Sensorless Rotor Temperature Estimation of Permanent Magnet Synchronous Motor under Load Conditions

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***Abstract* –The work proposes a method for estimating the magnet temperature in permanent magnet synchronous machines (PMSM's) under load conditions. The method implies an intermittent injection of a voltage pulse in the positive and negative d-axis of the motor. Thus, the difference of the resulting d-current responses depends on the machine operating point which is defined by the d-current, the q-current and the actual magnetization level of the permanent magnets. Since the magnetization of the magnets depends on the temperature, different d-current slopes reflect different temperature levels of the magnets. By applying a voltage pulse in the positive and negative d-axis of the motor, symmetry of the induced voltages can be achieved in a manner that the difference of the current responses from the positive and negative pulse is to a great extent speed independent.**

***Index Terms*-- Condition monitoring, permanent magnet machines, rotor temperature, magnet temperature estimation, saturation effects.**

I. INTRODUCTION

THE most widely-used rare-earth magnet in permanent magnet synchronous machines (PMSMs) is neodymium-iron-bore (NdFeB). This type of magnet characterizes with high intrinsic coercivity (H_{ci}) and big maximum energy product (BH_{max}). Thus, PMSMs manufactured with NdFeB-magnets reveal comparatively high power density. The motor size is significantly reduced by maintaining an excellent torque capability. A drawback of the magnet is its relatively low resistivity that gives rise to considerable eddy current losses especially when the motor is driven by pulse-width-modulated (PWM) inverter. In high torque and speed operation, eddy current and hysteresis losses are responsible for an abundant temperature rise in the magnets, [1]-[4]. While the temperature of the magnet increases, its remanent flux density B_r decreases. This process is reversible as long as the demagnetizing force does not reach the area of the intrinsic coercivity. Reversibility means that B_r will grow to its original value when the temperature is reduced again. In the motor, a decrease of the rotor flux linkage due to temperature dependent demagnetization will lead directly to lower electromagnetic toque output [5]. In torque control, this can be compensated either by a flux observer or indirectly when the temperature of the magnets is known, however more current is required.

The knowledge of the magnet temperature is not only a control issue but also a safety issue. The magnet intrinsic coercivity is a function of the temperature itself, as its absolute value decreases while the temperature rises. Therefore, at higher temperatures, excessive currents in the machine can lead to irreversible demagnetization of the magnets [6]. In general, the machine design should ensure that no irreversible demagnetization will occur in the machine under the expected operating conditions [7]. However, machine over-dimensioning can be avoided, if online magnet temperature estimation is available to assure continuous safe operation mode.

Due to rotation, measuring directly the temperature of the permanent magnets is very cumbersome. The most common techniques include battery powered devices [8]-[16], infrared sensors, [17]-[20], and slip rings, [21],[22]. Carrying out such measurements is rather expensive and their application is limited to laboratory and experimental setups since specific instrumentation is normally required. Therefore, significant efforts have been performed recently to develop techniques which do not require any temperature sensors to obtain the rotor temperature in PMSMs. Such techniques have been already reported in various papers. The most common approach is a thermal model of the machine. 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. Various issues of PMSM thermal modeling are discussed in [23]-[30]. An algorithm to estimate rotor temperature by using flux observer is successfully presented in [31]. This method requires an accurate modeling of the nonlinearities of the inverter. The nonlinear relation between current and flux is defined by a look-up-table (LUT). Furthermore a precise acquisitioning of machine and inverter parameters is required. An active parameter estimation method by using high frequency signal injection is demonstrated in [19] and [20]. 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.).

In this context, the paper focuses on a novel temperature-sensorless technique for estimation the temperature of the

permanent magnets of PMSM. The main idea of the method is to detect changes in the degree of saturation in the d-axis of the machine which are caused by variation in the magnetization level of the permanent magnets. These changes are reflected in the slope of the d-current response upon a voltage pulse in the d-axis of the machine, [32]. However, due to cross-coupling effects in the machine, the d-current response is also dependent on the q-current, since the q-current saturates additionally the d-axis of the motor. The present work investigates the influence of the q-current on the d-current response and presents a compensation approach that makes the proposed method suitable for applications where the q-current cannot be set to zero during temperature estimation procedure. The experimental results are validated on an interior permanent magnet synchronous machine (IPMSM).

