Sensorless Rotor Temperature Estimation of Permanent Magnet Synchronous Motor

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Abstract – **The work proposes a method for estimation of the magnet temperature in permanent-magnet synchronous machines by exploiting the d-axis saturation effects in the steel stator core produced by the d-current and rotor flux excitation. The method implies an intermittent injection of a voltage pulse in the d-axis of the motor. The resulting d-current response is a function of both the initial value of the d-current itself and the magnetization level of the magnets. Thus, a temperature dependent variation in the magnetization level of the permanent magnets is reflected in a variation of the d-current slope upon the voltage pulse. Experimental validation of the method is demonstrated with surface permanent-magnet motor.**

Index Terms—**magnet temperature, rotor temperature, permanent-magnet synchronous motor, saturation effects, voltage pulse injection**

I. Introduction

Due to their high power density, good efficiency and high dynamics, permanent-magnet synchronous machines (PMSM) have found a wide acceptance especially in the automotive industry concerning developments of electric and hybrid electric vehicles. In such applications the machine operating temperatures can vary between -40°C and 150°C. In this temperature range modern rare-earth magnets, predominantly used in the manufacturing of PMSM, experience variation of the magnetization level of up to 20%. As the temperature increases, a partial demagnetization occurs in the magnet. This process is reversible as long as the magnetizing force does not reach the intrinsic coercivity level. Reversibility means that the flux density will grow to its original value when the temperature is reduced again. The intrinsic coercivity level is a function of the temperature itself since it decreases by increasing the temperature. Thus the critical temperature, above which the demagnetization is no longer reversible, is a function of the magnet and the operating load line of the magnet, [1], [2]. Therefore the motor should be designed such that the expected operating temperature is below the critical one, [3]. If the temperature of the permanent magnets could be monitored under operating conditions, an optimized design of the machine can be achieved avoiding over-dimensioning while assuring safe operation mode, [4].

The knowledge of the magnet temperature is not only important to prevent irreversible demagnetization of the machine but also plays a significant role in torque control of PMSM. This issue is discussed in details in [5]. A decrease of rotor flux linkage due to a temperature dependent demagnetization effects will lead directly to a lower electromagnetic torque output.

Obtaining the rotor temperature in ac machines can be done by direct temperature measurements or indirectly by identification of motor parameters. Although direct temperature measurements techniques can give very precise temperature distribution in the rotor, their application is strictly limited to laboratory and experimental setups as they are rather suitable for verification work than for normal industrial usage. An overview of different approaches considering contact and non-contact measurement techniques is given in [6].

Indirect temperature estimation is based on three major approaches: thermal models, flux observers and active parameters estimation.

- Thermal models imply good knowledge of the geometry, cooling system and especially on the material specific parameters. Their application is rather limited to industrial usage with known environmental and operating conditions, [7]-[12].
- Flux observer method is successfully presented in [4] where by estimating the amount of demagnetization the rotor temperature can be obtained. This requires an accurate modeling of the nonlinearities of the inverter. The nonlinear relation between current and flux is defined by look-up-table (LUT). Furthermore a precise acquisitioning of the machine and inverter parameter is required.
- Active parameter estimation method by using high frequency signal injection is demonstrated in [13]. This approach is based on changes in the high frequency stator and rotor resistances due to temperature variation and concludes indirectly the temperature level in the permanent magnets. The robustness and accuracy of the method is strongly influenced by the non-ideal behavior of the inverter (dead time, dc bus voltage variation etc.), [13].

This paper presents a novel temperature-sensorless and robust technique for estimation of the temperature of permanent magnets of PMSM by indirectly exploiting the variation of the saturation level of the machine, caused by temperature dependent demagnetization. Experimental results on an interior (IPMSM) and surface permanent-magnet synchronous motor (SPMSM) are given to demonstrate basic relationships and applicability of the method.

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II. Basic Relationships of the Proposed Method

The influence of the permanent magnet flux density on the saturation effects in a steel stator core is the highest in the d-axis of the motor. The basic idea of the proposed method is to exploit this relationship by assuming that a variation in the magnetization of the permanent magnets will have the highest effect on saturation of the stator in the d-axis. By applying a voltage pulse in the d-axis of the motor, the resulting current response is evaluated and used indirectly as indicator for the magnetization and consequently as indicator for the temperature in the permanent magnets.

