Sensorless Control with Online Parameter Adaption for the PMSM

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***Abstract*-Speed-Sensorless control schemes for AC-Drives are today standard features in industrial drives. Yet the quality of the implemented systems is different depending mainly on how precise the AC-machine is modeled and on the accuracy of the parameters. The present paper introduces an online adaption of the parameters of the PMSM based on the fundamental machine model during normal operation. The performed investigations confirm the proposed method to be suitable for servo-drive systems with high dynamics but also point out its limits.**

***Index Terms* —Sensorless control, vector control, permanent magnet synchronous motor**

I. INTRODUCTION

In the literature excellent papers can be found that summarize the state of the art in the area of speed-sensorless control of AC-Drives [1], [2]. A coarse classification of the known methods leads to a general accepted classification in injection and fundamental wave methods. In principle they differ in the model of the machine that is used.

The first class of methods exploit the asymmetries of the machine that result either from the geometry of the design i.e. anisotropic rotor, from slotting or from the saturation of the iron path. In order to overcome the unobservability of the system at zero frequency, test signals with a frequency different from the fundamental are injected in the stator and allow the calculation of the unknown state variables based on the response of the system to the high frequency injection [3], [4]. However, the distinction of different anisotropies within a machine is difficult and their application is limited to machines that provide structural asymmetries to be detected. Therefore they are not yet widespread in industrial drives and are not considered in the following approach.

The second category of methods utilizes the classical dynamic equations of the AC-machine, whereby a sinusoidal flux density distribution in the air gap is assumed, neglecting space harmonics and other secondary effects. These approaches build the class of fundamental wave models. They are in principle based on the integration of the stator voltage equation as shown in Fig. 1 being L_s the stator inductance, R_S the stator resistance and $\underline{\Psi}_0$, $\underline{u}_S$, $\underline{i}_s$ and $\underline{\Psi}_s$ the space phasors of the permanent flux, of the stator voltage, of the stator current and of the stator flux, respectively. The quality of the models can be enhanced by Model Reference Adaptive Systems (MRAS) that compare the outputs of two machine models, with one of them depending on the motor speed and adapt the model until the correct matching is obtained.

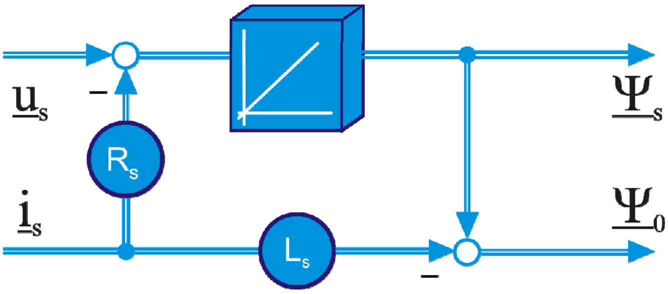

Fig. 1: Integration of the stator voltage

From the point of view of industrial motor drives the synchronous machine has become extremely interesting in motor drives. Permanent Magnet excited Synchronous Machines (PMSM) have the benefit of high efficiency, simple construction, low inertia and other advantages that are especially important in the area of servo-drives. Therefore this work focuses on the PMSM-drives and limits its scope to the fundamental wave models, in which the question of the parameter sensitivity arises. Even in the case that the machine parameters are well known at the time of commissioning, they change during operation due to saturation, temperature and demagnetization of the permanent magnets. The quality and the performance of the control rely on the model of the machine and consequently on the accuracy of the parameters in each operation point. Of course other effects have to be considered like the correct modeling of the inverter and the numerical integration.

In high demanding servo applications the temperature rise in the motor can be considerable especially due to the kind of cooling that is usually natural convection. It is evident that the temperature dependent value of the stator resistance affects significantly the accuracy of the model. A possible solution is to adapt this parameter by measuring the temperature of the stator and correcting the value of R_S if a temperature sensor is installed in the machine and an appropriate thermal model is included in the control. Yet the present work is intended to make the adaption in an alternative way.