II. Basic Principles

The influence of the magnet excitation on the saturation level of a stator steel laminated core is the strongest in the d-axis of the motor. Therefore, the presented method proposes that in a rotating machine a voltage pulse is applied in the d-axis while the d-current is measured. Thus, the resulting d-current response predominantly reflects saturation effects due to stator flux linkage produced by the q-current, d-current and the permanent magnet excitation. Assuming that the magnet magnetization level depends on the magnet temperature, T_m, the following relationship can be derived:

$$\frac{\mathrm{d}i_d}{\mathrm{d}t} = f(i_q, i_d, T_m) \qquad (1)$$

Since this is a strongly non-linear relationship, identification of (1) 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. In machines with big effective air gap, as it is the case in surface permanent magnet synchronous machine (SPMSM), the cross coupling inductances are lower than in IPMSM which reduces naturally the influence of the q-current in (1).

Using a common three-phase two-level bridge inverter, a corresponding switching pattern can generate a voltage pulse in the pure d-axis of the machine when the angle between the stator and rotor reference frames θ_{el} equals one of the 6 basic space vectors angles ($\theta_{el} = 0°, 60°, 120°, 180°, 240°, 300°$). For the sake of clarity, for the definition and implementation of the method $\theta_{el} = 0°$ is considered, as shown in Fig. 1. In a rotating machine, the voltage pulse is applied in phase ***a*** of the machine such that the electrical rotor position gets zero ($\theta_{el} = 0°$) in the middle of the pulse, as depicted in Fig. 2. The angles ($\theta_{el0}, \theta_{el1}$) between the rotor and stator reference frames at the time instant of the beginning t_0 and the end t_1 of the pulse for a given machine with p poll pairs depend on the speed n [rps] and the voltage pulse width t_{pw} [s], (2).

$$\theta_{el0} = \theta_{el1} = \frac{1}{2} 360° p n t_{pw}\,, \qquad (2)$$

As long as the θ_{el0} and θ_{el1} are kept small, the following relationships for the stator voltage and current components are fulfilled during the voltage pulse:

$$u_d \approx u_\alpha;\;\; u_q \approx u_\beta;\;\; i_d \approx i_\alpha;\;\; i_q \approx i_\beta \qquad (3)$$

Originally the proposed method was first reported in [32] with focus to the condition that during the voltage pulse the q-current is zero ($i_q = 0$). This simplifies significantly the relationship expressed in (1), since cross-coupling effects can be neglected. In the present analyses, the q-current is no longer considered zero and an approach for a q-current compensation in (1) is proposed in the following.

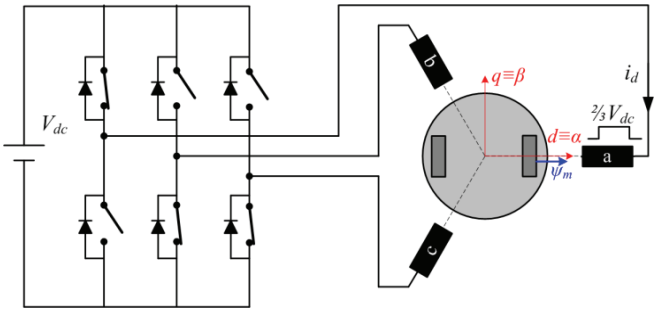


Fig. 1. Voltage pulse injection in the d-axis of the machine at θ_{el}=0°.

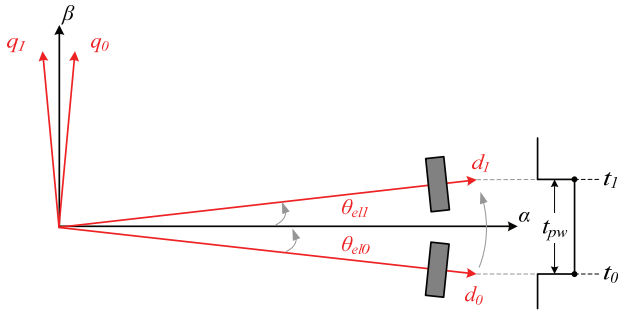


Fig. 2. Voltage pulse injection in a rotating machine; relative displacement of the d-axis along the voltage pulse duration.

