Saliency Tracking based Sensorless Control of AC Machines Exploiting Inverter Switching Transients

Peter Nussbaumer, Thomas M. Wolbank, *Member, IEEE*

***Abstract* -- Control of ac machines at zero frequency usually requires the presence of a rotor speed sensor. Sensorless control is so far possible around zero frequency when exploiting inherent saliencies of the machine. Current techniques use injected high frequency signals or the machine's step response to extract and identify magnitude and position of inherent saliencies. In this paper, a new method is presented to determine the inherent asymmetries using only the information provided during the switching transients of the machine current. While known techniques need an injected high frequency voltage, specific switching patterns, or modifications in the PWM scheme to exploit the current reaction, the proposed method is able to extract the necessary information from the transient current signal that directly follows the steep voltage change of the switching transition. Thus, the standard PWM scheme can be applied without modifications. Measurement results are presented to show the influence of the saliencies on the switching transition current ripple.**

***Index Terms*-- AC machines, Pulse width modulated inverters, Saliency detection, Sensorless control, Switching transients, zero frequency**

I. Introduction

SPEED sensorless control has developed in the past decades from an academic research topic to wide industrial application. The industrially applied techniques rely on integration of the machines back-emf to determine the flux position and deliver excellent performance in the medium and high speed/frequency range. With decreasing fundamental frequency, the influence of parameter variations increases leading to reduced accuracy. Finally When operated at zero frequency no stable operation is possible due to the lack of feedback for the integration [1]. In this operating range methods have to be applied that are able to track the inherent saliencies of the machine.

These saliencies are not visible in the frequency range of the fundamental wave, they can however, be measured when considering the high frequency or transient electrical properties of the machine.

Methods to extract saliency information so far are either based on the hf (high frequency) properties using an additional excitation of the machine by rotating or pulsating carrier signals [2]-[7], or on the transient current change due to voltage pulses imposed by switching patterns [8]-[10].

Considering the excitation, necessary to carry out the measurements, these methods are usually also denoted signal injection methods.

As the injected signal also has side effects in terms of acoustic noise emission, maximum inverter output voltage, and inverter switching frequency efforts have been made to integrate especially the transient excitation sequences into the fundamental wave PWM [11]-[13]. Though the switching sequence of the PWM can theoretically be used to extract the saliency information, one practical limit exists for all these methods. It is the minimum duration necessary for the current sensors to settle their output values after the signal ringing due to parasitic effects caused by the steep voltage change. Before these switching transients weaken a sampling of the currents or their derivatives is not practical. Thus the switching sequence of the standard PWM has to be modified at least during each sector transition when the duration of one of the active switching states gets too short for a proper measurement.

The proposed method avoids this measurement problem by directly evaluating the sensor signals with the switching transients superposed. In most applications, the measurement procedure can be finished even before currently applied methods can start the sampling of the sensors.

In the following, the measurement and evaluation procedure is presented and first measurement results are given to verify the possibility to extract the saliency information using the switching transients.

II. Saliency separation using high frequency or transient leakage

Though modern electrical machines are designed and manufactured symmetrical, there are always some inherent saliencies present. They are usually not visible in the fundamental wave behavior of the machine however, when looking at the high frequency or transient inductance there is a modulation detectable that can be exploited for speed sensorless control. The main saliencies applicable in this case are the stator/rotor slotting saliency, the rotor (material,shape,..) anisotropy saliency, as well as the main flux saturation saliency.

These saliencies influence the phase values of the high frequency or transient stator inductances. Their modulations thus correspond to the movement of the rotor or flux position. As the mentioned saliencies are inherent and not specifically constructed, their magnitudes are very small compared to the fundamental wave (usually clear below 10% considering induction machines).

To identify the phase values of the hf stator inductance two measurement sequences are possible what also separates the different proposed methods into two main groups.

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P. Nussbaumer is with the Department of Electrical Drives and Machines, Vienna University of Technology, Vienna, AUSTRIA (e-mail: peter.nussbaumer@tuwien.ac.at).

T. M. Wolbank is with the Department of Electrical Drives and Machines, Vienna University of Technology, Vienna, AUSTRIA (e-mail: thomas.wolbank@tuwien.ac.at).