Depending on the kind of magnet material used in the motors the permanent magnet flux decreases with higher temperature. This effect has also an impact on the accuracy of the model and therefore necessitates to find a method for the adaption of the parameter Ψ_0. The permanent magnet flux can be affected in the field weakening operation as well.

The machine inductances do not show any dependency of the temperature and an online adaption is therefore not necessary.

Until now the examined methods for the parameter adaption do not fulfill the needs of the correction of both R_S and Ψ_0. Usually the permanent magnet flux is assumed to be constant and the value of R_S is corrected or vice versa [5]-[8] and thus limiting their applicability. In [9] a method is introduced which is able to correct either the value of R_S or Ψ_0 depending of the actual operating point but a continuous adaption of both parameters is not possible.

The method proposed in the following makes a heuristic and simple approach and tracks both: the changes of R_S as well as of Ψ_0.

Two cases can be considered. On the one hand the operation with encoder, in which the sensorless scheme is not active but in stand-by and can be activated in case of failure of the encoder. The advantage of the parameter adaption is that this fault tolerant strategy switches over to a correctly tuned model and optimum sensorless control. This approach was presented in earlier works [10].

The present paper approaches solely the second case, in which the adaption of the parameters is performed in a control scheme without any encoder. This is certainly the more demanding requirement yet essential for an optimum performance of sensorless schemes and includes the adaption with encoder.

As servo-drives are in the main focus of applications of PMSM and they have always a load profile that contains operation cycles at low and high speed and at low and high torque it can be intended to use these changes of the operation point for the tracking and correction of the parameters so that no additional test signal is required. The adaption scheme presented in [10] exploits this idea and exhibits an excellent performance in drives with fast changing load or velocity profiles. However, until now its performance limits in case that the operation cycles exhibit only low dynamics have not been analyzed.

Based on the approach already presented in [10] the parameter tracking scheme is examined especially regarding its limitations imposed by slow changing load and velocity profiles and evaluated in detail according to measurements on industrial motor drives.

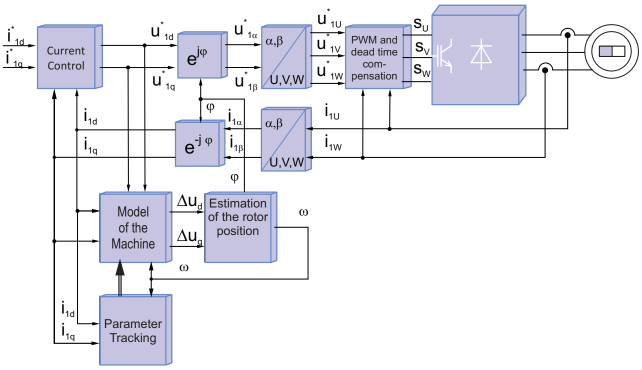

Fig. 2: Implemented sensorless control structure

II. PARAMETER TRACKING CONCEPT

The implemented sensorless control structure is depicted in Fig. 2. It is based upon the well-known field oriented control structure and estimates the rotor position φ and angular velocity ω according to the proposal of [11]. The voltage references u_d^* and u_q^* which are necessary for the implemented machine model substitute the real machine voltages in the corresponding reference frame. Thus, no further voltage transducer than the standard dc-link measurement is necessary. However, the error between voltage reference and real machine voltage caused by the nonlinear behavior of the inverter, especially the influence of the inverter dead time, has to be compensated to achieve a satisfying performance of the sensorless control. This is attained by the dead-time-compensation block in Fig. 2. A detailed description about possible inverter-compensation methods can be found in [9], [12].