III. Q-Current Compensation

Upon a voltage pulse in the d-axis of the motor, the actual q-current i_q influences the resulting d-current response di_d/dt in two different ways:

- The effective voltage in the d-axis of the motor is strongly dependent of the q-current over the speed. Thus, di_d/dt is directly affected by i_q.
- Due to cross-saturation phenomenon, the q-current influences the saturation level in the d-axis of the motor and affects indirectly di_d/dt.

A. *Effective Voltage in the D-axis of the Motor upon Pulse Injection*

For further machine analyses upon a voltage pulse generation, the motor voltage equations in the rotor reference frame are discussed first:

$$u_d = R_s i_d + L_{dd}^* \frac{di_d}{dt} + L_{dq}^* \frac{di_q}{dt} - \omega L_{qq} i_q - \omega L_{qd} i_d \qquad (4)$$

$$u_q = R_s i_q + L_{qq}^* \frac{di_q}{dt} + L_{qd}^* \frac{di_d}{dt} + \omega L_{dd} i_d + \omega L_{dq} i_q + \omega \psi_m \,, \tag{5}$$

where R_s is the stator resistance, ψ_m is the flux linkage produced by the permanent magnets, ω is the speed of the rotor reference frame with respect to the stator reference frame, and L_{dd} and L_{qq} are the inductances in the d- and q-direction of the machine respectively. The inductances L^* are the differential inductances with respect to the currents:

$$L_{dd}^* = L_{dd} + \frac{dL_{dd}}{di_d} i_d \tag{6}$$

$$L_{dq}^* = L_{dq} + \frac{dL_{dq}}{di_q} i_q \tag{7}$$

$$L_{qq}^* = L_{qq} + \frac{dL_{qq}}{di_q} i_q \tag{8}$$

$$L_{qd}^* = L_{qd} + \frac{dL_{qd}}{di_d} i_d \tag{9}$$

Assuming star connection of the motor, upon positive voltage pulse in the d-axis, $u_d = 2/3V_{dc}$ and $u_q = 0$, where V_{dc} is the inverter dc voltage. Thus, from (4) the following relationship for the d-current slope di_d/dt can be obtained:

$$L_{dd}^* \frac{di_d}{dt} = \frac{2}{3} V_{dc} - R_s i_d - \overbrace{L_{dq}^* \frac{di_q}{dt}}^{Term\ 1} + \overbrace{\omega L_{qq} i_q}^{Term\ 2} + \overbrace{\omega L_{qd} i_d}^{Term\ 3} \tag{10}$$

The differential inductance L_{dd}^* depends strongly on the d-axis saturation level of the machine which is in turn influenced by the magnetization level of the permanent magnets and the q-current i_q. Thus, when $i_q = const$, di_d/dt will change upon changes in the magnetization level of the magnets and can be used as indicator for the magnet temperature T_m. However, di_d/dt is strongly speed dependent according to (10), since the amplitude of the resulting effective voltage working on the d-axis of the motor upon pulse generation predominantly depends on the q-current i_q and the speed ω.

The speed dependency of di_d/dt can be eliminated by considering not only a positive ($u_{dP} = 2/3V_{dc}$) but also a negative ($u_{dN} = -2/3V_{dc}$) voltage pulse at the same q-current ($i_{qP} \approx i_{qN}$). This creates symmetry which eliminates *Term 1* and *Term 2* from (10) in (11).

$$L_{dd}^* \frac{d(i_{dP} - i_{dN})}{dt} = \frac{4}{3} V_{dc} - R_s (i_{dP} - i_{dN}) + \omega L_{qd} (i_{dP} - i_{dN}) \tag{11}$$

Thus, the difference of the d-current responses of the positive and negative voltage pulse $d(i_{dP} - i_{dN})/dt$, according to (11), is affected only by one speed dependent term which in turn depends on the d-currents i_{dP}, i_{dN}. The stator resistance voltage drop together with the speed dependent term can be neglected in (11) for most machines. The difference of the d-current responses $d(i_{dP} - i_{dN})/dt$ reflects distinctive changes in the magnetization level of the magnets while the q-current is constant.

