Initial Rotor Position Identification in Medium Voltage Synchronous Machines

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Abstract- **Electrically excited synchronous machines (SM) are a machine type commonly used in high power variable speed drives. For the realization of a high performance control scheme the knowledge of the actual rotor or flux position is mandatory and can be obtained by using a sensor attached to the shaft. To overcome the dependency on an encoder this information is obtained by adequate machine models which work reliably above a certain speed level. Yet, the encoderless identification of the initial rotor position is more challenging. In the following, a new identification method is presented which permits the detection of the SM's rotor position at standstill with a special focus on brushless excited SMs. Experimental results demonstrate the reliability of this method.**

Index Terms **—Sensorless control, synchronous motor, medium voltage drives**

I. Introduction

Encoderless control schemes for inverter fed AC-drives have shown increased acceptance in the last decades, especially for low voltage drives. Cost reduction and reliability improvement of the whole drive system are the reasons for intensive research in this area [1]. Meanwhile, the interest in encoderless controlled drives in the medium voltage area increases as well, aiming at an improvement of the total reliability by becoming independent of an encoder. Now, the question arises, whether the well established encoderless approaches in the low voltage range can also be applied in medium voltage drives.

In general, the sensorless control methods can be classified in two broadly accepted groups, the so called "fundamental wave models" and methods which exploit machine asymmetries [1][2]. The first group uses in principle the integration of the stator voltage to calculate the angle of the actual machine flux and thus allows the control of the drive. As these methods are based on the fundamental wave model of the machine, they can be implemented on any AC-machine. However, they fail if the drive is running at very low speed for a longer time since the induced stator voltages are nearly zero and the simple numerical integration drifts away. Nevertheless, a startup of the machine is possible if the initial rotor position was detected with a different approach and the critical speed region is passed through quickly.

The second group of methods exploits the machine asymmetries by injecting high frequency signals in the stator winding and evaluating the corresponding response to estimate the actual rotor or flux position [3-5]. In contrast to the fundamental wave models, the control of the drive is also possible at standstill or very low speeds. Unfortunately, these methods require special machine characteristics i.e. rotor asymmetries to detect the rotor or flux position and can therefore only be applied to a certain group of machines.

Especially the implementation of these methods in electrically excited synchronous machines is not always possible as the high frequency response only shows slight or almost no differences for a pulse is injected in direct or quadrature axis. In these machines, the high frequency response mainly depends on the parameters of the damper windings in both axes and less on the geometry of the rotor. Thus, the difference of the high frequency response in d- and q- axis can be even more pronounced in some cylindrical rotor machine than in a salient pole machine [6]. A further problem is that the d-axis can only be identified with 180° ambiguity as the pulse response is in general the same for pulses injected in positive or negative direction. In low voltage permanent magnet synchronous machines this problem is solved by monitoring the change of the saturation state of the mutual inductance when injecting a strong pulse in the stator. A pulse in d-axis increases the level of saturation and affects the value of the mutual inductance whereas a decreasing saturation level indicates that the pulse was injected in the negative d-axis [3][7]. Even though this method could be in principle implemented in electrically excited SMs, the presence of the damper winding impedes in most machines the examination of the saturation state. As a consequence, encoderless methods which rely on the injection of high frequency pulses can only be implemented on a few of the electrically excited synchronous machines.

Nowadays, the standard approach for the encoderless identification of the initial rotor position is the short circuiting of the stator winding by the inverter while increasing the field current as fast as possible with the excitation system [8]. Due to the changing magnetization state of the machine a voltage is induced in the stator winding leading to a measurable stator current. The direction of the resulting current space phasor is in negative d-axis and thus allows the identification of the rotor position. This approach works reliably in static excited machines as the field winding is directly accessible by slip rings and a field current with a high steepness (di/dt) can be impressed by the DC-excitation converter. However, in brushless excited machines the field current can only be controlled by the stator currents of the excitation system. As the overall inductance in brushless excited machines includes the rather large inductances of the excitation machine, the time constant of this system is much higher compared to the one with static excitation. In this configuration, the maximum steepness (di/dt) of the field current can be too low for a

Table 1: Identification or start-up methods depending on machine characteristics
(X=possible, - not possible, ? depending on dynamics of the excitation system)

	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
New method: "Low frequency signal injection"	X	X	X

measurable response in the stator current and thus the rotor position identification with this method is not possible.