One measurement setup is the continuous injection of a high frequency carrier signal (usually voltage) superposed to the fundamental wave. Then the machine response at this specific frequency is measured and evaluated [2]-[7]. Special care has to be taken for the inverter interlock dead time that influences the injected hf component at every sector crossing. This way of injecting a test signal has to be continuously done, an integration into the fundamental wave excitation is thus not possible.

The second possible measurement sequence is to use an excitation of the machine with voltage pulses and to measure the current step response [8], [9], [10]. The voltage pulses are realized by changing the switching state of the inverter. As the voltage step response is influenced by the transient inductance, the stator resistance, the back emf, and the dc link voltage, a set of at least two different active inverter switching states has to be applied to extract the value of the transient inductance. This pulse sequence has to be applied each time a measurement of the saliency position has to be taken.

To establish the fundamental wave excitation of the machine the PWM is continuously applying voltage pulses to the machine. In some operating states the corresponding current responses can directly be used for the saliency measurement [11]-[13]. An integration of fundamental wave excitation and pulse voltage injection (test signals) is thus theoretically possible. The practical limits of this integration can be found in the measurement setup. To identify the current derivative using standard industrial current sensors a set of two measurements is necessary, taking the current difference at two time instants as shown in Fig. 1.

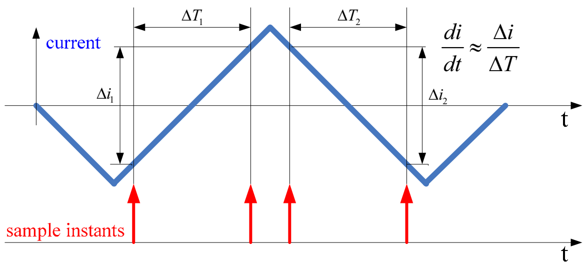

Fig. 1. Measurement of current difference by taking two samples per excitation pulse.

As shown in Fig. 1 the current derivative di/dt is approximated by taking the difference of the current samples Δi during a specific duration ΔT. The value of the minimum pulse duration is determined by the time necessary for the switching transients to settle plus the time ΔT that is determined by the sensor signal resolution. The current difference between the two samples must be high enough to allow also an accurate measurement of the modulation of the current difference caused by the saliencies. As mentioned above, this modulation is in the range of a few percent of the fundamental wave when considering induction machines. In practical measurements, the minimum time is in the range of 30-60µs.

To reduce this minimum necessary duration, in [14] the application of current derivative sensors is proposed. As only one sample is then necessary, the only limitation is imposed by the settling time of the sensor signals after the switching transients. The minimum time duration is then in the range of 10µs. As long as the pulse durations of the fundamental wave PWM are above this minimum value, an integration of the test signal is possible.

Similar current derivative sensors will also be applied in this investigation.

III. SENSOR SIGNALS AT SWITCHING TRANSIENTS

When the switching state of the inverter is changed a steep voltage change is initiated at the inverter output terminals leading to a transient excitation of the whole system consisting of inverter, cabling, and machine windings. Due to the parasitic capacitances and inductances of all system components the switching transition initiates a high frequency oscillation that is detectable in all sensor signals.

Measurements on the machine-under-test showed a winding to ground capacity in the range of 1nF and a phase to phase value of 500pF.

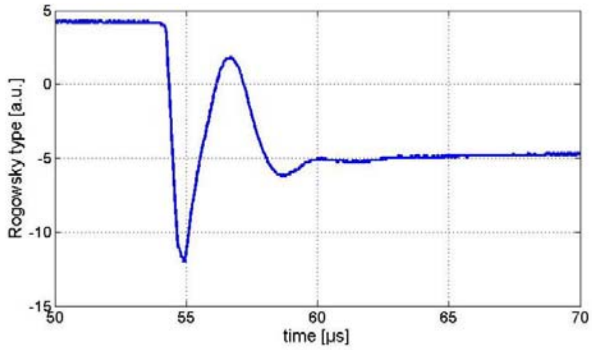

Fig. 2. Measured transients of Rogowsky type sensor excited by the switching of the inverter.

