Initial Rotor Position Detection in Electrically Excited Medium Voltage Synchronous Machines

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Abstract

In inverter fed, encoderless operation of the synchronous machine (SM), the rotor or flux position is mandatory for the control. This information is obtained based on the evaluation of the machine voltages and works reliably from a minimum stator frequency on. However, until now the rotor position identification at standstill is only possible if the machine exhibits special characteristics and therefore excludes the identification in most of the electrically excited SMs. The present paper introduces a novel approach based on low frequency signal injection which works properly in a wide range of SMs. Measurement results confirm the applicability of the approach.

1 Introduction

Electrically excited synchronous machines are one of the common machine types used in high power applications. In inverter fed operation of the SM like in all variable speed drives, the actual rotor or flux position has to be known to allow the control of the drive. Hence, by default a mechanical position encoder is installed at the shaft which delivers the desired information but also reduces the total reliability of the drive system as position encoders are prone to failures [1][2]. Therefore, a lot of research is dedicated to the control of the drive without any mechanical sensor today, by estimating the rotor or flux position with adequate models of the machine. The standard procedure uses an integration of the induced machine voltages to calculate the stator flux as it is depicted in principle in Fig 1. At moving machine this approach works very reliably whereas it fails if the machine is driven at very low speeds for a period of time since the induced stator voltages are nearly zero [1][2]. However, if the initial rotor position is known the machine can be accelerated from standstill out of the critical speed region with the explained method but it is important that the initial rotor position detection is reliable to avoid uncontrolled moving of the machine. Especially the acceleration in reverse direction must be avoided as in some special applications the bearings of the applied load can not be operated in reverse direction because of loss of lubrication.

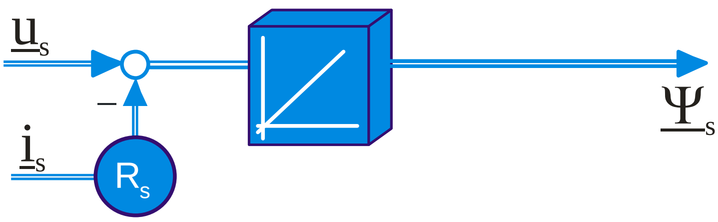


Fig 1: Principle calculation of the stator flux by integrating the stator voltages

Until today, several different methods can be applied in order to estimate the initial rotor position without any mechanical sensor. The first group of methods injects high frequency voltage pulses in different directions in the stator winding of the machine [3]-[5]. If the machine exhibits different behavior (different inductances) in the direct- and quadrature axis the response in the stator current can be utilized to estimate the angle position of the rotor. As the pulses can also be applied at moving machine these methods allow also a continuous operation in the low speed region. However, the rotor position can only be identified with 180°-ambiguity as the inductances of the machine are in principle the same whether a positive or negative (180° aside to the first) pulse is applied [3][6]. In order to eliminate this ambiguity, the field current of the machine is set to a high value and a strong pulse is injected in the two expected rotor positions. The idea is that the machine mutual inductance gets in saturation due to the high field current. A stator pulse in rotor direction will now increase the magnetization leading to a higher level of saturation and reduces the mutual inductance, whereas a