In theory, the asynchronous start-up could be another alternative. But for this method the field winding must be short circuited, which is generally not possible in brushless excited machines.

Table 1 gives an overview of the mentioned rotor position identification methods and start-up procedures. Especially for brushless excited machines which exhibit similar high frequency behavior in d- and q- axis, no reliable identification method for the initial rotor position is known up to now.

In the following, a new approach for the initial rotor position detection is introduced, based on low frequency signal injection in the stator winding. The stator current response as well as the response in the field current are examined and allow the identification in a wide range of synchronous machines including the crucial case with similar high frequency behavior in both axes and brushless excitation.

II. LOW FREQUENCY PULSE RESPONSE

The electrical system of a SM with damper winding can be expressed by the voltage and flux equations 1 to 12 [9]. Based on these equations an equivalent circuit which describes the electrical behavior of the SM in standstill can be specified as depicted in Fig. 1. In principle, every electrically excited synchronous machine exhibits different behavior in d- and q-axes as solely the d-axis contains the field winding. Even if the distinction of both axes is not possible with high frequency signal injection, the rotor identification can be achieved if the test pulse frequency is set adequately. Therefore, it is important to analyze the frequency response characteristic of the machine for the case that a voltage pulse is injected in d- or in q-axis. To calculate the response characteristic for a given machine the field voltage is assumed to be constant as the dynamics of the field current controller is quite slow. Therefore, the field voltage in the equivalent circuit in Fig. 1 can be considered as a short circuit for the frequency response calculation.

Voltage equations:

$$u_d = R_s \cdot i_d + \dot{\Psi}_d - \Omega \Psi_q \tag{1}$$

$$u_q = R_s \cdot i_q + \dot{\Psi}_q + \Omega \Psi_d \tag{2}$$

$$0 = R_D \cdot i_D + \dot{\Psi}_D \tag{3}$$

$$0 = R_Q \cdot i_Q + \dot{\Psi}_Q \tag{4}$$

$$u_f = R_f \cdot i_f + \dot{\Psi}_f \tag{5}$$

Flux equations:

$$\Psi_d = L_{S\sigma} \cdot i_d + \Psi_{md} \tag{6}$$

$$\Psi_q = L_{S\sigma} \cdot i_q + \Psi_{mq} \tag{7}$$

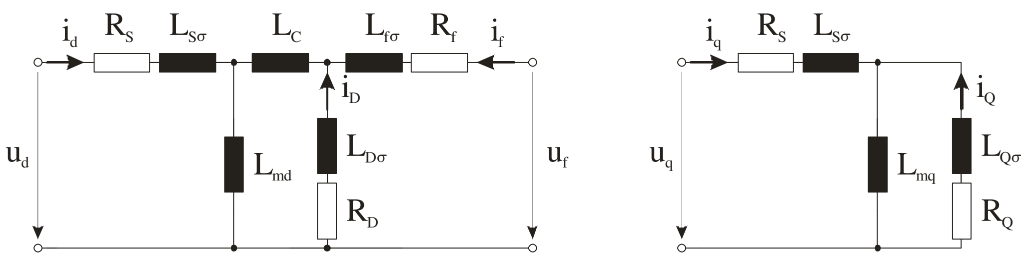
$$\Psi_D = L_C \cdot \left(i_D + i_f\right) + L_{D\sigma} \cdot i_D + \Psi_{md} \tag{8}$$

$$\Psi_Q = L_{Q\sigma} \cdot i_Q + \Psi_{mq} \tag{9}$$

$$\Psi_f = L_C \cdot \left(i_D + i_f\right) + L_{f\sigma} \cdot i_f + \Psi_{md} \tag{10}$$

$$\Psi_{md} = L_{md} \cdot \left(i_d + i_D + i_f\right) \tag{11}$$

$$\Psi_{mq} = L_{mq} \cdot \left(i_q + i_Q\right) \tag{12}$$



R_X	Winding resistance
$L_{X\sigma}$	Stray inductance
L_{mX}	Mutual inductance
L_C	Canay inductance

