Using Oversampling Techniques to Extract AC Machine Saliency Information

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Abstract- **Controlling an ac machine without speed or position sensor at zero frequency requires the extraction of its inherent or engineered saliencies. This extraction is currently linked to injected high frequency or transient test signals that are superposed to the fundamental wave. These test signals also affect noise emission, maximum inverter output voltage, and switching frequency. Different methods for an integration of the test signal injection into the fundamental wave excitation have been made, however a full integration in all operating states is still not possible. In this paper a method to extract the necessary saliency information without applying test signals is proposed and analyzed. It is based on oversampling techniques and uses the information that appears in current sensor signals during the switching transients. Different realizations are presented and their performance compared with respect to changes in the operating parameters. It is shown by measurement results that applying the proposed techniques it is possible to obtain the saliency information necessary for speed sensorless control.**

I. INTRODUCTION

In the past decade the topic of speed sensorless control has developed from an academic research field to wide industrial application. Industrial applications usually are based on integration of the machines back-emf (electromotive force) to deliver the flux information needed for control. These techniques have shown excellent performance in the medium and high speed/frequency range. One main problem however still emerges in the low speed range. When the fundamental frequency is low, the performance reduces due to the influence of measurement errors and parameter uncertainties. At zero speed, stable operation of the loaded machine is not possible due to the missing feedback from the back-emf [1]. Control problems in this operating range can only be overcome when additional information from the flux/rotor position is available exploiting for example the machine's inherent saliencies.

As the saliencies usually do not interfere with the fundamental wave of the machine, saliency information can only be extracted when considering the high frequency or transient electrical properties. This normally implies an excitation using test voltage phasors or switching patterns. Due to this additional excitation these methods are also denoted signal injection based in literature.

Sensorless methods that are able to work around zero speed are thus based on the high frequency behavior using an additional excitation by either harmonic carriers like rotating or pulsating signals [2]-[7], or they are based on the transient properties using step response resulting from test switching pulses [8]-[10].

Until recently the performance of the saliency information was the main focus of research while the impact of the injected signal on the operation of the drive was only rarely addressed. As the additional excitation also influences the drive with respect to acoustic noise emission, inverter switching frequency, efficiency, maximum inverter output voltage, efforts have been made to reduce these side effects. In [11]-[13] methods to integrate the transient pulse patterns into the fundamental wave PWM (Pulse Width Modulation) switching sequences are proposed.

Consisting of two active and one zero switching state the switching sequence of the fundamental wave, SVPWM (space vector PWM) can directly be exploited to obtain the saliency information as shown in [11]-[13]. In practical operation however, there exist operating states of the SVPWM where this direct exploitation is not applicable due to EMC (Electromagnetic Compatibility) and measurement issues. Every switching transition of the inverter leads to an excitation of the parasitic capacitances of inverter, machine, and the inductance of the cable. In addition, the steep voltage changes results in signal ringing of all measured quantities. Before a settling of these switching transients a sampling of any sensor signal will not deliver accurate values. Depending on the arrangement of the inverter and the machine it can be necessary to wait 10µs or even more before the measurements can be performed. Furthermore inverter interlock dead-time has to be added to obtain the minimum duration of each single inverter switching command needed to obtain a single current sample [14]. As a consequence the direct saliency extraction using only standard SVPWM excitation is not possible at low modulation indexes.

The goal of this investigation is to clearly reduce the mentioned minimum necessary pulse duration for the measurement by starting the sampling process with the switching transition. Using oversampling techniques offers different options to reconstruct the saliency information signal with the switching transition disturbances superposed. In many applications it is thus possible to finish the sampling process even before conventional methods have started the first measurements.

In the following the sampling and evaluation process is described and the influence of different setup parameters on the resulting saliency information performance is investigated.

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II. Extracting Saliency Information Using High Frequency or Transient Current Response

When measured, every machine shows some kind of asymmetries leading to saliencies. These saliencies and/or their specific change with the point of operation can be exploited for monitoring purpose or speed sensorless control.

In symmetrical non-salient machines these asymmetries are very small and usually not measurable considering the fundamental wave behavior only. Taking into account the high frequency or transient properties they can however, be exploited. The reasons for these inherent saliencies are the different levels of saturation along the circumference caused by the main flux distribution as well as the slotting of the lamination leading to a modulation of the high frequency (hf) or transient inductances.