The switching transients of the current derivative sensor are depicted in Fig. 2. The current derivative sensors applied in this investigation are of Rogowsky type. When designing these sensors the primary design parameters number of turns n, coils area A, and coil material (μ_r) influence both self- and mutual-inductance as well as the sensor bandwidth. It is thus possible to adapt such a sensor to the specific application of inverter fed operation. The bandwidth of the sensor can thus be intentionally set below the dominant frequency of the switching transients to directly act as a noise filter. As can be seen in the figure the switching transients still add a considerable noise level to the sensor signal making it usable for conventional measurement techniques only after the settling of these transients. For the specific measurement setup used, this settling time is around 10µs.

This settling time equals the minimum pulse duration necessary for each of at least two different switching states to perform the correct measurements and to extract the saliency information. Especially at low modulation indexes, it is obvious that a modification of the standard PWM is necessary to ensure this minimum pulse duration. If it is possible to avoid this blanking time during the switching transients standard PWM can be used without modification in almost the whole operating range.

When comparing the switching transients of the different phases it turns out that the distortion introduced by the inverter is almost identical for each phase what means symmetrical with respect to the complex space phasor plane. As will be shown it is possible to separate the distortion components from the share the saliencies have on the resulting signal using the proposed signal processing.

IV. MEASUREMENT OF CURRENT DERIVATIVE DURING SWITCHING TRANSIENTS

The measurement set-up consists of an induction machine, a voltage source inverter and measurement/control electronics. The 5,5kW machine has two poles, 36 stator slots and a rotor with 28 unskewed bars.

To extract the saliency information of the machine it is necessary to identify the changes in the current derivative imposed by the asymmetry what corresponds to the modulation of the sensor output signal after settling of the transients.

As shown in Fig. 2 a direct sampling of the correct di/dt value (corresponding to the voltage applied after the switching) is not possible within the first 10µs after the actual switching transition.

However, when establishing oversampling and applying signal processing algorithms, it is possible to extract signal indicators that correspond to the steady state value of the sensor and that thus contain the modulations of the sensor output due to the saliencies.

The measurement setup and resulting signal indicator values considered in the following are:

- (standard A/D conversion) successive approximation/pipeline, mean value during a specified time window
- (standard A/D conversion) successive approximation/pipeline, mean signal slope
- (delta/sigma conversion) modulator - sincK - fir filter

All evaluation methods considered have in common that a high number of samples is processed. In order to accurately extract the saliency induced modulation, it is important to guarantee an accurate selection of the sampled values for the further signal processing. The time instant of the actual switching transition is not identical with the instant of the switching command. The exact trigger for the sampling has thus to be derived based on the sensor output signal.

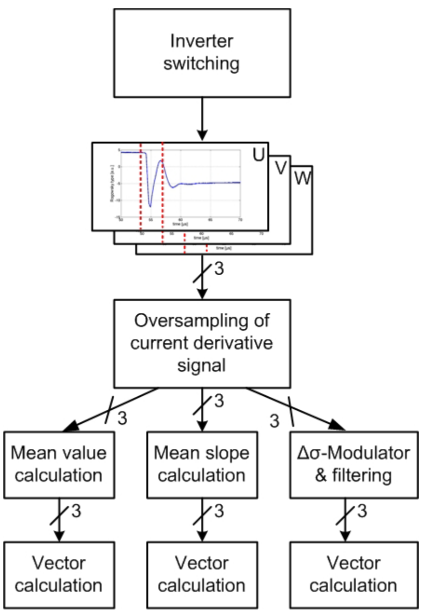

Fig. 3. Block diagram of excitation, measurement and data processing

The whole saliency detection scheme can be seen in Fig. 3, starting with the machine excitation by changing the inverter switching state. Then the sensor signals are sampled using high speed A/D converters to establish oversampling. The time duration selected for the further signal processing is limited to the switching transients as indicated by the two dashed vertical lines in the time traces of the sensor output signals. This oversampling is followed by different signal processing algorithms to calculate different characteristic signal parameters that all contain the modulation of the saliencies. In a final step the calculated phase indicators are combined to a vector.