Index:

S	Stator winding		f	Field winding
d	d-axis stator winding		D	d-axis damper winding
q	q-axis stator winding		Q	q-axis damper winding

Fig. 1: Equivalent circuit in standstill in d- and q-axes of the SM

A typical frequency response of an electrically excited synchronous machine is depicted in Fig. 2. It is obvious that the admittances in d- and q- axis vary significantly in the frequency range between 1 and 10Hz, mainly due to the field winding in the d-axis. Almost every synchronous machine, with salient poles or with cylindrical rotor, exhibits those large differences of the admittance of both axes in this frequency range. Thus, the frequency of the voltage test pulse should be chosen in the range where the admittance difference exhibits its maximum value. Of course, this value depends on the actual machine but our investigation has shown that it generally lies in the range of 1 to 10Hz. If several voltage pulses are injected in different directions in the stator winding, the d-axis can thus be identified by evaluating the current responses to the applied voltage pulses.

In addition to the stator current, the field current is affected from the voltage pulse injection as well and can also be used for the rotor position estimation. The quotient of the amplitude of the resulting AC-part in the field current and the injected voltage amplitude ($\hat{\imath}_f/\hat{u}_d$) is shown in Fig. 3, for a voltage pulse is injected in the d-axis. It is obvious that the field current response in the interesting frequency range, in which the admittances of both axes have the maximum difference, is sensitive enough for the later explained rotor position identification method. The main challenge in evaluating the field current response is the fact that it cannot be measured directly in brushless excited machines as it is not accessible. However, for control purposes the excitation system reconstructs the field current based on the envelope of the stator currents of the exciter as depicted in Fig. 4 and 5. Certainly, the resulting reproduced field current signal i_f' exhibits low accuracy but it is accurate enough for the proposed rotor position identification method.

For safety reasons, the field current must always flow during any operation of the inverter. Otherwise, the stator voltage pulses of the inverter are transformed to the field winding causing an overvoltage at the rotating diodes or at the field winding. In brushless excited machines the field current is therefore always kept above 30% of its nominal value.

III. REALIZATION OF LOW FREQUENCY TEST PULSES

As the machine is magnetized, the current pulse in the stator winding will develop torque and the machine can move during the test pulse injection. In addition, the stator admittance in the desired frequency range of the test pulse is very high so that a low voltage pulse can produce high stator currents. Thus, the amplitude of the voltage test pulses should be kept as low as possible in order to avoid excessive motion of the machine. The dc-link voltage of the inverter is kept at a constant value and

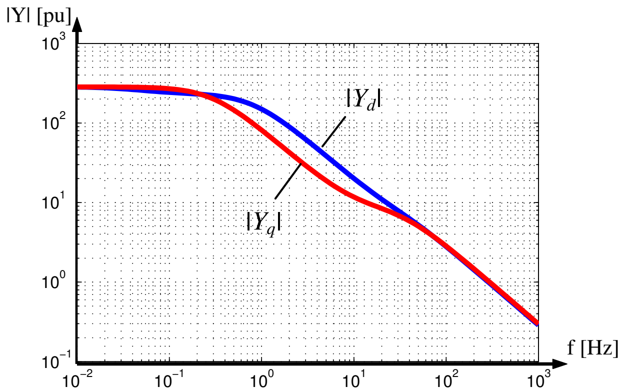


Fig. 2: Typical frequency response characteristics of a SM (here: 10MW salient pole machine; $1pu=\hat{I}_{1N}/\hat{U}_{1N}$)

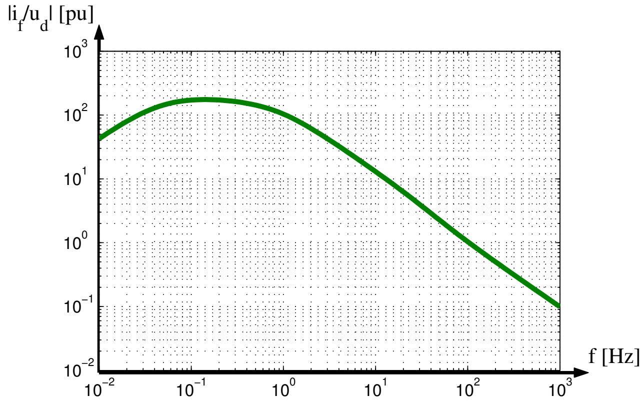


Fig. 3: Frequency dependence of the field current pulse response, for a pulse is injected in the d-axis (here: 10MW salient pole machine)