Two different approaches to determine the machine's transient inductance can be found in literature.

One is to superpose a high frequency carrier signal to the fundamental wave. This signal is usually a voltage signal. The machine's current response can be measured and evaluated at the frequency of the carrier signal to identify the hf inductance [2]-[7].

The other measurement procedure uses the current step response on voltage pulses applied to the machine for the identification of the transient inductance [8]-[10]. By evaluating the step responses of two different active inverter switching states the influence of stator resistance, back-emf and dc link voltage can be eliminated. Each time a rotor position information is needed, the standard SVPWM has to be modified and the voltage pulses applied.

To excite the machine with the fundamental wave the voltage source inverter (VSI) is constantly applying pulses according to the PWM-duty cycles. It is possible to employ the current response on these voltage pulses for saliency measurement in various operating conditions [11]-[13]. However, this integration of the pulse injection into the fundamental wave excitation comprises some difficulties for practical implementation. When using the current sensors of standard industrial drive systems it is necessary to sample the sensors at two different time instants during the time $\Delta\tau$ of one pulse excitation and to approximate the current derivative $di/d\tau$ by calculating the difference of the current samples Δi. Fig. 1illustrates this approach.

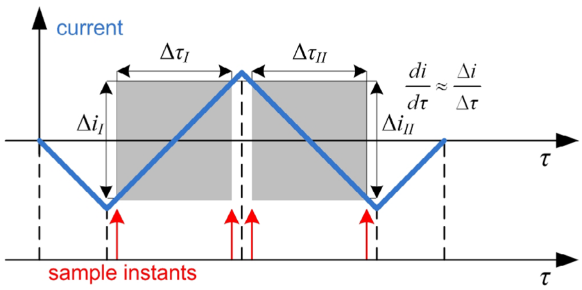

Fig. 1. Measurement of current difference using standard industrial current sensors

Due to this measurement configuration there exists a minimum pulse duration. The value of this minimum duration depends on the time the switching transients need to settle to the final value plus the time $\Delta\tau$ defined by the resolution of the current sampling. Furthermore the current difference has to be high enough to ensure an accurate identification of the saliency.

In [15] the possibility to reduce this minimal duration is presented by using current derivative sensors (CDI-sensors). With this approach only one sample is needed. Therefore single determinant for the minimum necessary duration of the voltage pulses is the settling time of the switching transients, usually in the range of 10 µs. In the proposed method similar sensors are applied.

III. Characteristics of Current Derivative Signal

A high frequency component is superposed to the current derivative, caused by the interaction of the steep voltage change due to the inverter switching and the parasitic inductances and capacitances of the whole system (inverter, cabling, machine windings). The signal trace measured with the Rogowsky type current derivative sensors during a switching operation is shown in Fig. 2.

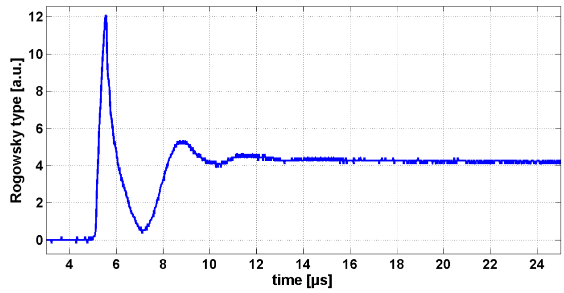

Fig. 2. Current derivative signal measured with Rogowsky type sensors during switching of the VSI (a.u. arbitrary unit)

The figure illustrates that the settling time can be expected around 10 µs. This time defines the minimal duration for each of the two voltage pulses that are needed for the extraction of the saliency information. The PWM-duty cycles under-run this limitation for low modulation indexes. In such cases the standard PWM has to be modified to guarantee the minimal pulse duration.

Using oversampling techniques it is possible to identify the machine's saliency even before the switching transient has settled. This approach will be further explained in the following sections.