Fig. 1 shows the demagnetization curves of the permanent magnets used in the IPMSM under test. It illustrates the temperature dependence of the flux density at various operating conditions, [1]. The operating point of the magnets is defined by a load line. For a given load line the slope defines how strong the magnetization will vary upon temperature (Fig. 1). For the motor under test the load line is not known. In order to quantify a variation of the magnetization upon temperature, the stator flux linkage is measured at no-load as a function of the permanent magnets temperature. The obtained results are shown in Fig. 2.

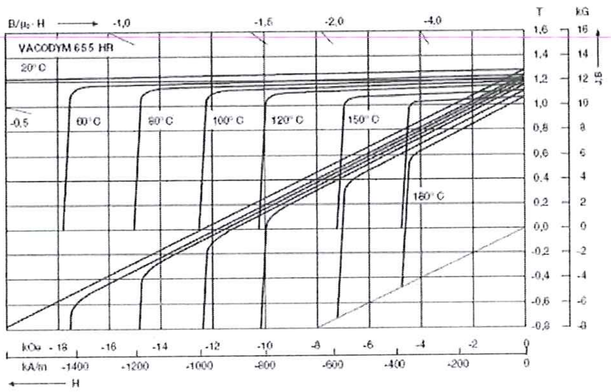


Fig. 1. Demagnetization curves data sheet of the Nd-Fe-B magnets used in the IPMSM under test (source Vacuumschmelze).

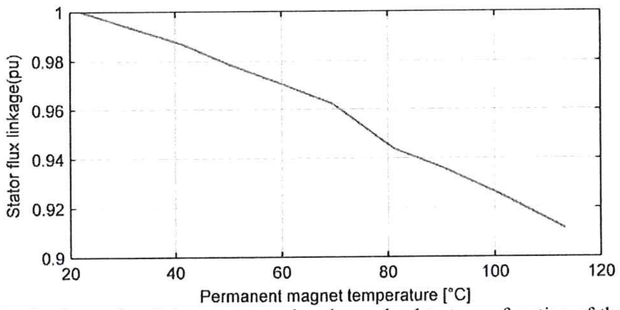


Fig. 2. Stator flux linkage measured under no-load test as a function of the temperature of the permanent magnets

In the following, an experimental setup is described that is carried out to visualize the basic relationships of the proposed method. As it is illustrated in Fig. 3, the d-axis of the rotor is aligned with the α-axis of the stator winding. This can be achieved by simply applying a stationary, not rotating, voltage space vector with zero degree angle and amplitude to produce as much as enough a current space vector to align the magnets with the motor phase **a**. Thus, it is assured that the magnetic axis of stator phase winding **a** is maximum magnetized by the rotor flux. At this position of the rotor, a voltage pulse with magnitude of 2/3 the dc bus voltage V_{dc} is applied in the pure d-direction of the machine by an inverter switching scheme depicted in Fig. 3. It should be noted here that by a corresponding rotor position, d-voltage pulse can be achieved by any of the 6 basic space vector switching patterns. The duration of the voltage pulse is selected for this experiment as much as 240μs for the sake of better visualization of the effects. The time trace of the resulting d-current i_d is measured at various temperatures of the permanent magnets as shown in Fig. 4.

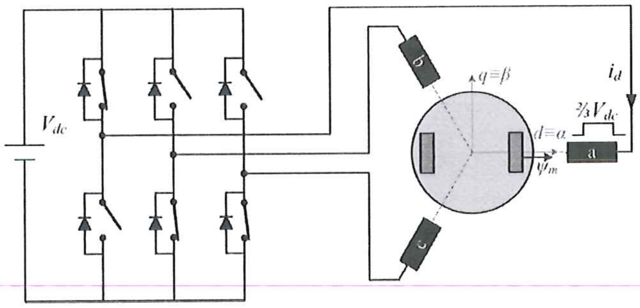


Fig. 3. Voltage pulse injection upon aligned stator and rotor reference frame at stand still