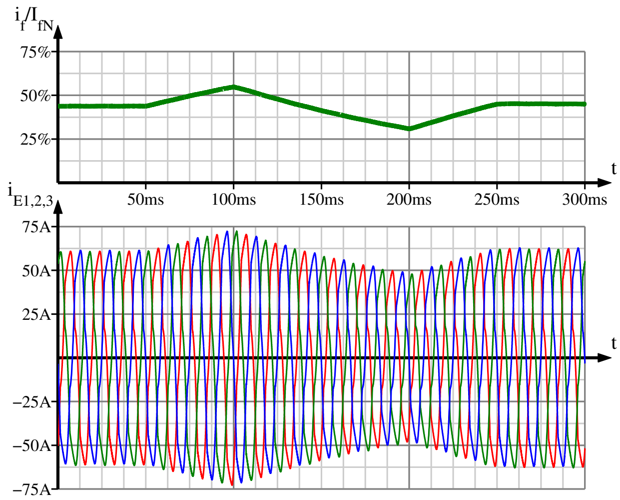


Fig. 4: Reproduction of the field current based on the exciter stator currents (simulation results)

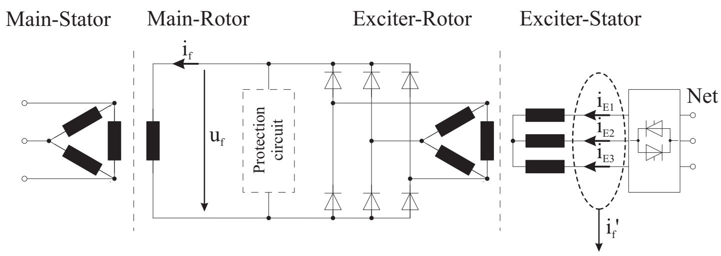


Fig. 5: Block diagram of the brushless excitation system

the test pulses are realized by a space vector modulation which allows the injection of the test pulse in any arbitrary direction γ_{Pulse} in the stator winding (eq. 13-15). Furthermore, a rectangular pulse is chosen as a test signal because it can easily be replicated by the inverter.

$$u_{U0}(t) = u_{Pulse}(t) \cdot \cos(\gamma_{Pulse}) \tag{13}$$

$$u_{V0}(t) = u_{Pulse}(t) \cdot \cos(\gamma_{Pulse} - 120°) \tag{14}$$

$$u_{W0}(t) = u_{Pulse}(t) \cdot \cos(\gamma_{Pulse} - 240°) \tag{15}$$

It is worth to mention that the realization of modulated, very small voltage amplitudes by a medium voltage inverter is a difficult task since several limitations e.g. minimum on-times of several ten microseconds must be considered. Hence, a large modulation period is necessary in order to realize the pulse. A typical value for the test pulse amplitude is 0.3% of the nominal machine voltage which can be well realized by setting the modulation period to a value of several milliseconds.

The pulse response is measured in the stator current component which lies in the same direction as the injected voltage pulse (i_{pulse}). This signal can be expressed by the three stator currents according to (16), where γ_{Pulse} is the angular position of the injected test pulse referred to the stator.

$$\begin{aligned} i_{Pulse}(t) = {} & i_U(t) \cdot \cos(\gamma_{Pulse}) \\ & + i_V(t) \cdot \cos(120° - \gamma_{Pulse}) \\ & + i_W(t) \cdot \cos(240° - \gamma_{Pulse}) \end{aligned} \tag{16}$$

As the modulation period for the rectangular test signal is very large, the resulting current with the modulated signal differs strongly from the ideal response (Fig. 6). However, its fundamental wave contains all the necessary information to identify the rotor position.