In the current investigation, the signal processing is done offline based on the values stored in a buffer. In the next step scheduled, the whole sampling and preprocessing will be done in an FPGA (field programmable gate array). The sampling is realized at 10MHz.

A. Data processing and signals based on standard A/D conversion

Using standard analog to digital (A/D) converters with 100ns conversion time and a resolution of 12 bit, the signal processing looks as described in the following.

The measurement and sampling procedure offers the possibility to calculate not only the mean value during an observation window, but also to determine the slope of the sensor signal what corresponds to the second time derivative of the phase current.

As shown in Fig. 2 the switching transition is clearly visible in the sensor signals for at least 6µs. The window length used for the further processing was thus varied between 2µs and 14µs to show its influence on the resulting saliency detection.

The influence of an observation window variation on the variance of the signal obtained after the mean value calculation is shown in Fig. 4 for a set of measurements taken at the same position of the saliencies. It can be seen that even if the whole window lies within the switching transient (~8µs) the variance is already quite low.

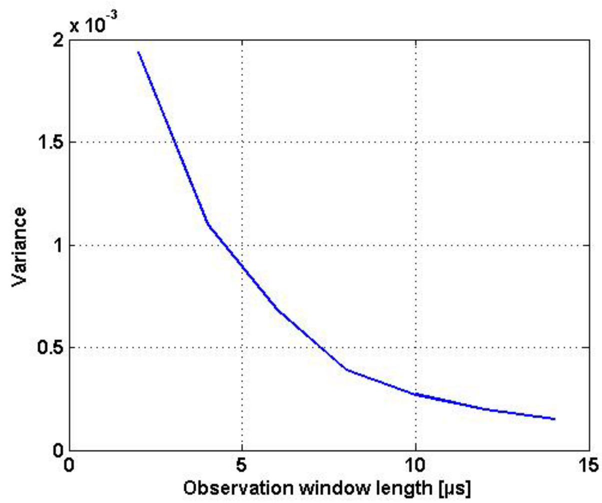

Fig. 4. Influence of observation window on statistical signal properties.

To show the influence of inherent saliencies on the signals obtained it is advantageous in a first step to have an exactly identified single saliency present in the machine. For this purpose, the slotting saliency of an unskewed machine was chosen. To avoid interaction with the saturation saliency the machine was operated without main flux at first. During one mechanical rotor revolution the construction-induced modulation of the transient leakage induction due to rotor slotting recurs N-times, where N is the number of rotor slots (28 for the machine-under-test).

Combining the results of the three phases to one resulting phasor (as indicated also in Fig. 3) leads to an asymmetry information phasor in the complex plane. The magnitude of the phasor corresponds to the significance of the asymmetry and its direction indicates the spatial position of the asymmetry. This asymmetry information is shown in Fig. 5. The figure shows the real (left) and imaginary (right) components of this phasor during two rotor slotting periods resulting in the phasor performing two periods during the measurement interval. The upper two figures are obtained when using the proposed method in combination with current derivative (di/dt) sensors and an observation window of the first 4µs within the switching transients. For comparison the diagrams in the lower line show the results using standard industrial current sensors in combination with two samples and calculation of $\Delta i/\Delta T$ in a separated voltage pulse sequence according to Fig. 1 (and with a pulse length of 50µs). The slotting period is highlighted by red vertical lines and the horizontal double arrow (in the upper left diagram for better identification of the slotting saliency).

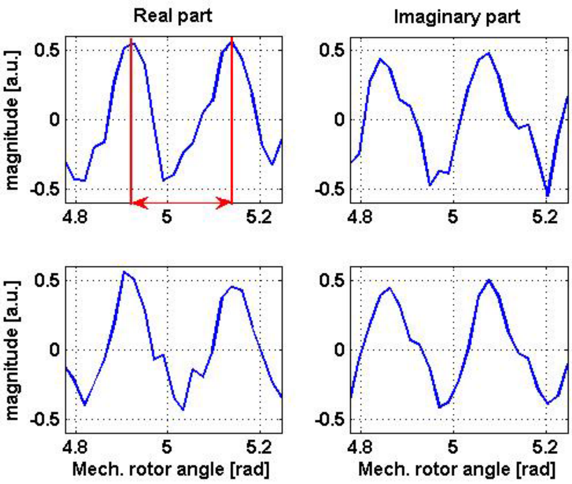

Fig. 5. Detection of slotting saliency using di/dt sensors (upper) and standard industrial current sensors (lower).

