Prediction of Slotting Saliency in Induction Machines with Respect to High-Frequency-Excitation Based Sensorless Control

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Abstract — Sensorless field oriented control (FOC) strategies have found their place in industry applications during the last few years. Stimulated by this development scientific research continues to improve their performance, which is directly linked to the estimation accuracy of flux and rotor position without a mechanical sensor by means of high frequency or transient excitation. The influence of induction machine (IM) design parameters on the rotor saliency, originating from interactions of rotor and stator slotting, is investigated with a focus on transient electrical machine behavior. As this saliency is often used to estimate rotor position in sensorless control schemes, effects attenuating or sustaining it have a straight impact on the control's quality. The present study features finite element (FE) simulations that are compared to measurements for a number of test machines, to validate the results. In a second step it aims at generating a more comprehensive view on the dependencies between saliency and machine design by conducting parameter variations by means of FE simulations, with a focus on stator short pitching and rotor skewing.

Keywords—finite element analysis; sensorless control; performance evaluation; induction machine;

I. INTRODUCTION

Starting about two decades ago sensorless field oriented control strategies have come a long way and are quite established in industry applications nowadays. Extensive scientific research in this area facilitated this development and led the way towards stable and reliable control algorithms at zero/low speed and high torque operation.

Although realizations may differ the basic concept stays the same. It relies on the tracking of saliency dependent stator inductance variations to derive a position signal. This can be achieved by injection of periodic or transient high frequency signals in addition to the fundamental wave. The periodic signals used are either of pulsating or rotating nature, or result from inverter switching when exciting the machine with the fundamental wave [1]-[6]. Transient injection methods use switching patterns to evaluate the transient current change [7]-[10]. These switching patterns are applied in addition to the PWM-sequence that excites the fundamental wave. However, additional signal injection involves side effects like acoustic

noise emissions, influence on switching frequency and efficiency, additional current ripple or decreased maximum inverter output voltage. In the recent years scientific research focused on resolving these drawbacks by integrating the transient excitation sequence into the PWM-sequence used for fundamental wave excitation [10]-[13].

The saliency signals, determined with the mentioned methods, are directly linked to machine slotting and saturation and can thus be used to estimate rotor and flux angle in sensorless control schemes. When exploiting one of them as control signal, the other acts as disturbance. The associated decrease in estimation accuracy basically depends on the components' spectral distance and their magnitude relative to each other. This has a direct impact on the control performance, which stays within tolerable limits as long as the signals are clearly distinguishable. Besides the main saliencies caused by saturation and slotting, usually also intermodulation components are present. These intermodulation effects are not focus of the present paper, though. Ways to reduce these disturbances are the application of neural networks [14], function approximation or correction tables [15], or special filtering methods [16]-[18]. Another possibility is to mitigate, sustain or create individual saliencies based on their origin, i.e. altering the machine design (e.g. geometry, material or winding scheme) [19].

The investigation in this paper concentrates on the identification of transient leakage inductance variations related to the rotor slotting. Applying a machine excitation with voltage steps using the switching of the inverter, the resulting transient current reaction contains information on all machine saliencies, whether designed, inherent (saturation, slotting, anisotropy) or even fault induced components (damaged rotor bars or windings, eccentricities). All these saliencies modulate the transient leakage inductance, which subsequently is visible in the machine current as response to the switching inverter. Thus, the rotor position signal needed for sensorless control can be derived non-invasively using the inverter's built-in current sensors.

To analyze the influence of machine design on the rotor slotting saliency, measurements on test machines were carried out. These machines differ in single design parameters, i.e.

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rotor skewing, stator winding scheme or number of stator and rotor slots. Due to the limited amount of specimen only tendencies concerning the influence of these parameters on the slotting signal could be identified [20]. In order to get a more comprehensive few and eventually find optimum designs additional investigations are needed.