B. Operating Point Considerations

Due to cross-saturation effects, the q-current creates flux in the d-axis of the motor contributing to the overall saturation level in this axis. Fig. 3 demonstrates a simplified presentation of flux saturation effects that occur in the machine upon voltage pulse injection in the d-axis. From the saturation point of view, the difference of the d-current responses $d(i_{dP} - i_{dN})/dt$ is strongly dependent of i_q, the operating point of the machine. The relationship between $d(i_{dP} - i_{dN})/dt$ and i_q can be identified by measuring $d(i_{dP} - i_{dN})/dt$ as a function of i_q at a constant magnet temperature ($T_m = const$), in order to guarantee constant permanent magnet excitation.

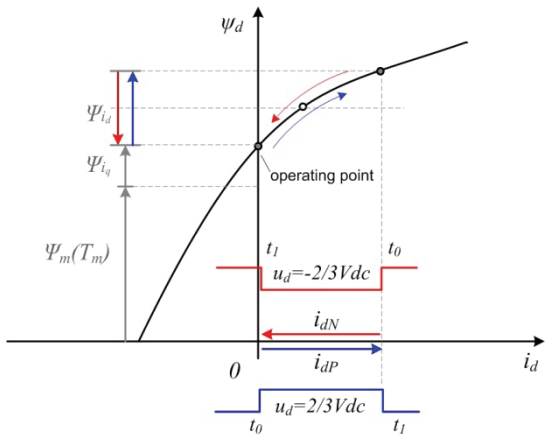


Fig. 3. Flux saturation effects in the d-axis of the motor due to permanent magnet, d- and q-current excitation upon voltage pulse generation

Upon a positive voltage pulse injection, the d-current i_{dP} increases and consequently the d-current excitation ψ_{id} in the d-axis of the motor grows. In the case of a negative voltage pulse, i_{dN} and ψ_{id} decline along the pulse duration. To make sure that the d-current responses of a positive and negative voltage pulse are affected alike by the permanent magnet excitation, ψ_{id} should vary symmetrical with respect to the positive and negative voltage pulse, as shown in Fig. 3. In practice, such symmetry is very difficult to establish. Therefore, in this work the problem is confined only to achieve symmetry of the positive and negative d-current responses. For the sake of clarity and better understanding of the proposed method, the current investigation is carried out under the condition that the positive voltage pulse is applied at the operating point of the machine. For a given reference q-current $i_{q(ref)}$, the operating point of the machine is also defined by the reference d-current $i_{d(ref)}$ set by the current controller. For the validation process in this investigation, $i_{d(ref)}$ is set to zero in the field oriented control, although this is not obligatory especially for IPMSM. This means for the temperature estimation procedure that the initial d-current at the beginning of the positive pulse is zero, $i_{dP(t_0)} = i_{d(ref)} = 0$ and the initial d-current of the negative pulse $i_{dN(t_0)}$ is chosen such that $i_{dP} \approx i_{dN}$ in the middle of the positive and negative voltage pulses respectively. Thus, the operating point of the machine moves upward from its origin upon a positive voltage pulse and downward to its origin upon a negative

voltage pulse, as demonstrated in Fig. 3. It should be noted here that the consideration how the voltage pulses are applied with respect to the machine operating point should be met with regard to the machine design and control application requirements. Theoretically, a voltage pulse generation can be realized also around the machine operating point, which will mean $i_{d(ref)} < 0$ for the positive voltage pulse and $i_{d(ref)} > 0$ for the negative voltage pulse according to Fig. 3.

IV. Experimental Validation of the Proposed Method At Various Load Conditions

In this section, magnet temperature estimation for various q-current values is compared for low and high speed.