When comparing the results using the conventional as well as the proposed method, it can be seen that the influence of the slotting saliency can be clearly extracted within the switching transients using the proposed oversampling method. The performance of the resulting signal when using the proposed method is not deteriorated even when using only 4µs window length.

Based on the sampled values of the di/dt sensors using standard analog to digital converters the time derivative of the sensor signal (difference between a set of subsequent sampled di/dt-values) can be determined using a short and fast algorithm. The average values of the difference can be calculated using a moving window within the set of sampled values. Then the time trace of the average value is obtained what delivers an estimate of the sensor output slope superposed with the switching transients. Applying this algorithm leads to the results shown in Fig. 6 (the lower two diagrams again show the results using standard current transducers and 50µs pulse duration).

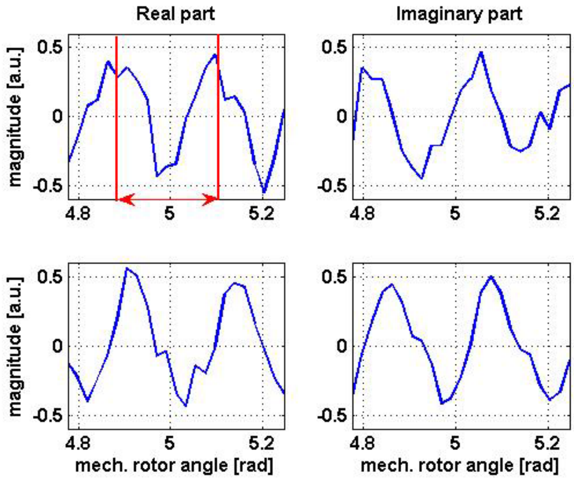

Fig. 6. Detecting the influence of the slotting saliency on the weighted sample difference value (upper), standard current sensors (lower).

Of course there is also a clear influence of the window length on the results obtained. For this investigation, the optimum window length was determined empirically to 3,5µs.

Comparing the results of Fig. 5 and Fig. 6 it can be seen that both, the mean value as well as the extracted slope of the di/dt sensor signal clearly describe the asymmetry caused by the slotting.

B. Data processing and signals based on delta-sigma modulation

A very attractive alternative to fast sampling standard analog to digital converters is the usage of delta sigma converters. Especially in high power inverter applications, the single-bit data transmission offers high robustness against EMI (electromagnetic interference). In addition, due to the high rate of oversampling and the fact that the switching transients always have a predefined phase angle a very effective filtering of the distortions can be realized.

As the combination of modulator and filter offers some degree of freedom, the basic structure of this conversion applied in this investigation is summarized in the following. For more details on delta-sigma modulation techniques see for example [15].

Delta sigma conversion is well established in audio consumer applications. The conversion consists of a modulator and a filter. The modulator converts the analog signal into a digital data stream. In the second stage a filter is used to increase the resolution and to reduce quantization noise what is also called noise shaping. The modulator consists of a set of integrators a comparator and a single-bit digital-to-analog converter. The input signal of the modulator is passed through the integrators. Using the comparator, this signal is converted to a bit stream. This bit stream is passed through a digital-to-analog converter and fed back again to the integrator inputs where it is subtracted.

Usually a set of two integrators is applied leading to a second order modulator. Using a higher order increases stability problems of the modulator.

The second stage of the delta-sigma conversion is the low pass filter. It removes the quantization noise and by reducing the data rate (also called decimation) it increases the resolution. Usually a combination of sincK and finite impulse response (FIR) filters is applied. The sincK filter establishes the first step of the decimation and has thus to operate at sampling frequency. The advantage of the sincK filter is that no digital multipliers are necessary what makes it ideal for hardware realization using e.g. a field programmable gate array (FPGA).

Due to the oversampling, the quantization noise is shifted to high frequencies where it can be removed very effectively by the filtering. The delta sigma modulator with the feed back has a more effective high pass behavior with respect to the quantization noise and low pass properties for the input signal than other oversampling methods.