With this in mind an induction machine FE model was established to predict the influence of design on the slotting signal, when one design parameter is changed, whereas the others are kept constant. In the following, simulations carried out with this model are compared to measurement results for the mentioned test machines to prove its reliability. In a second step an extension with additional simulation results is made to analyze the transient machine behavior, show single parameter dependencies and discuss their possible impact on sensorless control strategies. The present paper thereby concentrates on the saliency caused by the rotor slotting, represented by a modulation of the transient current slope, and its dependency on stator pitching and rotor skewing.

II. SALIENCY SIGNAL EXTRACTION

The machine saliencies are determined based on the excitation of the machine by voltage steps. In order to get a measurable response from the machine an excitation signal is needed. The source of this signal is the drive's inverter, which is used to generate a fundamental wave excitation, for example by means of pulse width modulation (PWM). The involved voltage pulses cause transient phase current responses that can be measured by the drive's inherent current sensors.

Due to the high frequency excitation the squirrel cage prevents the flux from penetrating the rotor and limits it to alternating between stator and rotor tooth tips, causing a high amount of zig-zag flux. This recurring transition makes the air gap quite dominant, linearizes the measured current response and introduces a rotor position dependent current slope modulation. More specifically, the changing positions of rotor/stator teeth and slots relative to each other modulate the current slopes when the rotor is turned. Tracking of this modulation allows for extraction of the rotor slotting saliency component. In case the rotor is turned by one mechanical revolution, the modulation exhibits a periodicity equal to the number of rotor slots N_r .



Fig. 1: Current change phasor trajectory of a two pole machine. α : excitation direction (= phase L1), $l(\gamma)$: spatial leakage inductance distribution, γ : angular position of maximum leakage inductance, n: periodicity factor.

Another important saliency is connected to the saturation of the electrical steel used to build rotor and stator core. Here the pole number corresponds to the number of saturation maxima within the machine. The current responses show a distinct dependence on the saturation level in excitation direction and therefore on the flux position. Hereby only the saturation level is of importance, not the flux direction. This means that magnetic north and south poles are equal. As a consequence the saliency modulation's harmonic order with respect to one mechanical revolution is equal to the pole number (= 2*p), where p is the number of pole pairs. Of course there exist additional saliencies within the machine, amongst them the ones introduced by rotor eccentricity or material anisotropy. Their influence on sensorless control is not further considered in this work, though. For saliency signal derivation the reader is referenced to [21].

In Fig. 1 an example of the saliency signal's graphical manifestation for a two pole machine is given, similar to the ones occurring in chapter V. The figure shows the trajectory formed by the tip of the current change phasor $\Delta \underline{i}_S / \Delta \tau$. This phasor itself is composed of a constant part $\Delta \underline{i}_{S,const}/\Delta \tau$, representing the average current change (resulting from the symmetrical machine) and a changing part $\Delta \underline{i}_{S,mod}/\Delta \tau$, depending on the corresponding leakage inductance distribution $l(\gamma)$. The maximum inductance position is given by the mechanical angle γ , which forms the electrical angle of the current change phasor trajectoriy by multiplication with the saliency periodicity factor n. For one revolution of the saliency this factor equals the number of inductance maxima. This means n=2 in case of the saturation saliency for a two pole machine. With regard to the rotor slotting saliency *n* equals the rotor slot number N_r .

III. COMPARISON OF MEASURMENT AND SIMULATION

In this chapter the simulation results are compared to measurements in order to validate their applicability. Detailed information on measurement setup and FE model can be found in [20] and [22], respectively. As the used model is a 2-dimensional representation of the real IM, the lack of an axial dimension hinders the straight incorporation of rotor skewing. The majority of test machine combinations are composed of skewed squirrel cage rotors, though. Therefore the well known multi-slice FE method was used to account for the effect caused by skewed rotor bars. A uniform slice distribution with a number of 5 slices was chosen [23].



Fig. 2: Comparison of measurement and simulation of slotting modulation magnitudes. X-axis corresponds to pitching (first value) and skewing (second value); *f*: full-pitched and *u*: unskewed, respectively.

Fig. 2 compares measurement and simulation results for a number of 7 test machines, with similar geometries but different stator winding pitching and rotor skewing. The machine with full-pitch (f) stator winding and unskewed (u) rotor serves as reference. Thus, the slotting modulation's magnitude is set to a value of 1. The good agreement with the measured results proves the quality of the FE model. As can be seen from the figure, skewing and short pitching influence the slotting modulation magnitude and act as reduction factors in case of the shown machine designs.