ISBN 978-3-8007-3431-3

pulse in reverse direction will decrease the magnetization and thus increases the mutual inductance. An adequate analysis of the corresponding current responses can eliminate the 180°-ambiguity. Unfortunately, these methods can not be applied to machines with similar high frequency behavior in direct- and quadrature axis which is mainly influenced by the stray inductances of the field and damper windings. Even in salient pole SMs the high frequency pulse response can thus be identical in the two axes and a distinction of both axes is not possible with this method. Furthermore, some electrically excited SMs exhibit only a slight saturation or the influence of the damper winding prevents the evaluation of it so that the rotor position identification using high frequency signal injection is finally only possible on few machines with special characteristics.
A further method to identify the rotor position at standstill is the short circuiting of the stator winding by the inverter while increasing the field current as fast as possible by the excitation system. The change in flux will lead to a small current flowing in that stator component which lies in the direction of the field winding and thus allows the identification of the rotor position. In static excited machines (with slip rings on the rotor) the field winding is directly accessible and the field current can be dynamically influenced by some kind of DC-converter, resulting mostly in a clearly visible response in the stator current. On the contrary, in brushless excited machines the field winding is not directly accessible but its current can be controlled by the stator voltages of the excitation machine. Hence, the overall inductance in the excitation path is quite high as it includes the inductances of the excitation machine as well and thus prevents a fast increasing field current in most of the machines. In this case the resulting stator current response is often too low for a proper identification of the rotor position.
In theory the asynchronous start up of the machine would be possible as well. For this purpose the field winding must be short circuited in order to prevent over voltages in the winding. As this is generally not possible in brushless excited machines this method can only be applied to static excited machines but in this case the previous mentioned method is preferred.

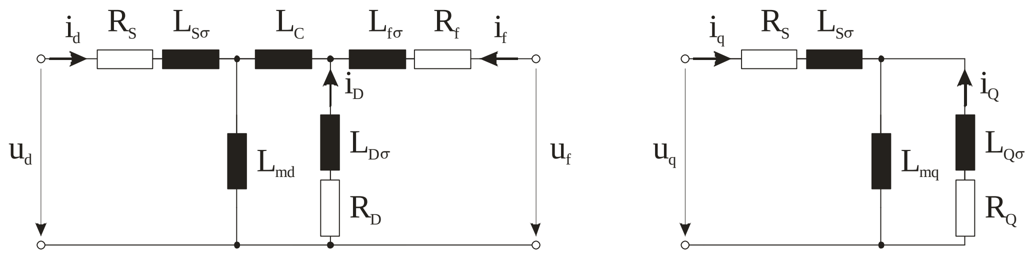
	Similar high frequency behavior in both axes	Brushless-excitation	Machine with no evaluable saturation
High frequency signal injection	-	X	-
Fast increasing field current	X	-	X
Asynchronous start up	X	-	X
Low frequency signal injection with field current analysis	X	X	X

Table 1: Applicable identification or start up methods depending on machine characteristics

Each mentioned method can only be applied if several conditions regarding machine parameters are fulfilled. Especially for machines with brushless excitation and similar high frequency behavior in both axes no method is present until now with which a proper identification of the rotor position can be guaranteed. In the following, a novel approach based on low frequency signal injection with analysis of the field current is introduced which is able to identify the rotor position for a wide range of electrically excited synchronous machines including the crucial case with brushless excitation and similar high frequency behavior (Table 1).

2 Low frequency pulse response of the machine

The equivalent circuit in standstill of the SM in the d- and q- axis is shown in Fig.2 [7]. Even for cylindrical rotor machines with identical mutual inductances and damper windings in both axes, the equivalent circuits in both axes differ from each other as only the d-axis contains the field winding. However, in those machines a high frequency pulse will result in almost the same response in the stator current whether it is injected in d- or q- axis as the high frequency behavior in both axes is almost the same. The question arises if it is possible to detect a difference in the stator current response in both axes if the frequency of the voltage test pulse is set adequately. For this reason the frequency response characteristic of the two axes is calculated ($Y_d(\omega)=I_d(\omega)/U_d$, $Y_q(\omega)=I_q(\omega)/U_q$). The field voltage is assumed to be constant during the test pulse injection as the dynamic of the field controller is in general slow compared to the frequency of the injected signal. For the calculation of the frequency response characteristic the field voltage can then be approximated as a short circuit. Typical characteristics of a salient pole and a cylindrical rotor SM are depicted in Fig. 3 and Fig. 4, respectively.



u_d	Stator voltage in d-axis	u_q	Stator voltage in q-axis
i_d	Stator current in d-axis	i_q	Stator current in q-axis
L_{md}	Mutual inductance in d-axis	L_{mq}	Mutual inductance in q-axis
R_S	Resistance of the stator winding	$L_{S\sigma}$	Stray inductance of the stator winding
R_f	Resistance of the field winding	$L_{f\sigma}$	Stray inductance of the field winding
R_D	Resistance of the damper winding in d-axis	$L_{D\sigma}$	Stray inductance of the damper winding in d-axis
R_Q	Resistance of the damper winding in q-axis	$L_{Q\sigma}$	Stray inductance of the damper winding in q-axis
L_C	Canay inductance		