It is thus possible to adapt the conversion process to the specific signal properties. The decimation filter allows an increased resolution by realizing a moving average over a specific number of samples. In the specific application considered in this paper, this moving average can effectively be applied to filter also specific signal noise components introduced by the switching transition.

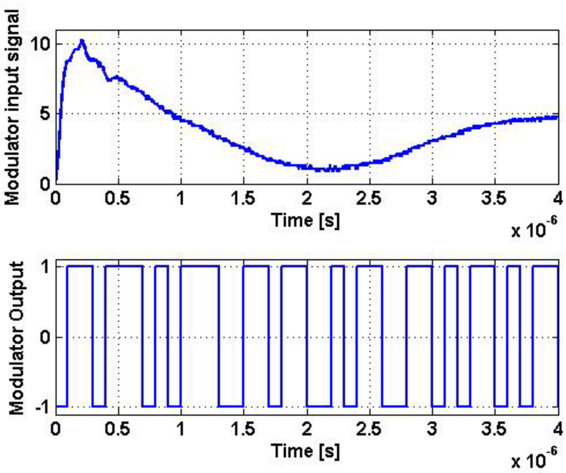

Fig. 7. Output of di/dt sensor and corresponding sigma modulator signal during switching transients at a modulator frequency of 10MHz.

For the following measurements, a second order modulator was chosen together with a sinc3 filter. The parameter modified during the tests was the decimation factor.

In Fig. 7 the sensor and modulator signals of a delta-sigma modulation are shown during a switching transition. The upper diagram depicts the time trace of the di/dt sensor during the first 4µs after the switching transition. This signal equals the input signal to the modulator.

When choosing the length of the observation window equal to the duration of the switching transition an oversampling rate of ~32 is possible for a modulation frequency of 10MHz. If only the mean value during this observation window is exploited it means that only the dc value is exploited leading to very high SNR of theoretically 85dB. After applying the filtering and downsampling according to the sinc3 a value corresponding to the steady state di/dt is obtained with high precision and low distortions. The accuracy of the resulting signal is shown in Fig. 8 for two different rotor positions and observation windows (solid/dashed phasor). Using 10MHz sampling rate and a decimation of 16/32 the corresponding observation window is 4,8µs/9,6µs.

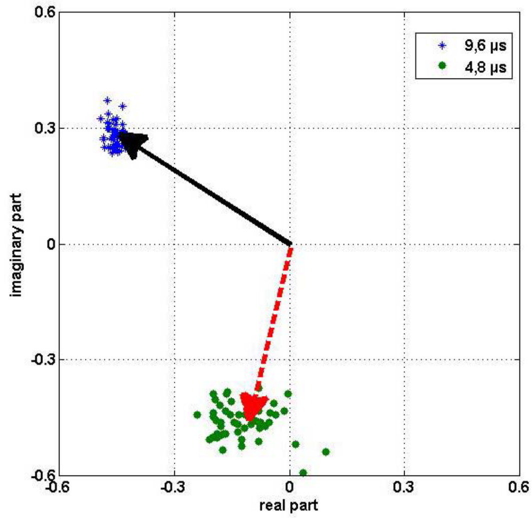

Fig. 8. Accuracy of saliency signal obtained for zero rotor (slotting) speed exploiting di/dt signals during switching transient (observation window 4,8µs (red, dashed)/ 9,6µs (black, solid)) and applying delta-sigma modulation at 10MHz.

After applying the filtering and down-sampling according to the sinc3 a signal with low distortions is obtained, correlated to the steady state di/dt. Measurement results for mechanical standstill are depicted in the figure. The resulting saliency signal (slotting saliency position) is represented by the black (solid) phasor. The dots around the tip of this phasor represent subsequent measurements for the same saliency (rotor) position. A second set of measurements is done at a different rotor position and using a 4,8µs observation window (red, dashed phasor). As can be seen the accuracy of the measurement is high enough to allow a clear identification of the slotting saliency and with a quality that is comparable to measurements taken in combination with standard current transducers and 50µs pulse duration.

To further prove the possibility to detect saliencies by applying delta-sigma modulation, the results for measurements over two rotor slots are depicted in Fig. 9.