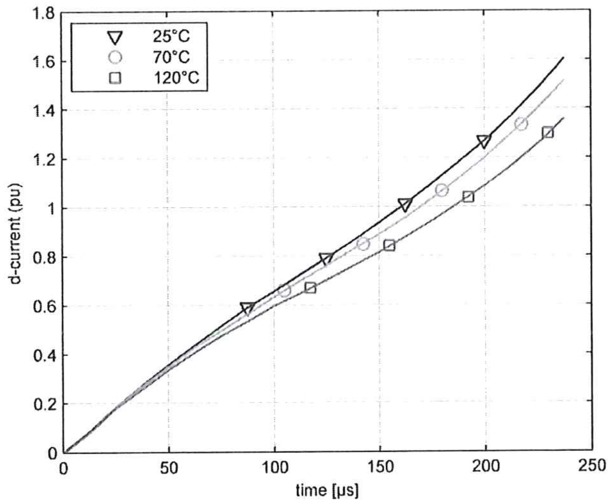


Fig. 4. D-current measured upon voltage pulse with amplitude of 2/3 V_{dc} and duration of 240μs. The motor under test is an IPMSM with aligned stator and rotor reference frame.

The obtained curves demonstrate two basic phenomena:

- The gradient of the current curve increases due to an increase in the level of saturation. Consequently the level of the d-inductance L_d drops. This is a non-linear function of the additional stator flux linkage produced by the d-current i_d excitation.
- The gradient of the current curve decreases while the temperature rises. The portion of stator flux linkage

produced by the permanent magnet flux goes down. This effect is provoked by a temperature dependent demagnetization of the permanent magnets (Fig. 2).

It can thus be concluded that the d-current slope $\Delta i_d/\Delta t$ is a function of the d-current i_d itself and the temperature of the permanent magnets T_m as given in (1):

$$\frac{\Delta i_d}{\Delta t} = f_{i_q=0}(i_d, T_m) \tag{1}$$

By inverting (1) a relation for T_m is obtained.

$$T_m = f_{i_q=0}\left(i_d, \frac{\Delta i_d}{\Delta t}\right) \tag{2}$$

Since this is a strongly non-linear relationship, identification of (2) has to be done by measurements. The degree of non-linearity depends strongly on the construction type and especially on the size of the effective air gap of the machine. A bigger air-gap will reduce the effect of i_d in (2), resulting in a better linear behavior of (2).

III. DEFINITION OF THE PROPOSED METHOD

The proposed method assumes that in a rotating machine, a voltage pulse is applied in the d-axis while measuring the d-current i_d. The saturation level of the machine experiences the highest effect of the permanent magnet magnetization level in its d-axis namely. This setup implies on the one hand the highest dependency of the d-current slope $\Delta i_d/\Delta t$ from the permanent magnet magnetization level and on the other hand $\Delta i_d/\Delta t$ is not influenced by the back electromotive force. By a corresponding switching pattern a voltage pulse can be generated in the pure d-axis of the machine when the angle between the stator and rotor reference frames θ_r equals one of the 6 basic space vectors angles ($\theta_r = 0°, 60°, 120°, 180°, 240°, 300°$). For the sake of clarity, for the definition and implementation of the method $\theta_r = 0°$ is considered. Thus, by aligning the dq-rotor reference frame with the $\alpha\beta$-stationary reference frame of the stator, the following relationships for the stator voltage and current components are fulfilled:

$$u_d = u_\alpha;\;\; u_q = u_\beta;\;\; i_d = i_\alpha;\;\; i_q = i_\beta \tag{3}$$

As the method requires a voltage pulse injection in the d-axis, which means $u_q = u_\beta = 0$, the motor voltage equation becomes

$$u_d = R_s(i_d + ji_q) + j\omega_r\psi_m + \frac{d}{dt}(L_d i_d + jL_q i_q) \tag{4}$$

where R_s is the stator resistance, ψ_m is the flux linkage produced by the permanent magnets, ω_r is the speed of the rotor reference frame with respect to the stator reference frame, and L_d and L_q are the inductances in the d- and q-direction of the machine respectively. Equation (4) is then decomposed in its real and imaginary components:

$$u_d = R_s i_d + \left(\frac{dL_d}{di_d} i_d + L_d\right)\frac{di_d}{dt} \tag{5}$$

$$-\omega_r\psi_m = R_s i_q + \left(\frac{dL_q}{di_q} i_q + L_q\right)\frac{di_q}{dt} \tag{6}$$