Fig 2: Equivalent circuit in d- and q- axes of a synchronous machine

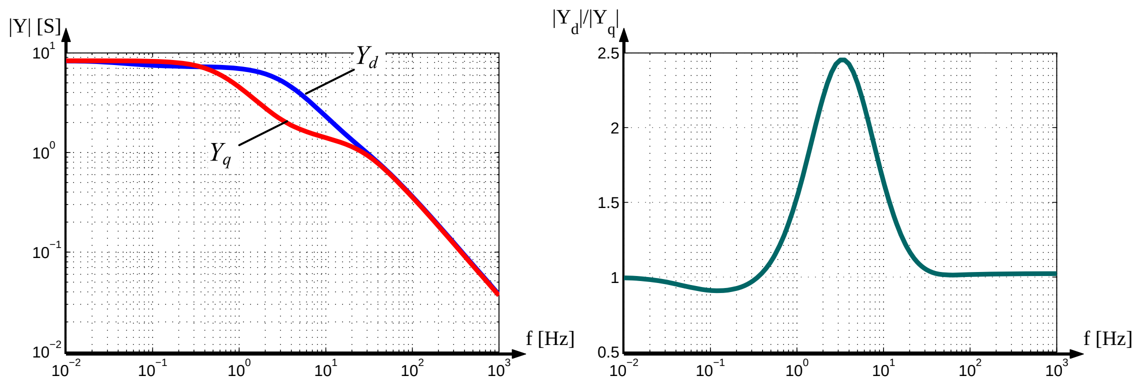


Fig. 3: Frequency response characteristics of a salient pole SM (P=1.2MW, U_N=3300V, f_N=50Hz) L_{md}=52mH, L_{mq}=23mH, $L_{s\sigma}$=3.1mH, $L_{f\sigma}$=3.9mH, $L_{D\sigma}$=1.6mH, $L_{Q\sigma}$=1.3mH

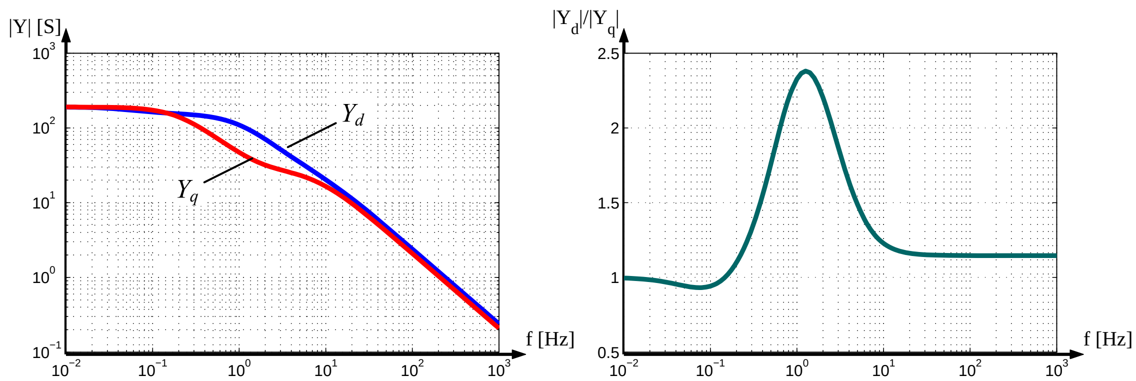


Fig. 4: Frequency response characteristics of a cylindrical rotor SM (P=4.7MW, U_N=3100V, f_N=75Hz) L_{md}=3.2mH, L_{mq}=3.0mH, $L_{s\sigma}$=0.44mH, $L_{f\sigma}$=0.70mH, $L_{D\sigma}$=0.35mH, $L_{Q\sigma}$=0.35mH

It is obvious that the value of the mutual inductance has almost no effect on the high frequency behavior of the machine. Thus, the high frequency admittance difference (Y_d/Y_q) between both axes can even be more distinctive in a cylindrical rotor machine than in a salient pole machine as it is mainly influenced by the stray inductances of the field and damper windings (Fig. 3, 4).