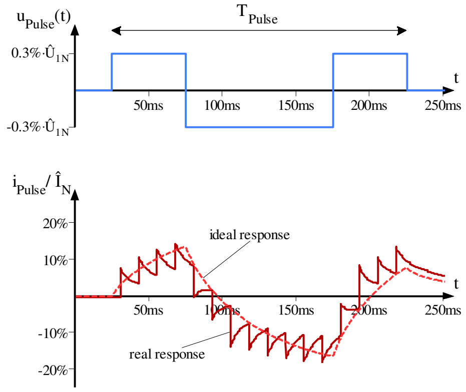


Fig. 6: Modulation of the voltage test pulse and its stator current response (simulation results)

The pulse responses in the stator current component i_{pulse} as well as in the field current i_f depend on the angle error $\Delta\gamma$, which is defined as the angular difference between injected pulse direction γ_{Pulse} and d-axis γ (17).

$$\Delta\gamma = \gamma_{Pulse} - \gamma \tag{17}$$

In Fig. 7 the ideal current responses are shown when injecting the test pulse in different directions relative to the d-axis.

In order to evaluate the current responses in the different directions, an adequate indicator quantity is necessary which concentrates all the desired information of the pulse response signal into one quantity. In this case the rms-value of the stator current component in pulse direction I_{pulse} as well as the change in the field current ΔI_f are used as indicator quantities which can be calculated online during each pulse injection according to (18) and (19). The field current indicator ΔI_f indicates the increase or decrease of the field current during the time interval $0<t<T_{Pulse}/4$, where $t=0$ represents the starting time of the pulse injection.

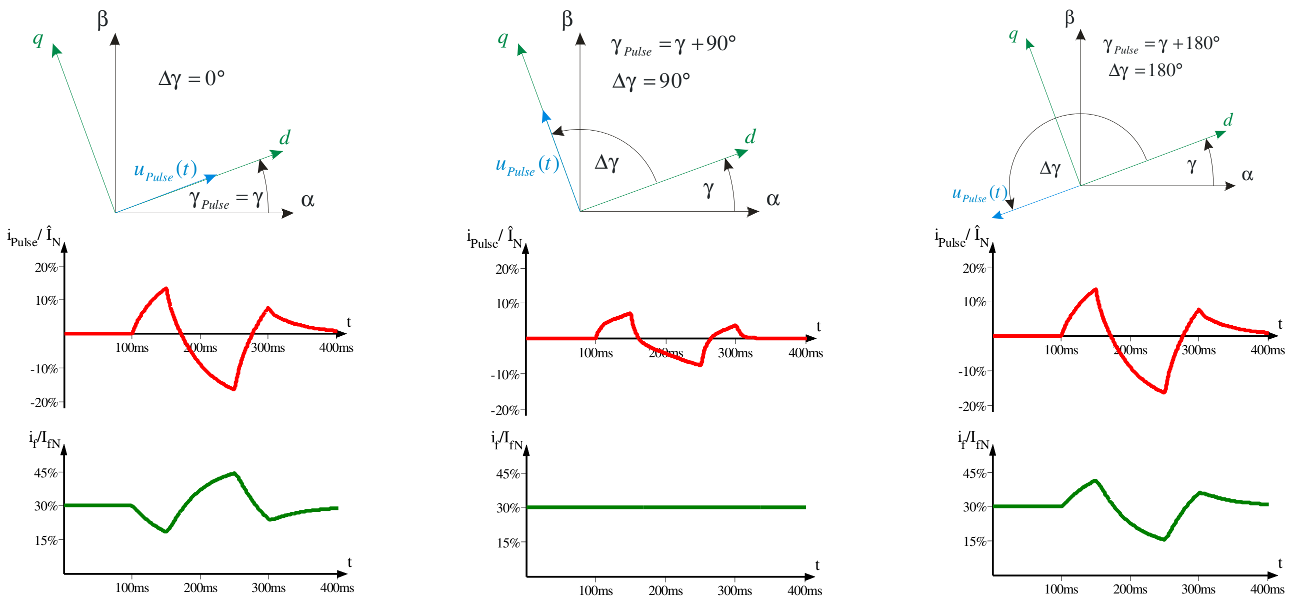


Fig. 7: Test pulse injection in different directions and their (ideal) current responses (simulation results)

$$I_{Pulse} = \sqrt{\frac{1}{T_{Pulse}} \int_0^{T_{Pulse}} i_{Pulse}^2(t) \cdot dt} \tag{18}$$