A. Experimental Setup

The motor under test is an IPMSM with parameters listed in Table I. The rotor is specially manufactured to accommodate thermal sensors. Before the magnets were assembled, holes through the rotor lamination with diameter of 2 mm were laser drilled in different locations, Fig. 4. The used sensors are thermocouples of type K. Fig. 4 shows a rotating instrumentation that measures and converts the thermocouples signals to absolute temperature values and transmits these via infrared optical data link to a stationary receiver. A detailed description of the device is given in [8].

The field oriented space vector control together with the proposed voltage pulse generation is implemented on C6747, a floating point digital signal processor (DSP). The inverter operating PWM frequency is set to 20kHz. The injected voltage pulse width t_{pw} for the magnet temperature estimation is set to 25µs. According to (2), the angular deviation between the rotor and stator reference frames upon the beginning of the voltage pulse is very small, which assures that $i_a \approx i_d$ for the time duration of the voltage pulse. Therefore, in order to determine the d-current slope, the phase current i_a is oversampled by the DSP synchronously to the voltage pulse at sample rate of 500ns.

For the validation of a d-current slope di_d/dt when estimating the magnets temperature, the measured phase current i_a curve is linearized by polynomial interpolation

$$y(t) = S_a t + P \tag{12}$$

where the weighting factor S_a represents the estimated slope of the curve upon voltage pulse generation and the offset P represents i_{at_0}, which is approximately equal the initial d-current $i_{d(ref)}$ set by the current controller. Since the voltage pulse duration is given in µs and the current is measured in per unit values, the unit of the estimated slope S_a is current per unit per µs [pu/µs].

TABLE I: Parameters of the IPMSM Under Test

Nominal power	10 kW
Nominal voltage	440V
Nominal current	25 A
Nominal frequency	320 Hz
Nominal speed	4800 rpm

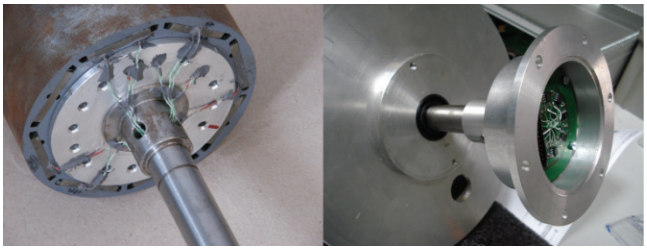


Fig. 4. Realization of temperature measurements in the IPMSM under test.

B. Experimental Results

In the following, experimental results obtained for temperature estimation carried out for $i_q = 0.2; 0.6; 1.0\ [pu]$ at speed n=300rpm and n=3000rpm are compared. The goal is to determine the method applicability and sensitivity with respect to the q-current and motor speed. The setup fully implies the theoretical approach presented in sections II and III. Indicator for the magnetization level of the permanent magnets is the difference (13) between the current responses from a positive and negative pulse in the d-axis of the motor, linearized according to (12):

$$S_{aPN} = S_{aP} - S_{aN} \tag{13}$$

It should be noted here that the voltage pulse duration for the positive and the negative pulse is the same (t_{pw}=25µs). The initial d-current for the positive pulse is kept zero $i_{d(ref)P}=0$, while the initial d-current for the negative pulse $i_{d(ref)N}$ varies according to the condition that the positive and negative d-current responses cross in the middle of the pulse duration in order to guarantee symmetrical excitation ψ_{id}. Similar consideration are valid for the q-current since ψ_{iq} should be kept constant too. The d-current response crossing is demonstrated in Fig. 5 where d-current responses upon positive and negative pulse generation are depicted for $i_q = 1.0pu$, at motor speed n=300rpm and magnet temperature $T_m = 25°C$. For the same setup, the differences of the positive and the negative voltage pulse current responses for various magnet temperatures are depicted in Fig. 6. By increasing the temperature in the magnet, a partial demagnetization occurs which leads to lower saturation level in the d-axis of the motor affecting the slope of the current response over the inductance. The slope decreases as the inductance goes up. The change of the current slopes along the magnet temperate T_m is demonstrated in Fig. 7, where the estimated slopes S_{aPN} of the corresponding current differences $i_{dP} - i_{dN}$ are depicted as a function of T_m for $i_q = 0.2;\ 0.6;\ 1.0pu$ at motor speed n=300rpm and n=3000rpm. The deviation of the curves for low (n=300rpm) and high (n=3000rpm) speed is almost negligible, especially for bigger i_q values. This assumes that a LUT that establishes the relationship between S_{aPN} and T_m, obtained at standstill for a given constant q-current ($i_q = const$), is valid for the entire motor speed range. This is an important aspect of the proposed method, since a LUT for a machine can be easier obtained at standstill than at high speeds. For example if