In general, every SM shows a similar frequency response characteristic with small differences in the two axes for high and very low frequencies but great differences in the medium frequency range. Even in machines with identical mutual inductances, the machine exhibits great differences between both axes in this frequency region (Fig. 4). The maximum difference in the frequency response curve lies for most machines in the frequency range between 1 and 10Hz. Thus, even if the response of a high frequency pulse in the two axes does not show any notable difference, the two axes can be distinguished if the pulse frequency f_{Pulse} is chosen to that value where the machine frequency response characteristic exhibits the maximum difference.

3 Realization of low frequency pulses

During any voltage injection in the stator, the field current must flow for safety reasons. Otherwise, the stator voltage is transformed to the field winding and can cause over voltage. In brushless excited machines the exciting current is therefore always kept over 30% of the nominal value. As the machine is excited, the pulse response in the stator current can generate torque and finally unwanted motion of the drive, particularly as the test pulse period is quite long. To avoid this, the amplitude of the voltage test pulse should be kept as small as possible. As the inverter dc-link voltage is at a fixed value, the test pulses are realized by a space vector modulation which allows the injection of the test pulses in any arbitrary direction γ_{Pulse} in the stator winding (Fig. 6, eq. 1-3). It is worth to mention that the modulation of very low voltage pulses on a medium voltage inverter is quite challenging since several limitations like minimum turn-on times of the power switches of several ten microseconds must be considered. In order to achieve very low amplitudes (typically 0.3% of the nominal machine voltage) the period of the modulation is chosen very large (several milliseconds) in comparison to the minimum turn-on times. A square wave signal was selected as test pulse as it can be replicated best by the inverter. In Fig. 5 the modulated voltage test pulse as well as its response in the stator current component i_{Pulse} is shown. As the voltage pulse is modulated, the real current response differs a bit from the ideal one. The stator current component i_{Pulse} is the component of the stator current that lies in the same direction as the injected voltage pulse (eq. 4).

$$u_{U0}(t) = u_{Pulse}(t)\cdot\cos(\gamma_{Pulse}) \quad (1)$$

$$u_{V0}(t) = u_{Pulse}(t)\cdot\cos(\gamma_{Pulse} - 120°) \quad (2)$$

$$u_{W0}(t) = u_{Pulse}(t)\cdot\cos(\gamma_{Pulse} - 240°) \quad (3)$$

$$i_{Puls}(t) = i_U(t)\cdot\cos(\gamma_{Pulse}) + i_V(t)\cdot\cos(120° - \gamma_{Pulse}) + i_W(t)\cdot\cos(240° - \gamma_{Pulse}) \quad (4)$$