$$\Delta I_f = i_f\left(t = \frac{T_{Pulse}}{4}\right) - i_f\,(t = 0) \tag{19}$$

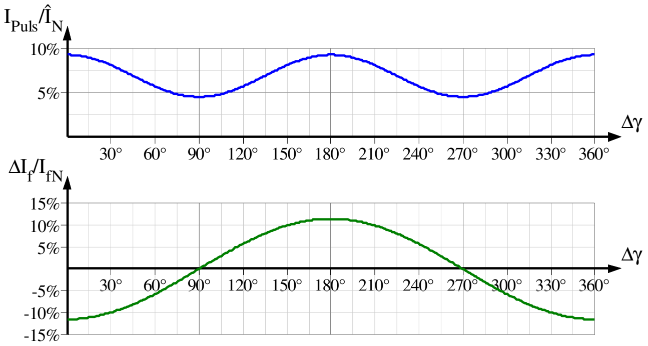


Fig. 8: Dependence of the indicator quantities to the angle error $\Delta\gamma$

The dependence of the stator current indicator I_{pulse} and field current indicator ΔI_f on the angular error $\Delta\gamma$ are shown in Fig. 8. In contrast to the stator current response, the field current allows the identification of the d-axis without 180°-ambiguity as it differs if a pulse is injected in positive or negative d-axis.

IV. Identification Method

As mentioned above, the rotor position identification with solely the stator current indicator I_{pulse} leads to the 180°-ambiguity as the d-axis lies at one of the two positions where the indicator quantity exhibits its maximum value (Fig. 8). On the contrary, the field current indicator ΔI_f would allow the complete identification of the rotor position but it exhibits low accuracy in brushless excited machines as it is based on the reconstructed field current signal (Fig. 4). By using both indicators, the advantages of high accuracy of the stator current indicator and the elimination of the ambiguity by the field current indicator are combined.

For the evaluation of the pulse responses with the proposed method, the offset value of the stator current indicator $\overline{I_{Pulse}}$ (20) as well as the amplitude $\hat{I}_{pulse}$ (21) must be measured at commissioning of the drive. This can be achieved by injecting several voltage pulses in steps of 15° 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 and compute:

$$\overline{I_{Pulse}} = \frac{I_{Pulse}(\Delta\gamma = 0°) + I_{Pulse}(\Delta\gamma = 90°)}{2} \tag{20}$$

$$\hat{I}_{Pulse} = \frac{I_{Pulse}(\Delta\gamma = 0°) - I_{Pulse}(\Delta\gamma = 90°)}{2} \tag{21}$$

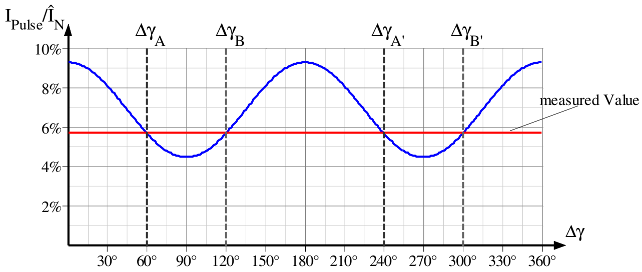


Fig. 9: Possible rotor positions obtained by measuring I_{pulse} at one position

In order to detect the rotor position at standstill, a voltage pulse is first injected at the position γ_{Pulse}=0° and the stator current indicator I_{pulse} is measured according to (18). With this information, four possible angle errors are obtained as depicted in Fig. 9.

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 different positions. By using the characteristics of the machine measured during the commissioning e.g. Fig. 8, four possible angles can be calculated by eq. 22-25.

$$\gamma_A = -\frac{1}{2} arccos\left(\frac{I_{Pulse} - \overline{I_{Pulse}}}{\hat{I}_{Pulse}}\right) \tag{22}$$

$$\gamma_B = 180° - \gamma_A \tag{23}$$

$$\gamma_{A'} = \gamma_{A'} + 180° \tag{24}$$

$$\gamma_{B'} = \gamma_{B'} + 180° \tag{25}$$

In order to find out, 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. 22, 23) and the corresponding indicator quantities $I_{Pulse,A}$, $I_{Pulse,B}$, $\Delta I_{f,A}$ and $\Delta I_{f,B}$ are measured.