Equation (5) and (6) describe the momentary state of the machine when the rotor and stator reference frames are aligned. It is assumed here that there are no cross-coupling effects between L_d and L_q. The proposed method exploits the resulting relationship from (5) by neglecting the stator resistance voltage drop. Thus, equation (5) becomes

$$u_d = L_d'\frac{di_d}{dt} \tag{7}$$

$$L_d' = \frac{dL_d}{di_d} i_d + L_d\,. \tag{8}$$

L_d' depends on the d-axis saturation level of the machine which is in turn influenced by the magnetization level of the permanent magnets. According to (7), by directly measuring the d-current slope di_d/dt, variation of L_d' can be detected. Thus, di_d/dt will change upon changes in the magnetization level of the magnets and can be used as indicator for the magnet temperature. Since (8) has a non-linear character, a distinctive relationship between di_d/dt and T_m for a given machine can be established by using a look-up-table (LUT). This is identified during a commissioning phase by direct measurements of T_m and di_d/dt.

In a rotating machine the proposed method requires the knowledge of the rotor position, either using a rotor position sensor or a sensorless method, so that the d-axis can accurately be traced. Upon alignment with the stator reference frame, a voltage pulse is injected in the d-axis to produce a rise in the d-current i_d. It is assumed here that during the voltage pulse, the change in the rotor position is negligible.

IV. METHOD IMPLEMENTATION AND CONTROL INTEGRATION

In a practical implementation of the method and its integration into a control strategy, the injected voltage pulse width t_{pw} plays a significant role for both, the performance of the motor and the sensitivity of the method. For a given machine, a trade-off should be found where the pulse width is as small as possible for minimum influence on the produced motor torque but enough to provide sufficient current rise that distinctively reflects variations in the rotor demagnetization. For this particular validation setup, injected voltage pulse width t_{pw} smaller than or equal the pulse width modulation (PWM) period PWM_{prd} is considered. On the one hand, this simplifies the practical programming of the proposed algorithm and on the other hand the resulting t_{pw} provides acceptable sensitivity in the validation process as it will be demonstrated later by the obtained experimental results. It should be noted here that the operating PWM frequency for the inverter is set to 20KHz which means $t_{pw} \leq 50\mu s$.

The electrical rotor position is denoted here with θ_{el}. Detecting the d-axis is then confined to predicting the moment when $\theta_{el}=0$ in a rotating machine. According to the adopted strategy here, the voltage pulse generation procedure is activated such that $\theta_{el}=0$ will occur in the middle of the PWM period (Fig. 5). A software module, called d-axis tracer

(Fig. 6), continuously observes the absolute mechanical rotor position θ_m and predicts θ_{el} with respect to the middle of the next PWM period following the execution of the module by applying the following calculation:

$$\theta_{el} = \theta_{el(n)} + \frac{3}{2}\Delta\theta_{el(n)} + \Delta\theta_{el(n)}\frac{\tau_{DT}}{2} \qquad (9)$$

where

$$\Delta\theta_{el(n)} = \theta_{el(n)} - \theta_{el(n-1)}$$

$$\tau_{DT} = \frac{t_{DT}}{PWM_{prd}}$$

The last term of (9) accounts for the inverter dead time t_{DT}. It should be noted here that a synchronized capturing of the absolute rotor position θ_m with respect to the beginning of a PWM period is essential otherwise (9) would not be valid in this form. Furthermore it is assumed that change in the machine speed from one PWM period to the next is negligible ($\Delta\theta_{el(n+1)} = \Delta\theta_{el(n)}$).