In order to estimate the rotor position and angular velocity, the voltage errors Δu_d and Δu_q between the voltage references and the model voltages $u_{d,model}$ and $u_{q,model}$ are calculated.

$$\Delta u_d = u_d^* - u_{d,model} \tag{1}$$

$$\Delta u_q = u_q^* - u_{q,model} \tag{2}$$

The model voltages depend on the actual angular velocity and the machine currents according to the well-known equations of the machine:

$$u_{d,model} = R_s \cdot i_d + L_d \cdot \frac{di_d}{dt} - L_q \omega i_q \tag{3}$$

$$u_{q,model} = R_s \cdot i_q + L_q \cdot \frac{di_q}{dt} + L_d \omega i_d + \Psi_0 \omega \tag{4}$$

The stator currents i_d and i_q are gained by transforming the measured machine currents with the estimated rotor position angle φ. It is evident that if all model parameters (stator resistance, inductances, permanent flux, the estimated rotor position and the estimated angular velocity) are correct, the values of the voltage errors become zero. Whereas a wrong rotor position or a wrong angular velocity leads to voltage errors in d and q axis since the model does not fit to the physical system.

In PMSM with surface mounted magnets the inductance values of L_d and L_q do not differ significantly and the voltage errors can be calculated as given in (5) and (6) [11].

$$\Delta u_d \approx \Psi_0 \omega \sin \Delta\varphi \approx \Psi_0 \omega \Delta\varphi \tag{5}$$

$$\Delta u_q \approx \Psi_0 \left(\omega \cos \Delta\varphi - \omega_e \right) \approx -\Psi_0 \Delta\omega \tag{6}$$

The angle error $\Delta\varphi$ and angular velocity error $\Delta\omega$ are defined as the differences between estimated values and the real values. For small angle errors $\Delta\varphi$ the equations (5), (6) can be simplified by approximating the trigonometric terms as $\sin(\Delta\varphi) \approx \Delta\varphi$, $\cos(\Delta\varphi) \approx 1$.

As detailed described in [11], the rotor position φ and angular velocity ω can be estimated based on the two voltage errors Δu_d and Δu_q. However, the objective of the present investigation is rather the parameter tracking concept than the sensorless control itself.

The equations (5) and (6) are only valid if the model parameters fit to their real machine parameters. Any discrepancy between model and real machine affects the voltage errors and therefore degrades the performance of the encoderless rotor position estimation [11]. The following equations consider the influence of parameter variations on the voltage errors ($\Delta R_S = R_{S,model} - R_{S,real}$, $\Delta L_{dq} = L_{dq,model} - L_{dq,real}$, $\Delta\Psi_0 = \Psi_{0,model} - \Psi_{0,real}$):

$$\Delta u_d \approx \Psi_0 \omega \Delta\varphi - \Delta R_s \cdot i_d - \Delta L_d \cdot \frac{di_d}{dt} + \Delta L_q \omega i_q \tag{7}$$

$$\Delta u_q \approx -\Psi_0 \Delta\omega - \Delta R_s \cdot i_q - \Delta L_q \cdot \frac{di_q}{dt} - \Delta L_d \omega i_d - \Delta\Psi_0 \omega \tag{8}$$

On the one hand the voltage errors allow an estimation of the rotor position and angular velocity, whereas parameter variations decrease the accuracy of the estimated values. On the other hand, the voltage errors deliver information about parameter variations so that the parameters can be adjusted if the influence of the angle error and velocity error can be decoupled from parameter variations.

By assuming that the encoderless control is stable, the angle error $\Delta\varphi$ will be in the range of some degrees but will not drift away. As the estimated rotor position is gained by integrating the estimated angular velocity, the relation between angle error $\Delta\varphi$ and velocity error $\Delta\omega$ is given by:

$$\Delta\varphi = \int \Delta\omega \cdot dt \, . \tag{9}$$

For this reason the average value of the velocity error $\Delta\omega$ must be zero, otherwise the angle error $\Delta\varphi$ would drift away.

It is therefore obvious that (7) cannot be used to adjust the model parameters, because the angle error $\Delta\varphi$ can be different from zero even under steady state conditions. Since the actual value of the angle error is unknown, the voltage error caused by parameter variations cannot be decoupled from the influence of the angle error.