direct magnet temperature measurements are not available, constant reference rotor temperatures can be set by heating-up the machine at standstill in environmental chamber while measuring S_{aPN}.

In order to demonstrate the dependency of the d-current slopes S_{aPN} from the q-current i_q, measurements at constant magnet temperatures $T_m = 25; 40; 60; 80°C$ are carried out for various q-current values ($i_q = 0.2;\ 0.3;\ 0.4;\ 0.6;\ 0.8;\ 1.0pu$). The case $i_q = 0$ is not discussed here, as this has been already a subject in [32]. For the proposed method, the best scenario would be if the dependency of S_{aPN} from i_q is linear and not influenced by the magnet temperature. As the obtained curves in Fig. 8 show, for the machine under test, linearity is observed for $i_q > 0.4pu$. Furthermore, the relationship between S_{aPN} and i_q is to a great extent independent from the magnet temperature. This means for the method commissioning that the relationship ($S_{aPN} \sim i_q$) for a given motor can be identified potentially at a single magnet temperature ($T_m = const$) and assumed constant along the entire motor operating temperature range.

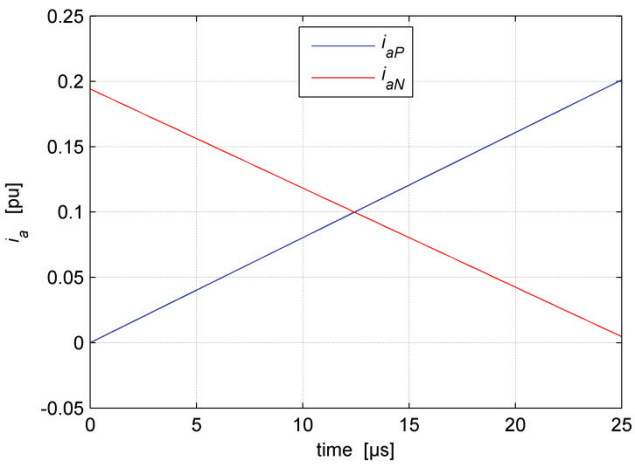


Fig. 5. D-current response upon positive and negative voltage pulse in the d-axis of the motor (i_q=1.0pu, n=300rpm, T_m=25°C); linearized current curves by polynomial interpolation.