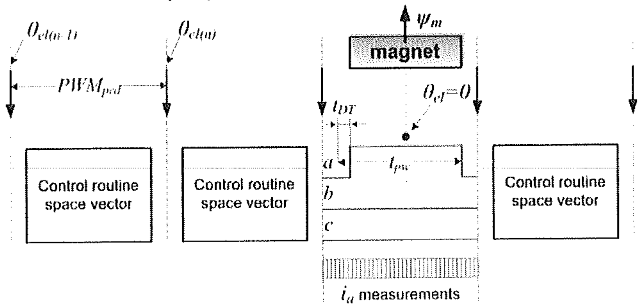


Fig. 5. Time scheduling of the control algorithm and the temperature estimation.

The integration of the voltage pulse generation algorithm into a conventional field oriented control schema (FOC) is demonstrated in the Fig. 6. The d-axis tracer sets a flag upon θ_{el}=0, which in a combination with a start command forces interruption of the running control routine and activates the d-axis voltage pulse generator for the following PWM period.

Synchronously to the injected voltage pulse in the phase a of the motor, measurements of the phase current i_a are triggered for the duration of the PWM period, see Fig. 5 and Fig. 6. The sample rate for i_a is set to 250ns. The initial value of i_a upon beginning of a PWM period, where θ_{el}=0, is assumed to be equal the d-current reference component $i_{d(ref)}$, given by the control circuit, i_a=$i_{d(ref)}$. Different initial values for i_d mean different initial saturation levels in the d-axis of the motor (Fig. 4). Thus, for the proposed implementation there are two tuning parameters that define the operating point of the method and consequently its sensitivity: $i_{d(ref)}$ and the injected voltage pulse width t_{pw}. The dc bus voltage V_{dc} is assumed to be constant.

Under normal operation conditions, it is expected that the permanent magnets together with steel rotor core have a high thermal constant so the temperature veries relatively slowly. Thus, the proposed control routine interruption for the temperature estimation will be triggered at intervals of one minute or longer. Thus, the eventual negative effects on the machine performance under normal operation will be minimized.

The proposed algorithm together with the current slope measurements are implemented on single floating point DSP (C6747) in combination with analog-digital converters (ADS8422 - 16bit resolution, 4MSPS).

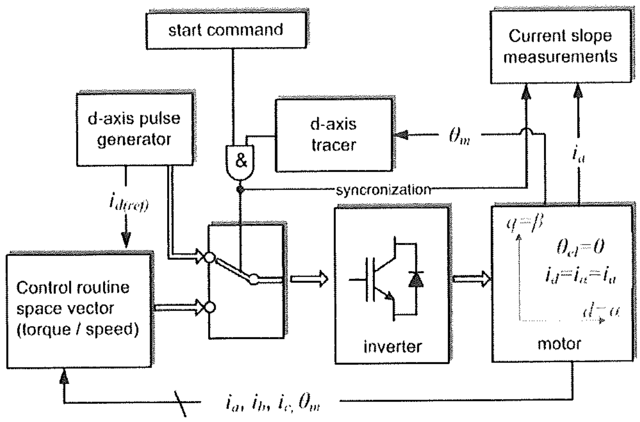


Fig. 6. Block diagram of the control algorithm.

V. DIRECT ROTOR TEMPERATURE MEASUREMENTS

For an accurate verification of the proposed method, specially designed rotor temperature measuring device is used [6]. The instrumentation is based on contact measurements using thermocouples, a microcontroller for the data processing and infrared optical link for data transmission between the rotating and the stationary part. Up to 12 sensors can be sampled simultaneously with frequency of 10Hz. The rotating circuit is powered by PP3 9V rechargeable battery that provides an effective continuous operation time of about 8 hours. A hollow shaft is used to conduct the wires of the thermocouples up to the instrumentation, (Fig. 7). The accuracy of the measured temperature signals is about ± 1.5°C. For this particular verification setup, temperature sensors directly mounted on the permanent magnets are considered.

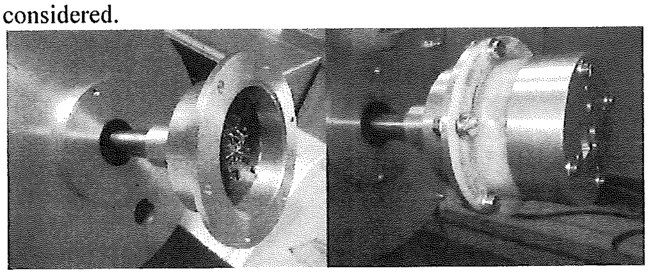


Fig. 7. Contact rotor temperature measuring device used for verification of the proposed method.