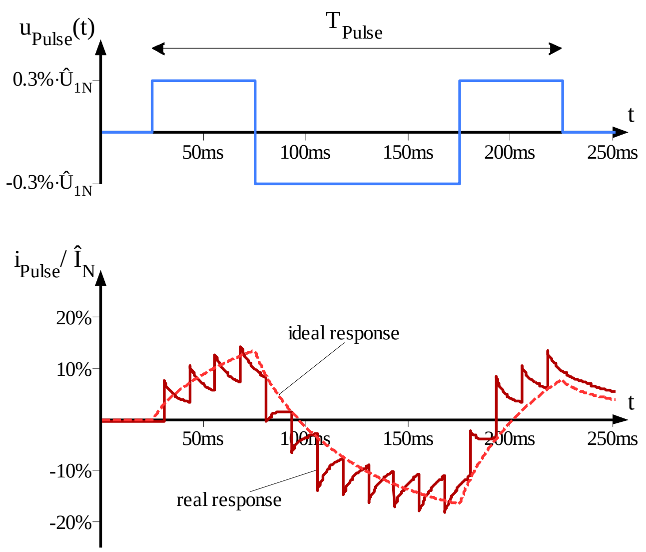


Fig 5: Injected voltage pulse and its current response

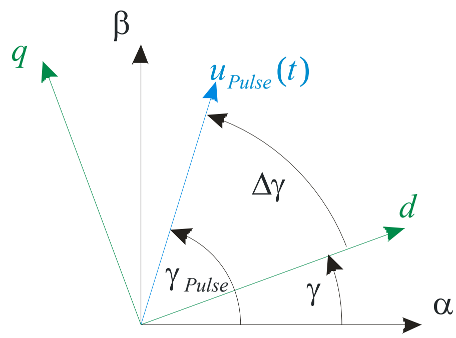
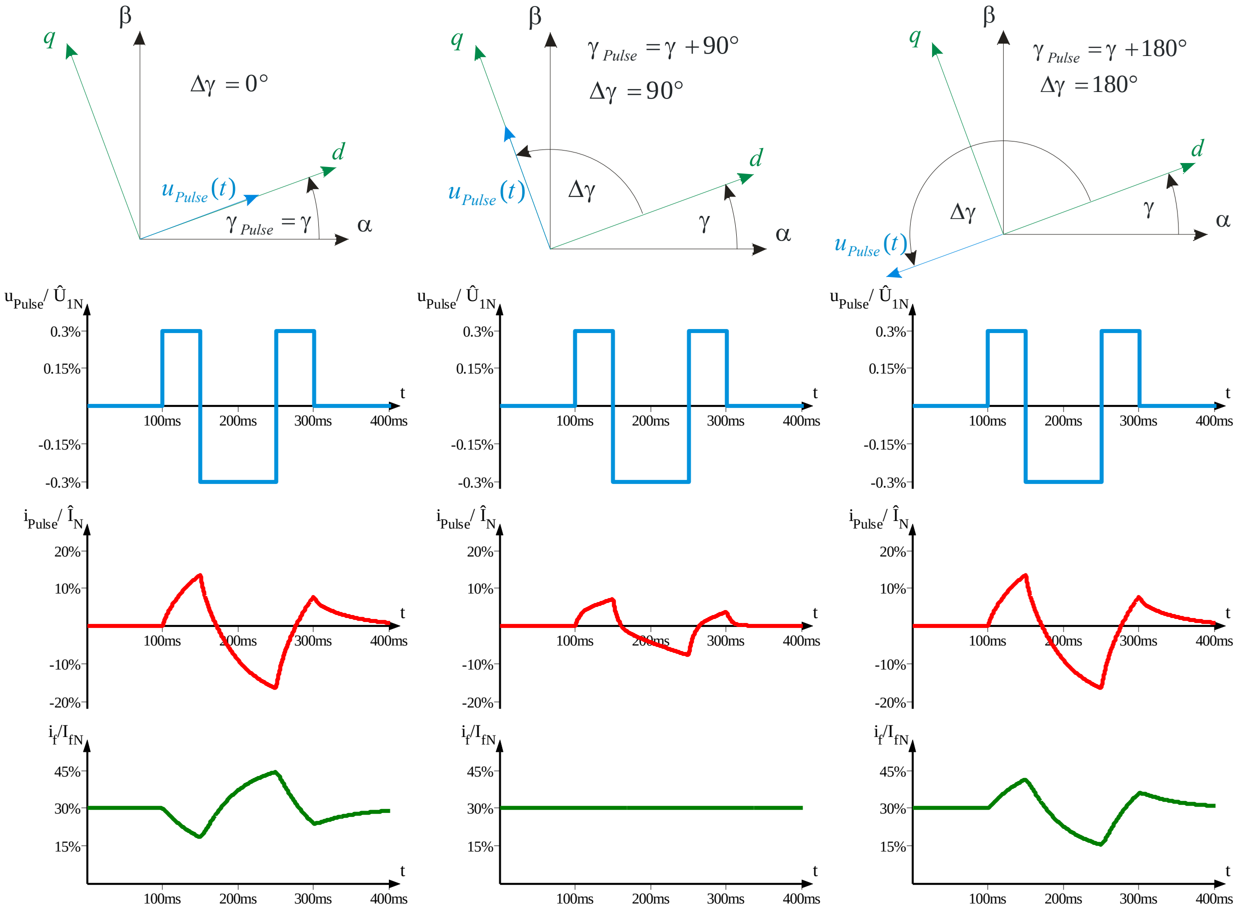