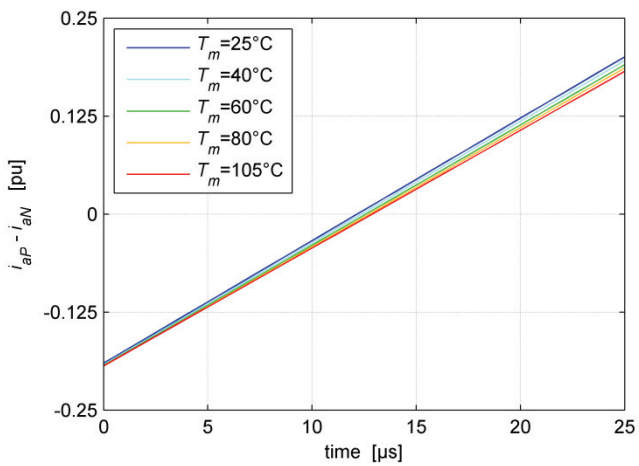
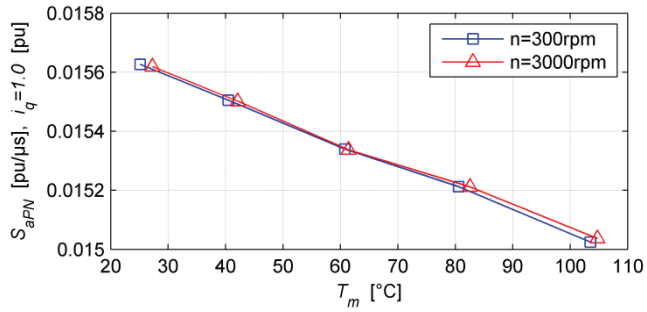
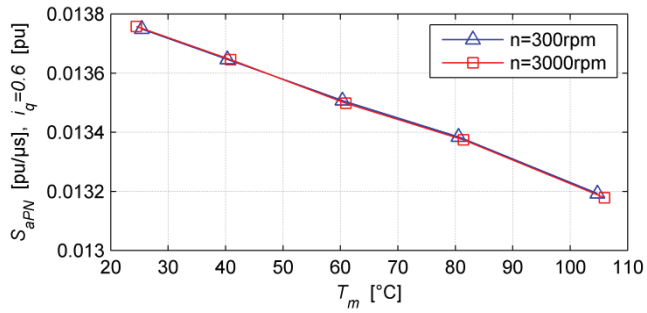


Fig. 6. The difference of the current responses $i_{dP} - i_{dN}$ upon temperature (i_q=1.0pu, n=300rpm); linearized current curves by polynomial interpolation.



a)



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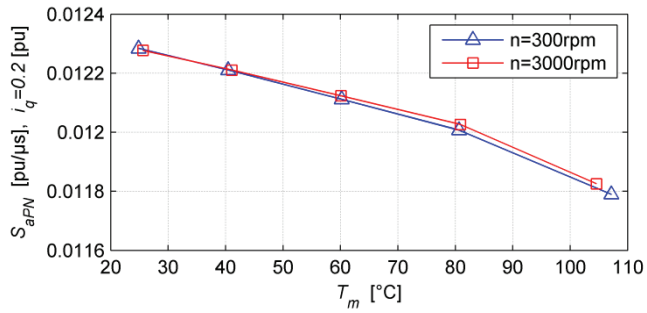

c)

Fig. 7. The slopes S_{aPN} of $i_{dP} - i_{dN}$ upon temperature estimation as a function of the magnet temperature for n=300rpm and n=3000rpm; a) i_q=1.0pu; b) i_q=0.6pu; c) i_q=0.2pu.

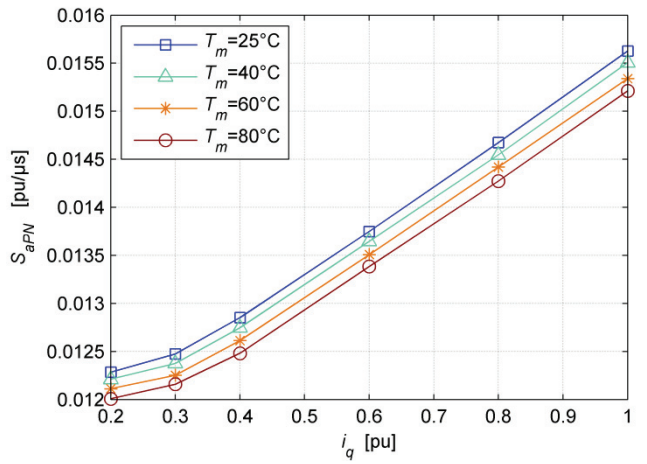

Fig. 8. The slopes S_{aPN} of $i_{dP} - i_{dN}$ upon temperature estimation as a function of the q-current i_q captured at various magnet temperatures (n=300rpm).

V. CONCLUSION

A method to estimate the permanent magnet temperature in IPMSM under loaded conditions has been presented. The influence of the machine operating point on the method has been discussed and compensation with respect to the q-current has been proposed. In general, the method characterizes with high accuracy along the entire motor speed range. It can be adapted for almost every type of PMSM and is independent of the applied digital motor control. The influence on the motor performance can be considered to a great extent negligible.

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