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. 7).

V. Experimental Results

The approach proposed in this work was tested on a brushless excited SM fed by a three level medium voltage inverter. In Table 2 the nominal values of the machine are presented.

First, the angular dependence of both indicator quantities was measured by injecting several voltage pulses in steps of 15° in the stator and evaluating the corresponding currents. The results for a pulse frequency of 2Hz are depicted in Fig. 10.

Table 2: Nominal machine values

P_N	1.06MW	M_N	45kNm
n_N	225min^{-1}	f_N	15Hz
U_N	3300V	I_N	186A

With the method explained in section IV the rotor position can be detected with an error of less than 12° of the electrical angular position on the given machine which is certainly a rather rough estimation than a precise measurement but guarantees the controlled start up of the drive.

The mentioned unwanted motion of the machine was examined by injecting the voltage pulse in the q-axis which is considered to be the most crucial case. The mechanical angle of the rotor was measured during the pulse injection and is shown in Fig. 11. The motion of the drive is less than ±2.2° and is acceptable for most applications.

VI. CONCLUSION

In this paper a novel method for the detection of the initial rotor position in electrically excited synchronous machines without encoder is proposed. By exploiting the fact that the admittance in direct and quadrature axes of electrical excited SM exhibits large differences in a given frequency range, voltage test pulses in this frequency range are injected in the stator. The evaluation of the current response in the stator as well as in the field winding allows the identification of the rotor position even in cylindrical rotor machines with brushless excitation. Simulation and experimental results validate the applicability of the identification procedure.

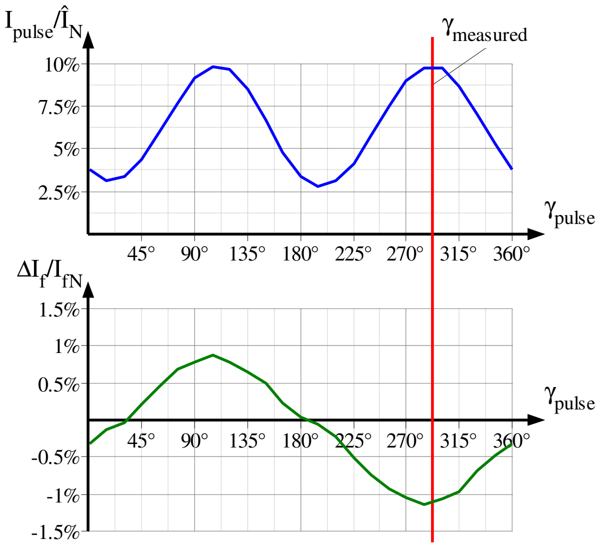


Fig. 10: Dependence of the indicator quantities to the angular error

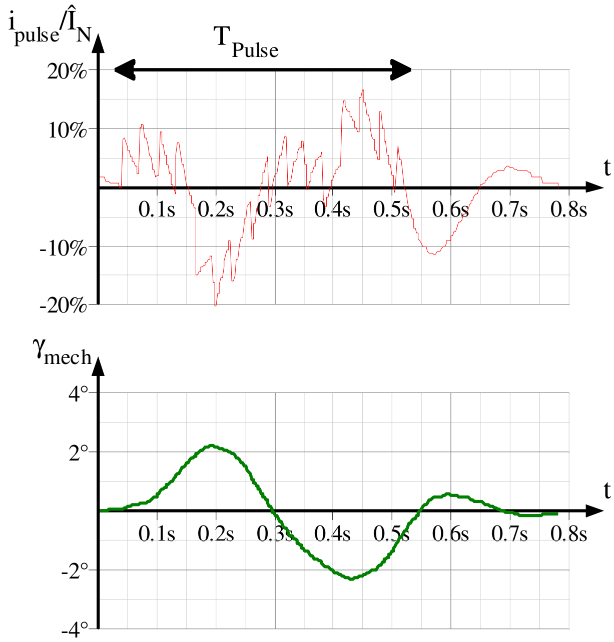


Fig. 11: Motion of the rotor during test pulse injection

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