Equation (8) differs from this restriction as the average value of the velocity error $\Delta\omega$ is zero. Since the examined parameter variations are caused by the changes of the machine temperature, the time constant of the parameter variations (several minutes) lies decades above the expected changes in the velocity error (some milliseconds). If an integrator structure is used to adapt the parameters, the influence of the velocity error $\Delta\omega$ on the voltage error Δu_q can be neglected. Hence, equation (8) can be used for the sensorless control and for parameter adaption at the same time due to the big difference in the time constants.

The same considerations can be applied to the derivative term of the current di_q/dt in (8) as the average value of this term is zero as well. The approximated voltage error in q axis can therefore be computed as:

$$\Delta u_q \approx -\Delta R_s \cdot i_q - \Delta L_d \omega i_d - \Delta\Psi_0 \omega \tag{10}$$

If only the base speed range is considered for the parameter identification, equation (10) becomes even simpler since the flux producing component of the stator current i_d is zero (11).

$$\Delta u_q \approx -\Delta R_s \cdot i_q - \Delta\Psi_0 \omega \tag{11}$$

It is obvious that both temperature dependent parameters, stator resistance R_S and permanent flux Ψ_0 influence the voltage error Δu_q. Unfortunately, equation (11) is underdetermined since it contains two unknown machine parameters. In order to decouple both unknown variables, more information would be necessary.

The basic idea of the parameter tracking approach presented here is that this equation can be solved if it is evaluated in at least two different machine operating points, with their corresponding currents (i_{q1}, i_{q2}), speeds (ω_1, ω_2) and resulting voltage errors (Δu_{q1}, Δu_{q2}). Index “1” represents the machine variables in the first operating point, index “2” those in a second operating point. In that case, the following equation system can be solved as there are two equations for the two unknown variables:

$$\Delta u_{q1} = -\Delta R_s \cdot i_{q1} - \Delta\Psi_0 \omega_1 \tag{12}$$

$$\Delta u_{q2} = -\Delta R_s \cdot i_{q2} - \Delta\Psi_0 \omega_2 \tag{13}$$

It is important to mention that this simple idea is only valid if the stator resistance R_S and permanent flux Ψ_0 did not change notably between the two operating points. If the machine temperature has changed considerably between the two operating points the identification of the two parameters with this approach will fail. Thus, for this approach the machine needs to run frequently in different operating points in which the time between two operating points should be significant lower than the machine thermal time constant.

This simple method has yet some disadvantages as the calculation requires two discrete operating points and is therefore not suitable with ongoing variations in speed or torque. Fig. 3 shows a different method to decouple the two machine parameters which is also based upon the above explained idea but uses two weighted integrators for the identification of the parameters. With this configuration it is possible to decouple the parameters, even if the machine is driven with continuous changing speed or torque profiles. However, the above explained conditions about changing operating points still need to be fulfilled.

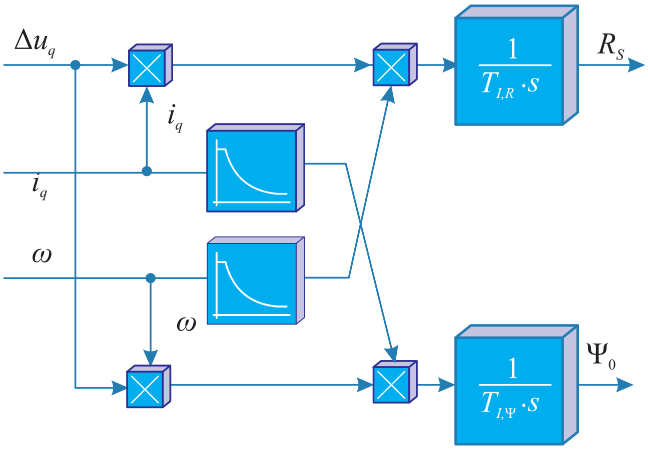

Fig. 3: Decoupling of the voltage error

TABLE I
TIME CONSTANTS OF THE ADAPTION-CONTROLLERS

Stator resistance adaption	$T_{I,R}$	0.75s
Permanent flux adaption	$T_{I,\Psi}$	1.5s

The two integral controllers adjust the model parameters R_S and Ψ_0 so that the voltage error Δu_q becomes zero. To decouple the impact of the two parameters the two controllers are equipped with different weighting factors which depend on the actual operating point.