Fig 6: Injection of the voltage test pulse in any arbitrary direction

The response in the stator current depends on the angle errors $\Delta\gamma=\gamma_{Pulse}-\gamma$ which is the difference between injected pulse direction γ_{Pulse} and direction of the field winding γ. In Fig. 7 the ideal stator current response as well as the pulse response of the field current is shown for different angle errors. The field current is also measured for control purposes and no additional sensors are necessary. In static excited machines the field current is measured directly whereas it is reconstructed based on the stator currents of the excitation system in brushless excited machines.



a) $\Delta\vartheta = 0°$ b) $\Delta\vartheta = 90°$ c) $\Delta\vartheta = 180°$

Fig. 7: Injection of voltage pulses in different directions and their (ideal) current responses

In the case of the stator current, the pulse responses show a 180°-ambiguity whereas the response in the field current allows a clear estimation of the rotor position.

For the evaluation of the rotor position according to the pulse responses in the stator current, an adequate indicator quantity is necessary. In this case, the rms-value of the stator current in pulse direction I_{Pulse} is calculated (eq. 5). Its angular dependence to the angle error $\Delta\gamma$ is depicted in Fig. 8. Furthermore, the field current indicator ΔI_f according to eq. 6 is calculated after each pulse injection, which indicates whether the field current increases or decreases in the time period $0 < t_{Pulse} < T_{Pulse}/4$ where t_{Pulse} is the time after starting the pulse injection. With this information the 180°-ambiguity can be eliminated as explained in the following.

$$I_{Pulse} = \sqrt{\frac{1}{T_{Pulse}} \int_0^{T_{Pulse}} i_{Pulse}^2(t) \cdot dt} \quad (5)$$

$$\Delta I_f = i_f\left(t_{Pulse} = \frac{T_{Pulse}}{4}\right) - i_f\left(t_{Pulse} = 0\right) \quad (6)$$

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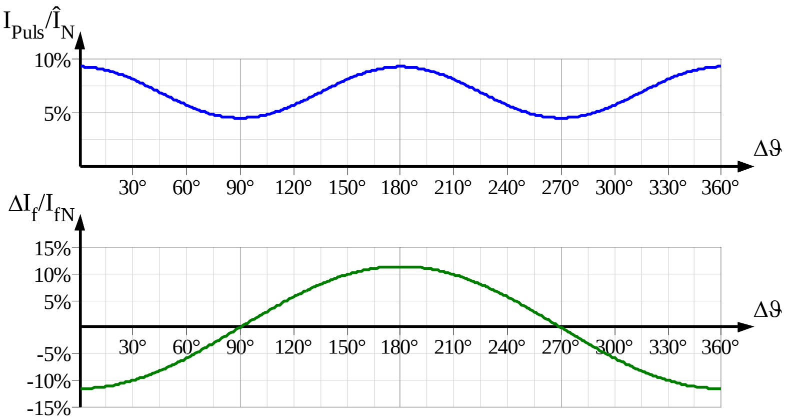

Fig. 8: Dependence of the indicator quantities to the angle error $\Delta\gamma = \gamma_{Pulse} - \gamma$ at a 1200kVA machine

4 Evaluation method

For the rotor position identification with the proposed method, the average value of the stator current indicator $\overline{I}_{Puls}$ as well as the amplitude $\hat{I}_{Puls}$ must be measured at commissioning of the drive. This can be achieved by injecting several voltage pulses in steps of 5° to each other in the stator and evaluating the corresponding stator current indicator I_{Pulse} at each position to obtain a curve similar to Fig. 8.
In order to detect the rotor position at standstill in the normal operation, a voltage pulse is first injected at the position γ_{Pulse}=0° and the stator current indicator I_{Pulse} is measured according to eq. 5. With solely one measurement of the indicator at a certain position, four possible angle errors are obtained as depicted in Fig. 9.