VI. EXPERIMENTAL VERIFICATION OF THE METHOD

For the verification process a SPMSM is chosen since it is considered more suitable for the developed method compared to an IPMSM according to the assumptions made in section

III. Generally a SPMSM has a large effective air-gap, which results in small stator reactance and small electric time constant. Further important consequence of the large air-gap is the reduced effect of saliency, therefore it can be assumed $L_d \approx L_q$. The motor parameters under test are listed in Table I.

TABLE I
PARAMETERS OF THE SPMSM UNDER TEST

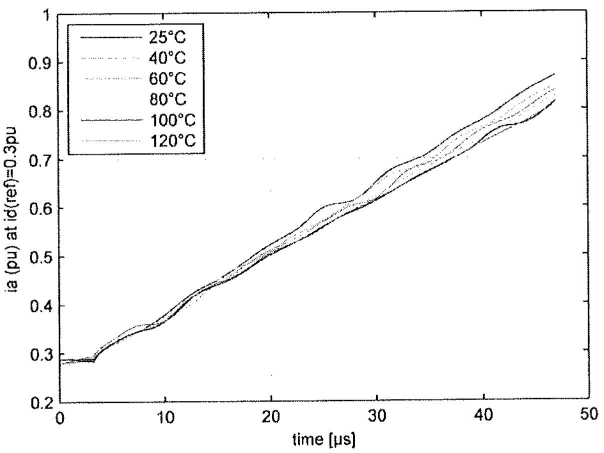
Nominal voltage	480V
Nominal current	23 A
Nominal frequency	400 Hz
Nominal speed	6000 rpm
Winding Resistance	0.32 Ω
Winding Inductivity	2.6 mH

The motor is operated at speed of 2000rpm at no load and PWM operating frequency is set to 20KHz. The effective time duration of the injected voltage is set 45μs. The current rise of i_a is then measured at various permanent magnet temperatures and for a given d-current initial value, $i_{d(ref)}$. The obtained current curves are linearized by polynomial interpolation

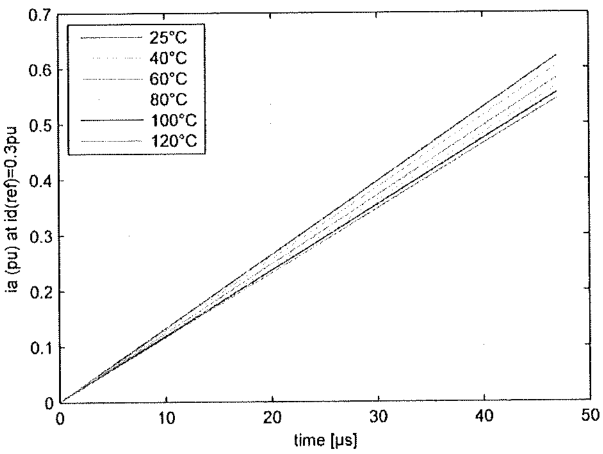
$$y(x) = ax + b \tag{10}$$

where the weighting factor a represents the estimated slope of the corresponding curve $\Delta i_a/\Delta t$ and the offset b represents $i_{d(t=0)}$.

For $i_{d(ref)}=0.3$ of the motor nominal current, the measured phase current i_a upon injected voltage pulse at various temperatures of the permanent magnets is shown in Fig. 8a and the corresponding linearized curves by eliminating the offset are shown in Fig. 8b. As it is observed, the current slope $\Delta i_a/\Delta t$ is a function of the permanent magnet temperature, (Fig. 9). The current slope $\Delta i_a/\Delta t$ decreases, since the d-axis saturation will drop upon demagnetization of the magnets caused by temperature rise. Thus, by quantifying variations of $\Delta i_a/\Delta t$ an indicator for the actual temperature of the permanent magnets is obtained. Since $\Delta i_a/\Delta t$ does not change linearly (Fig. 9), a LUT should be considered.



a)



b)

Fig. 8. Current i_a response upon voltage pulse temperature estimation with d-current initial value $i_{d(ref)}=0.3pu$; a) actual current measurements with 250ns sample rate; b) linearized current curves by polynomial interpolation with eliminated offset.