The impact of the stator resistance error ΔR_S on the voltage error Δu_q increases with higher current whereas the impact of the flux error $\Delta\Psi_0$ increases with higher speeds. Thus, it is reasonable to adapt the stator resistance at operating points with high currents and low speeds and the permanent flux vice versa.

Therefore, the voltage error Δu_q is multiplied in a first step with the stator current i_q to increase the gain in the resistance-adaptation-loop for higher current values. In a second step the gain is reduced with higher speed values. The mechanism for the flux adaption behaves vice versa. Thus, the resulting gains in the two controller loops are high if the actual operating point prefers an adaption of the corresponding parameter and are low if the adaption of this parameter is inappropriate.

As stated above, the drive needs to run frequently under at least two significant different operating points in order that the parameters can be decoupled. Operation cycles of the drive with frequent changes in the load torque and machine speed ease the parameter identification.

III. EXPERIMENTAL RESULTS

The experimental results presented in the following validate the robust behavior of the proposed parameter tracking method in the case that the machine is operated under the above stated conditions with dynamic changing loads and velocities. Furthermore the limits of the parameter tracking approach at low dynamics are demonstrated. All presented results were achieved in speed sensorless operation of the machine.

Fig. 4 shows the mechanical setup. The nominal values of the machine and inverter are shown in Table II.

TABLE II
NOMINAL VALUES AND MACHINE PARAMETERS

Nominal Values			
Power	0.51kW	Voltage	320V
Speed	4050min^{-1}	Current	1.5A
Torque	1.2Nm	Pole Pairs	4
Machine Parameters (at 20°C)			
Stator Resistance	10.9Ω	Permanent linked flux	157mVs
Inverter			
DC-Link voltage	560V	PWM-frequency	4kHz

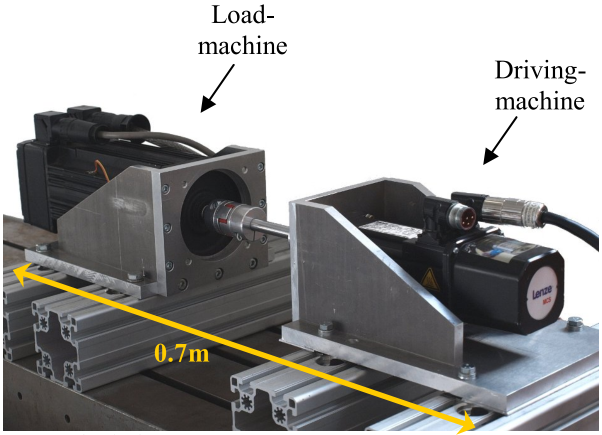

Fig. 4: Mechanical setup

A periodical speed reference n^* and load torque reference M^* was used to emulate a process with high dynamics. The speed and load profile are depicted in Fig 5. The parameters were tracked by using the proposed method for the drive running in the velocity control mode with the periodical velocity reference signal n*. The temperatures of the motor housing and of the motor winding were monitored and additionally the stator resistance was measured as reference at the beginning and at the end of the cycle.

Fig. 6 shows the identified parameters and measured values. Experiments with other speed and torque profiles lead to corresponding results.

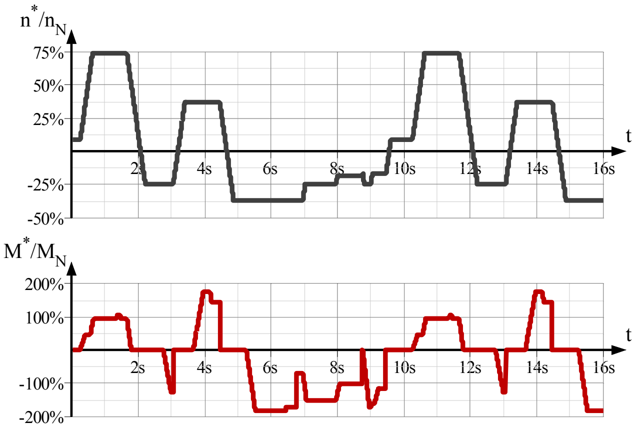

Fig. 5: Periodical speed and load torque references in per unit.