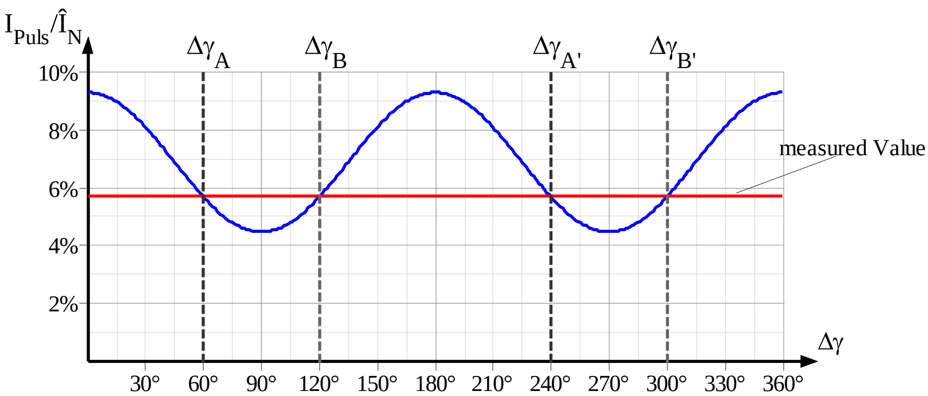

Fig. 9: Possible rotor positions obtained by measuring I_{Pulse} at one position

Two of the resulting positions lie either in positive or negative d-axis and need to be distinguished from the other obtained positions which lie at a different position. With the measured values from the commissioning the four possible angles errors can be calculated by eq. 7-10.

ISBN 978-3-8007-3431-3

$$\Delta\gamma_A = \frac{1}{2} arccos\left(\frac{I_{Pulse} - \overline{I_{Pulse}}}{\hat{I}_{Pulse}}\right) \tag{7}$$

$$\Delta\gamma_B = 180° - \Delta\gamma_A \tag{8}$$

$$\Delta\gamma_{A'} = \Delta\gamma_{A'} + 180° \tag{9}$$

$$\Delta\gamma_{B'} = \Delta\gamma_{B'} + 180° \tag{10}$$

In order to proof which of the identified angle positions lie in positive or negative d-axis, two further pulses are injected in the directions γ_A and γ_B (eq. 11, 12) and the corresponding indicator quantities $I_{Pulse,A}$, $I_{Pulse,B}$, $\Delta I_{f,A}$ and $\Delta I_{f,B}$ are measured.

$$\gamma_A = \gamma_{Pulse} - \Delta\gamma_A = -\Delta\gamma_A \tag{11}$$

$$\gamma_B = \gamma_{Pulse} - \Delta\gamma_B = -\Delta\gamma_B \tag{12}$$

The angle position at which the stator current indicator ($I_{Pulse,A}$ or $I_{Pulse,B}$) has the higher value, is the one which lies in d-axis or 180° aside to it (Fig. 8). In order to eliminate the 180° ambiguity the field current indicator at this position (either $\Delta I_{f,A}$ or $\Delta I_{f,B}$) must be evaluated as well. If the corresponding value is positive the examined position equals the negative d-axis whereas the angle lies at positive d-axis if the value is negative (compare Fig. 8).
The advantage of this approach is that the rotor position identification bases in general on the stator currents which can be measured with high accuracy. Only the sign of the field current indicator is evaluated which eases the identification in brushless excited machines, where the field current can not be measured with high accuracy.

5 Experimental results

At the moment experimental results are solely present for a downscaled low voltage machine (P_N=25kW, U_N=400V, f_N=50Hz) fed by a two level inverter, which is controlled with all limitations like a three level medium voltage inverter. The experimental setup is depicted in Fig. 10.