IV. ROTOR SKEWING VARIATION

The present paper is focused on the slotting saliency obtained from high frequency or transient excitation. Thus, rotor skewing plays an important role for the slotting modulation magnitude, which can be seen in Fig. 2. Simulations with the mentioned multi-slice FE model give the skewing factor for transient pulsed voltage excitations. Its course is similar in shape to the one shown in Fig. 3, which shows a dampened periodic manifestation and gives information on the influence of skewing variation on the slotting signal. Therefore some conclusions concerning the sensibility of sensorless rotor position as well as flux position estimation can be drawn from Fig. 3.



Fig. 3: Reduction factor as result of rotor bar skewing. The skewing s refers to the rotor slot pitch, e.g. sq=1 denotes a skew by one rotor slot pitch.

Rotor position estimation:

In order to get a clearly detectable position signal the rotor slotting modulation has to be maximized. From this follows:

- 1. The maximum magnitude is achieved when using an unskewed squirrel cage. However, this comes with disadvantages like undesired higher harmonic air gap fields, torque ripple, vibrations and noise.
- 2. If skewing is needed to reduce these undesirable effects, the second (right) maximum in Fig. 3 can be used, to still get as much rotor slotting magnitude as possible.

Flux position estimation:

If the flux position is to be determined by means of the saturation saliency, the rotor slot signal acts as a disturbance. It is then desirable to choose a skewing near 1 rotor slot pitch (RSP) to get a maximum reduction factor for the rotor slotting modulation and facilitate the saturation saliency position estimation.

V. STATOR SHORT PITCHING VARIATION

The windings analyzed in this chapter have two layers and use simple winding step shortening. Starting from the test machine combinations in Fig. 2, which use full-pitch, 7/9 and 5/6 short pitched windings, the influence of this design parameter will be shown. This is done by completing the picture with additional simulation results for various short pitching steps, starting from the full-pitched case until a short pitching of 2/3 plus one additional step is reached. This limit is chosen with the fact in mind that usually short pitchings are realized down to a value of 2/3. The results for the test machines, constructed with the three mentioned windings, were extended with the combinations given in Table I.

	I ADLE I	
	Machine 1	Machine 2
N_s/N_r	36/44	24/44
p (pole pairs)	1, 2, 3	2
short pitching	11/18-18/18, 5/9-9/9, 3/6-6/6	3/6-6/6

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<u>Machine 1</u>:

Results for the simulations of machine 1 are given in Fig. 4-Fig. 5. The 1/6 short pitching is not depicted as this combination cancels out the rotor slotting modulation for reasons that will be discussed in chapter VI.

1/9 short pitching steps:

Fig. 4 shows the influence of 1/9 step shortening (from 9/9 to 5/9) on the resulting rotor slotting trajectory, in case of a 4 pole winding. Each of the traces depicted, shows the modulation of the current change phasor due to the slotting saliency obtained. Starting from the full-pitched case (9/9) the modulation's magnitude decreases until it reaches its minimum at 7/9 and starts increasing again for 6/9 (=2/3) and the 'uncommon' 5/9 pitching.

With respect to flux position estimation the minimum value at 7/9 represents the optimum value for minimum distortion of the saturation signal by rotor slotting. The center of the trajectories depicted, that represents the average current slope, is increasing monotonically. This expresses the increasing current linkage needed to generate a given flux value in the air gap if the same number of turns is used, a drawback of shortpitched windings. If this disadvantage is acceptable for a given application an increased slotting magnitude can be achieved, when using a 6/9 or the even the uncommon 5/9 pitching. This on the other hand is favorable in rotor position control, where a reliable rotor position signal is needed.