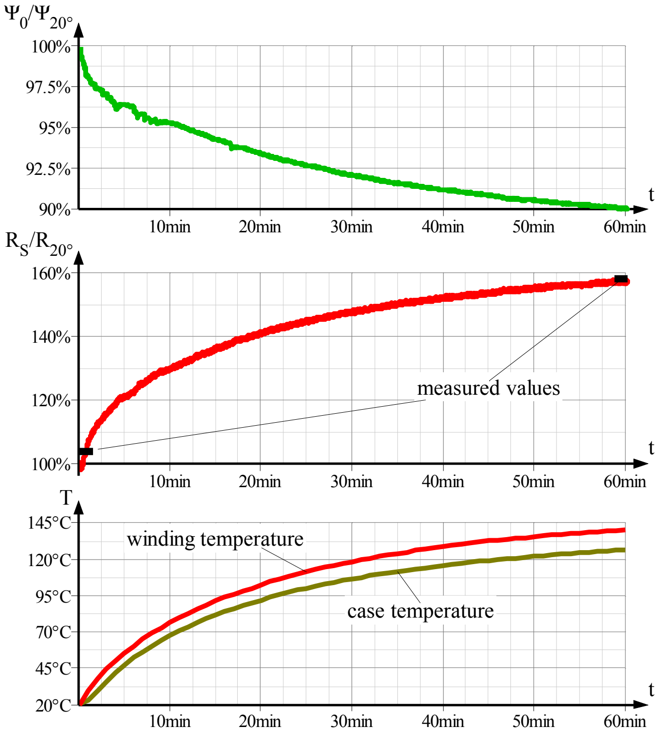

Fig. 6: Identified machine parameters related to nominal values at 20°C and measured machine temperatures. Operation according to Fig. 5

In order to analyze the behavior of the tracking method at low excitations of the electrical system, the machine was driven with a profile of reduced dynamics as depicted in Fig. 7. The results in Fig. 8 show that the parameters can still be identified correctly. However, the parameter signals exhibit a low ripple.

Further measurements with the same torque reference like in Fig. 7 but constant speed reference show that the parameter tracking method works stable under this conditions but yields to a constant error in both identified parameters. Thus, for a proper operation, the speed and the torque of the machine should vary frequently.