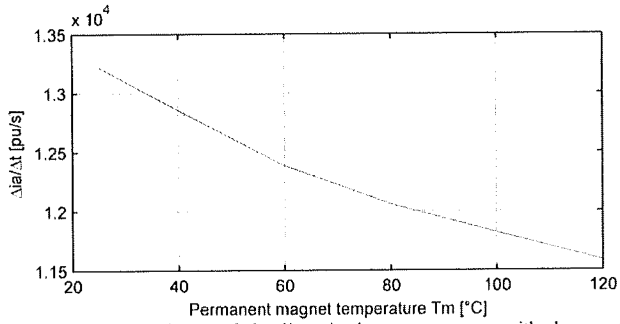


Fig. 9. Estimated slopes of the linearized current curves with d-current initial value $i_{d(ref)}=0.3pu$ as a function of the permanent magnet temperature

Measurements under the same condition but at different d-current initial values, $i_{d(ref)}= 0.0 / 0.2 / 0.3 / 0.4 / 0.5pu$, are carried out. By comparing the deviations between the maximum (T_m=25°C) and minimum (T_m=120°C) values of $\Delta i_a/\Delta t$ as a function of $i_{d(ref)}$, an operating point of the method can be selected for a desired sensitivity and performance. For the motor under test, the highest deviation of the current slope $\Delta i_a/\Delta t$ occurs at $i_{d(ref)}=0.2$ and $i_{d(ref)}=0.3$ (Fig.10), which implies the highest sensitivity of the method at these points for this machine.

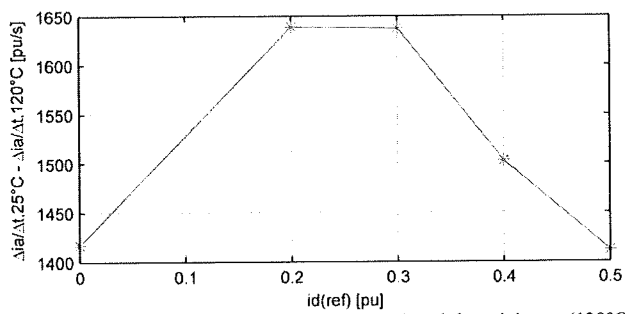


Fig. 10 Deviation between the maximum (25°C) and the minimum (120°C) values of the estimated current slopes as a function of d-current initial value $i_{d(ref)}$.

VII. DISCUSSIONS AND PERSPECTIVES

The presented method inevitably introduces certain performance degradation in the machine. Subject of ongoing research is to investigate the torque ripples due to the d-axis voltage pulse. The problematic is even more distinctive in the case of IPMSM, where $L_d \neq L_q$, as this implies reluctance component in the electromagnetic torque. The verification of the method is so far carried on at no-load. In future work, the attention will concentrate on investigating the saturation effects produced by the q-current i_q in the d-axis in order to identify the method dependency of i_q. A special attention will be paid on IPMSM as the combination of saturation effects due to the three excitation sources (magnets, i_q, i_q) is relatively complex, [14].

Potential sources for errors in the method are indentified in the accuracy of tracing the d-axis at higher speeds and the assumption to neglect the stator voltage drop in Eq. (8). However, the last can be easily compensated by knowledge of the stator temperature, which is meanwhile state-of-the-art in modern machines.

VIII. CONCLUSION

An estimation of the permanent magnet temperature in PMSM has been achieved by exploiting the saturation effects in the d-axis of the motor. The presented method uses a relationship between the variation of the d-inductance of the motor and the magnetization level of the permanent magnets due to temperature variation. Thus, a d-current response due to a voltage pulse applied in the pure d-direction of the motor is associated with a distinctive temperature level in the magnets. Performance and sensitivity issues of the method have been addressed and experimental verification on SPMSM has been demonstrated. Tuning, improvements and extended applicability of the method are subjects of ongoing research.

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