1/18 short pitching steps:

Fig. 5 illustrates the impact of short pitching for a 2 pole winding. It starts with full-pitching (18/18) and reduces the pitching in steps of 1/18 down to 12/18 (=2/3), plus the next step (11/18). If corresponding pitching numbers are compared, i.e. 9/9 (Fig. 4) and 18/18 (Fig. 5), 8/9 and 16/18 etc., the two pole winding (1/18 steps) shows reduced slotting magnitudes compared to the 4 pole case (1/9 steps). Due to this reduction, which will be discussed in the next chapter, the 1/18 pitching seems better suited for flux position estimation purposes.



Fig. 5: Slotting trajectories due to short pitching in steps of 1/18, p=1.

The only exception is the 7/9 (smaller magnitude) and 14/18 (bigger magnitude) pair, for which the roles are swapped. Similar to Fig. 4 a modulation of the slotting magnitude is observable, showing a minimum for 15/18 pitching. Due to the similarities the same conclusions concerning rotor and rotor flux position estimation can be drawn for the individual short pitching steps, as done in the 1/9 case.

Machine 2 – 1/6 short pitching steps:

Fig. 6 finally shows the slotting trajectories when 1/6 pitching steps are applied. The courses exhibit an overall increased slotting magnitude. The pitching dependent change of the modulation magnitude is decreased, though. This means that no distinct minimum of the depicted traces is exhibited as seen for the 7/9 (Fig. 4) and 15/18 (Fig. 5). Consequently this machine design is less suited for flux position estimation than machine 1. Therefore the best choice in this case is the fullpitch winding. On the other hand this makes it a better candidate for rotor position estimation, due to the increased rotor slotting modulation.

VI. DISCUSSION

This chapter discusses the reasons for the differences in the slotting trajectories shown above. Some winding configurations seem to strengthen the visibility of the slotting modulation in the stator change trajectory, while others weaken or even cancel them. To analyze these effects the stator winding is divided into its elementary components, i.e. the conductors in the N_s stator slots. Each of these slots is opposed to a certain rotor slot position.



Fig. 6: Slotting trajectories due to short pitching in steps of 1/6, p=2.

Fig. 7 shows this relationship, which means that, dependent on the ratio N_s/N_r , some stator slots will be opposed to rotor teeth others to rotor slot openings. As already mentioned above, these different positions correspond to certain permeance levels, which vary along the air gap. If this permeance variation is approximated by a sine wave with the frequency $1/N_r$ and the wave length of 1 RSP (as indicated in Fig. 7), the occurring stator and rotor slot combinations can be described for each rotor position by N_s phase shifted phasors, one for each stator slot. The projection of each phasor equals the permeance of the stator winding conductor placed in the corresponding slot.



Fig. 7: Relative stator and rotor slot position dependence on the ratio N_s/N_r . Approximated permeance levels.

Every stator slot houses one elementary part of the stator winding, which thus directly interacts with the rotor position dependent permeance value. According to the used stator winding scheme, all basic winding parts are connected to each other, forming the machine's turns, coils, coil groups and eventually the whole phase. Consequently the corresponding phasors, representing single winding parts, can be used to describe the overall permeance modulation seen by the stator winding. This procedure will be used in the following to interpret the results obtained in the previous chapter.

Machine 1:

The procedure is explained for machine 1 with N_s =36 stator and N_r =44 rotor slots. Fig. 7 and equation (1) illustrate that the phase shift (in terms of the permeance function) between the phasors of two adjacent stator slots can be calculated in terms of rotor slot pitches (RSP) or with respect to the approximating sine function in degrees (°).

$$\delta = \frac{Nr - Ns}{Ns}RSP = \frac{2}{9}RSP \quad \Leftrightarrow \quad \frac{2}{9} \cdot 360^{\circ} = 80^{\circ}$$
(1)

<u>9/9 (full-pitch)</u> stator winding:

First the full-pitch double layer winding of machine 1 with 4 series connected poles and 3 phases is analyzed. As the whole machine consists of 36 stator slots it has 36/4=9 stator slots per pole and 36/(4*3)=3 slots per pole and phase. This resembles 3 series-connected coils. Each coil spans one pole pitch and consists of two coil sides separated by 9 slots. The coil sides represent forward conductors and return conductors. Therefore $3^{*}2=6$ phasors exist per pole and phase, 3 for the forward and another 3 for the return coil sides. Fig. 8 displays this forward phasors (black). As the forward coil sides are in adjacent slots, the phase shift between each of them is 80° (1). Between one forward and the corresponding return conductor lie 9 stator slots what corresponds to a shift of $9*\delta=720^\circ$. As this equals a full number of revolutions, forward (black) and return (red) phasors have the same angular position and thus are parallel in Fig. 8. Due to the series-connection of all coil sides the phasors can be added geometrically.



