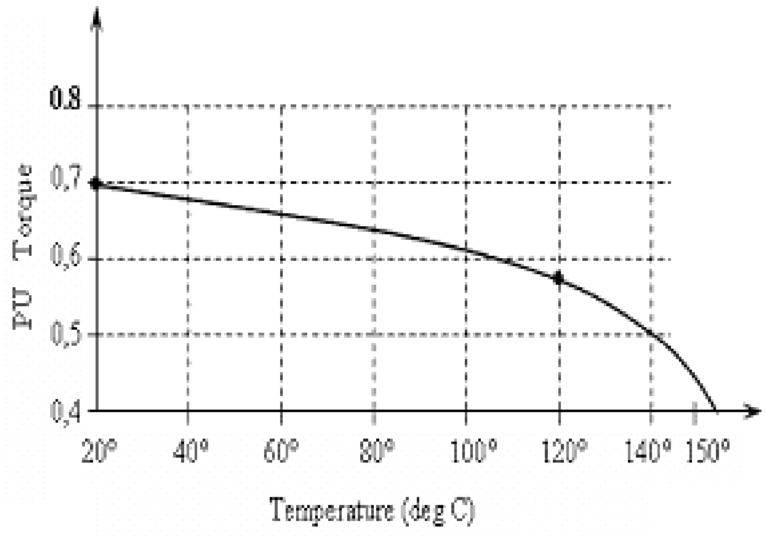

Fig. 4 – Efficiency vs. temperature [2].

In the above analysis it is assumed that the magnet and copper winding are at the same temperature**.** This is somewhat true in the case of machines which operate at very low duty cycle. In most of the other cases the copper temperature will be above the magnet temperature. It is note that a small temperature difference between the winding and magnet has only minimum effects on the efficiency (the main demanded for cooling system of the PM NdFeB motor).

In several applications as the armature heats up, the current must be reduced to avoid exceeding the rated armature dissipation [5].

The "hot" current found to be:

$$i_{ah}^{(sq)} = \frac{i_a^{(sq)}}{\sqrt{1 + \Psi_{Cu} \cdot (\theta_w - 20^{\circ})}}. \tag{17}$$

In this case, the ratio a "hot" torque to "cold" torque will be:

$$\frac{T_{\delta k}}{T_{\delta c}} = \frac{1 + \frac{\alpha_B}{100}\left(\theta_{PM} - 20°\right)}{\sqrt{1 + \Psi_{Cu}\left(\theta_w - 20°\right)}}. \tag{18}$$

4. **CONCLUSIONS**

The study shows that the effect of elevated temperature on the demagnetization characteristic is usually to degrade the performance of the motor: firstly by decreasing the magnet flux and therefore the torque; secondly, by requiring the operating current to be limited because of the upward migration of the knee-point into the second quadrant.

At a higher efficiency, motor has a positive slope to the torque-temperature characteristics. On the other hand, the efficiency decreases with the temperature and this variation is influenced by the magnetic saturation.

To obtain a constant torque from a PM motor over a wide temperature range, a temperature compensation to adjust the current is required.

The discussion in this paper was concentrated on PM motors with trapezoidal back EMF waveform at low speed. The idea could be extended in others PM motor types.

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