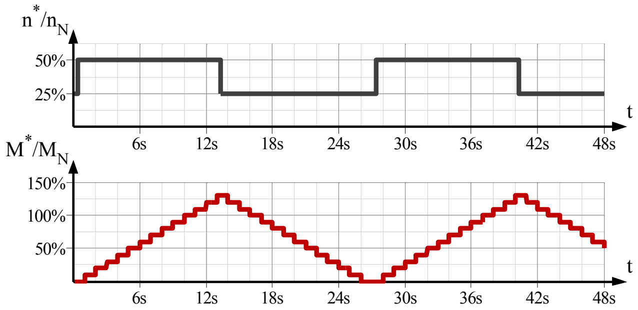

Fig. 7: Periodical speed and load torque references with reduced dynamics

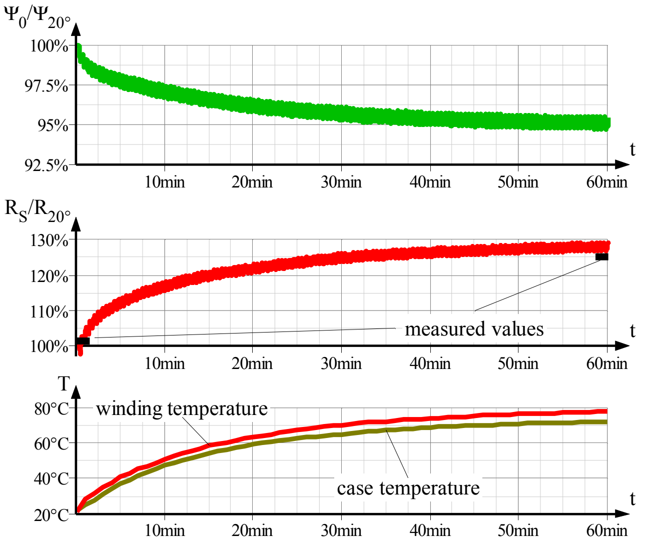

Fig. 8: Identified machine parameters related to nominal values at 20°C and measured machine temperatures. Operation according to Fig. 7

If the period of the test profile in Fig. 7 is increased in the range of the thermal time constant (see Fig. 9), the machine temperature exhibits a direct response to the load profile. The condition that the temperature did not change notably between two significant operating points is no longer fulfilled and the identification of the parameters fails as the identified resistance is considerable higher than the measured one. The machine temperature and identified parameters are shown in Fig. 10.

The experimental results point out the conditions which need to be fulfilled for the proper function of the parameter tracking method:

The machine torque and speed have to change significantly and frequently and the time between two significant different operation points must be far below the thermal time constant to ensure that the machine temperature has not changed notably.

Under these conditions, the method is able to identify the machine parameters as the experimental results confirm. Further measurements with different PMSM validate the robustness of the method [10].

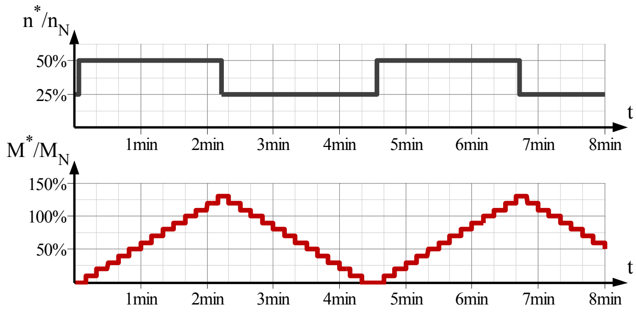

Fig. 9: Periodical speed and load torque references with low dynamics

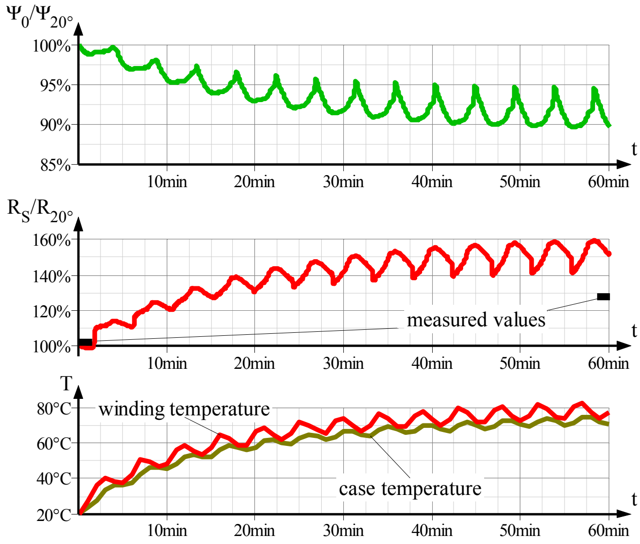

Fig. 10: Identified machine parameters related to nominal values at 20°C and measured machine temperatures. Operation according to Fig. 9

IV. CONCLUSIONS

A method for the adaption of the parameters of the model of the PMSM is presented that works in speed sensorless controlled machines and takes into consideration the thermal changes of the stator resistance R_S and of the permanent magnet flux Ψ_0. It is a heuristic scheme that utilizes the operation cycles of the drive in order to achieve the tracking of the parameters and works reliably in a wide operation range with certain limitations regarding the thermal time constant of the system.

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