Fig. 8: Forward and return permeance phasors of one pole (left) and direction of resulting phasor for each individual pole (right). All pole permeance phasors exhibit same phase and therefore generate a slotting signal in the winding.

The resulting phasor of all coil sides points towards 80° (Fig. 8, right) and its length is an indicator for the order by which the different slot modulations amplify or attenuate each other. So far only one pole of one phase has been considered. The machine consists of 4 poles, though. The integer number of 11 (= 44/4) rotor slots per pole makes for the same angular direction of the resulting phasor for each pole. Again the permeance modulation is amplified. This is the reason why the 9/9 winding with the given ratio N_s/N_r exhibits a slotting signal. In the following a scenario is shown, where the overall permeance variation modulates the winding in such a way that the individual parts cancel each other out.

<u>6/6 (full-pitch)</u> stator winding:

As already mentioned in chapter V, machine 1 (with 6 pole winding) does not exhibit a current slope modulation. This will be explained in the following by application of the same procedure as before.

Equation (1) remains unchanged in this case as the slot numbers do not change. The increased pole number however, reduces the number of slots per pole to 36/6=6 and the number of slots per pole and phase to 36/(6*3)=2. This can be seen in Fig. 9 where only 2 phasors (black) for the forward coil sides exist (80° apart), one less than in Fig. 8. Forward phasors stay

the same as in the previous case; the corresponding return conductors are located 6 stator slots away what corresponds to a shift of $6*\delta=480^\circ$. As a consequence, the return phasors (red) are shifted by $480^\circ-360^\circ=120^\circ$ with respect to the forward phasors (black). Compared to the previous case this gives an attenuated geometric sum. Although the slotting modulation is slightly reduced, it does not explain the total cancelation observed in chapter V. This effect can be explained with the phase shift between the 6 poles that occurs for this specific rotor slot number. As already mentioned, the phase shift between slots separated by one pole pitch is 120° , which yields that the sum phasors of the 6 machine poles are shifted by this value as well. Fig. 9 illustrates these conditions and makes it obvious that the permeance modulation in the stator winding is cancelled out, if the poles are connected to form a single phase.



Fig. 9: Forward and return permeance phasors of one pole (left) and direction of sum phasors for each individual pole (right). At any one time two pole permeance phasors exhibit the same phase and amplify each other. However, all pole phasors supperposed interfer destructively and yield no permeance variation.

VII. CONCLUSION

The present paper analyzes the influence of rotor skewing and stator winding short pitching on the sensitivity of leakage reactance measurements using high frequency or transient excitation.

Considerations start with measurement results of a number of test machines with different stator windings and rotor skewings, which show the reduction effect of rotor skewing and stator short pitching on the slotting modulation in the stator current change spectrum. In order to extend these measurement results, a 2D multi-slice FE model has been implemented. The presented simulation results give a more comprehensive view on the influence of skewing and short pitching on the rotor position signal and stress the great impact of the stator and rotor slot ratio. The results of these considerations can be applied to assess and eventually identify suitable configurations for rotor position or flux position estimation with saliencybased sensorless control strategies.

Furthermore, the presented results show quite distinct characteristics that may not be obvious at first glance, e.g. attenuating effects that can increase to the point of complete slotting signal cancelation. To understand the origins of these effects the influence of the air gap modulation on the smallest winding parts, the coil sides in the stator slots, are analyzed. Bringing the considerations down to these basic parts, the air gap permeance variations are expressed in terms of phasor theory. With this tool the winding's overall permeance modulation is derived and the mentioned effects can be explained.

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