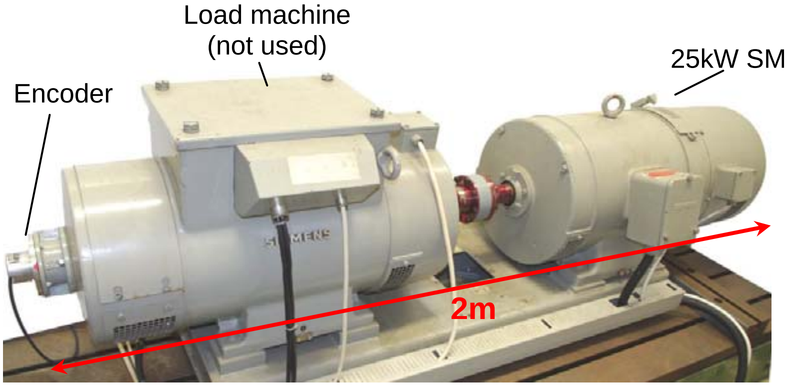

Fig. 10: Experimental setup

First of all, the angular dependence of both indicator quantities was measured by injecting several voltage pulses in steps of 5° to each other in the stator and evaluating the corresponding currents. The results are depicted in Fig. 11.

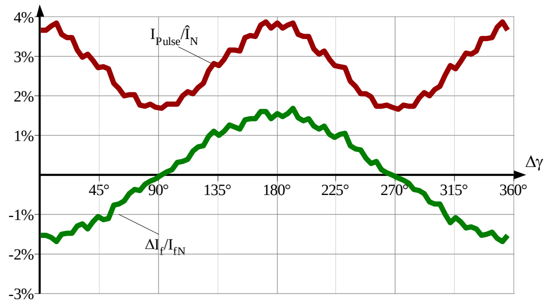

Fig 11: Dependence of the indicator quantities to the angular error (Measurements 25kW SM)

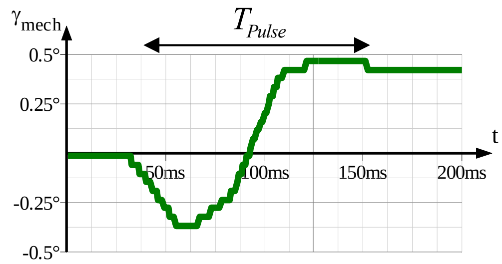

Fig 12: Motion during test pulse injection (Measurements 25kW SM)

It is obvious that the identified indicator quantities exhibit a great ripple. The reason for this is that the voltage injection in arbitrary positions (e.g. γ_{Pulse}=5°,10°,15°,…) can not be replicated with high accuracy, as the pulse is modulated by switching two corresponding active vectors (e.g. at 0° and 60°) with a very large modulation period (Space Vector Modulation). However, the final identification method described in chapter 3 leads to an acceptable accuracy as in this case the first pulse is injected in the direction of an active vector of the inverter at 0°. Therefore, the realization of the injected pulse for the rotor position estimation is very accurate.
With the explained method in chapter 3 the rotor position can be detected with an error of less than 12° of the electrical angular position on the given 25kW machine which is certainly rather a rough estimation than a precise measurement but allows the controlled start up of the drive.
The mentioned unwanted motion of the machine was examined as well by injecting the voltage pulse in the q-axis which demonstrates the most crucial case. The mechanical angle of the rotor was measured during the pulse injection and is shown in Fig. 12. The motion of the drive is less than 1° and thus can be neglected.

6 Conclusion.

A novel method for the detection of the initial rotor position in electrically excited synchronous machines without encoder is proposed. It injects low frequency pulses in the stator as the admittance in direct and quadrature axes exhibits the greatest difference at those frequencies and hence allowing the identification even in cylindrical rotor machines with brushless excitation. The pulse responses in the stator as well as in the field winding are measured and analyzed for the rotor position estimation. Simulation and experimental results validate the applicability of the identification procedure.

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