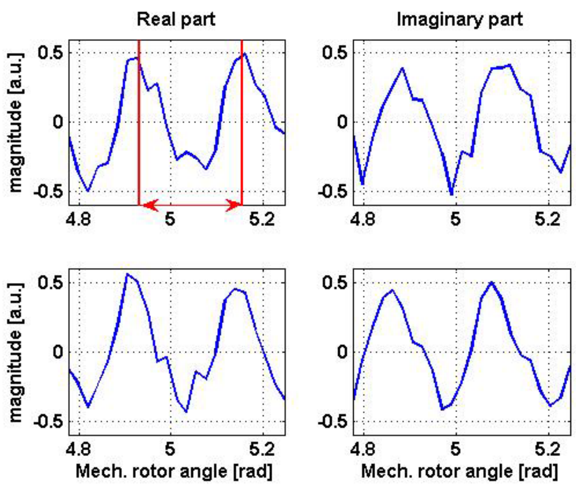

Fig. 9. Slotting saliency signal gained by applying the delta-sigma approach at a modulator frequency of 10MHz and a decimation of 16 (observation window length of 4,8µs) (upper) and with standard current transducers (lower).

A modulator running at 10MHz and a sinc3-Filter with a decimation of 16 (corresponding observation window length equals 4,8µs) were used for the saliency detection. As can be seen the accuracy is high enough to allow a clear identification of the slotting saliency and with a quality comparable to measurements taken in combination with standard current transducers and 50µs pulse duration.

V. Influence of Fundamental Excitation on Switching Transients and Extracted Signals

All previous measurements have been made without fundamental wave excitation. Thus the various influences of the fundamental wave on the switching transients have not been covered. The proposed method is based on an elimination of the switching transients from the sampled signals by using oversampling techniques. This elimination of course cannot be perfect, leading to a remaining influence of the fundamental wave. First measurements revealed that this influence is visible in an additional harmonic component related to the fundamental wave current. This harmonic can be identified feed forward and then further reduced by compensation. At this point investigations that are more thorough are scheduled to clearly determine this interaction.

VI. Comparison of Oversampling Techniques and Practical System Realization

Considering the performance of the commercially available A/D converters in the low to medium price range, it has to be said that currently the successive approximating A/D converters achieve a sampling rate of around 10MHz (100ns conversion time). Other A/D converter topologies like pipelined ADCs achieve much higher sampling rates and are therefore a possible alternative to successive approximation A/D converters.

On the other hand when using delta sigma converters it is necessary to adapt the filter/decimation to this specific measurement (current derivative sensor signals), as the application to extract saliency information is different from most other signal processing methods. It is thus necessary to use separate modulators and filters. The modulators currently commercially available are of second order and have a maximum sampling rate of 20MHz. Under these constraints it is currently advantageous to prefer the successive approximation or pipelined to the delta sigma conversion. When using oversampling techniques to filter the switching transients, one important factor is the accurate triggering of the sensor signal. In this investigation the trigger was realized by a combination of the switching command and the sensor output signal. In order to extract the saliency information from the sensor signals it has to be guaranteed that the position of the observation window is not changed with respect to the switching transition.

VII. Conclusions

Extraction of ac machines inherent saliencies offers the possibility to estimate the flux/rotor position without mechanical sensor. A new method to extract this saliency information was presented. It offers the possibility to sample the necessary signals even during periods where the switching transients prevent conventional methods from delivering useful information for sensorless control.

The method is based on oversampling techniques that are applied to current derivative sensors in the current investigation. Though not shown in the paper, it can be extended when using standard current sensors instead. It enables an effective means of eliminating the distortion caused by the switching transients introduced by the inverter.

Two main oversampling methods are applied to the problem of saliency extraction of ac machines. Standard A/D conversion as well as delta-sigma conversion. Both methods are tested on the slotting saliency of an unskewed induction machine. It was shown that both oversampling methods are able to extract the saliency information with the comparable signal to noise ratio as conventional methods that need minimum duration of the voltage pulses after the settling of the transients. The method is thus able to extract saliency information without injecting additional switching patterns or modifications to the PWM.

VIII. References

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