IV. Extraction of Saliency Information During Switching Transients

As stated above the machine's asymmetries cause changes in the current derivative and therefore a modulation in the final value of the current derivative sensor signal. The new approach proposed is to use oversampling techniques and signal processing to extract this modulation of the machine's transient inductance before the signal transients have settled. Thus, the minimum pulse duration can be reduced significantly.

Different signal processing algorithms can be taken into account to extract the saliency information. In the following, two different strategies are going to be investigated in terms of performance subject to their characteristic parameters:

- Fast sampling standard a/d (analog-to-digital) conversion: calculation of mean value during specific time window
- Delta sigma conversion: Delta-sigma modulator – sinc^k-filter

Regarding the first method the investigated parameters are sampling rate and the window length for the mean value calculation. The influence of the delta-sigma modulator's data rate and the filter's decimation factor on the quality of the saliency signal is the focus of the studies concerning the delta-sigma approach. One important issue of both methods is to wisely choose the analyzed sample values. Due to inverter interlock dead-time the switching command and the actual switching instant are time-delayed. Thus the detection of the exact trigger for the sampling is challenging. A last section of this paper addresses this subject.

To compare the quality of the different saliency identification algorithms it is advantageous to ensure that only a single exactly identified saliency is present in the machine. Two different saliencies are considered in this investigation:

- Slotting saliency
- Saturation saliency

To guarantee that the only present saliency is the one caused by the slotting, the machine is operated without main flux. The rotor is turned over two rotor slots with an approximate resolution of 10 measurement sequences per slot. To analyze the saturation saliency the machine at standstill is excited with main flux. Measurements are performed with changing direction of excitation over one electrical revolution with angle step-size of 10°.

As this is a first evaluation of the proposed method, all investigations are done offline using measurement data gained from a test stand.

A. *Saliency information extraction using standard a/d conversion and data processing*

This approach is based on oversampling of the current derivative signal and calculation of all samples mean value during a certain time interval. Two parameters strongly influence the accuracy of the resulting asymmetry signal – the sampling rate and the observation window length. For this reason these parameters are varied in the following investigation.

By increasing the sampling rate, more values for the mean value calculation at constant window length exist and therefore accuracy increases. The sampling rate is varied between 10 and 100 MHz in the present evaluation.

Without further considerations one would think with longer observation window the accuracy also increases. However, this is only partly true. When the observation window length matches the duration of one or more periods of the high frequency oscillation superposed to the current derivative signal, the accuracy can be regarded better compared to longer window lengths.

A comparison of the saliency signal accuracy and further explanations are given in the following section.

To identify the saliency, measurement results of the three phases are combined to a phasor containing the asymmetry information.This phasor is hence denoted asymmetry phasor. The phasor's magnitude relates to the significance of the asymmetry, its direction to the spatial position.

For the following experimental results one single asymmetry is present – either slotting or saturation. For a comparison with the conventional measurement setup, a configuration using standard industrial current sensors and 50µs pulse duration is chosen. In Fig. 3 this comparison is depicted for the slotting saliency for an observation window length of 2.5µs and a sampling rate of 80 MHz.

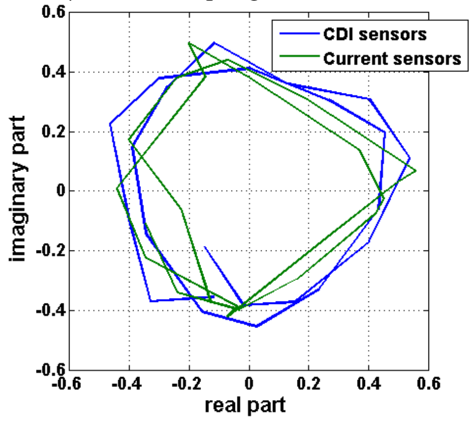

Fig. 3. Comparison of slotting signal using standard measurement approach (green) and oversampling approach (blue) (observation window length: 2.5µs; sampling rate: 80MHz)

The figure shows the trace of the asymmetry phasor for a rotation over two rotor slot periods (resulting in one phasor rotation per slot). As can be seen the quality of the asymmetry signal applying the proposed oversampling method (blue trace) is the same as for the standard measurement scheme (green trace). Thus, the minimal pulse duration could be clearly reduced from about 50µs as the optimum value for the conventional approach to 2.5µs.

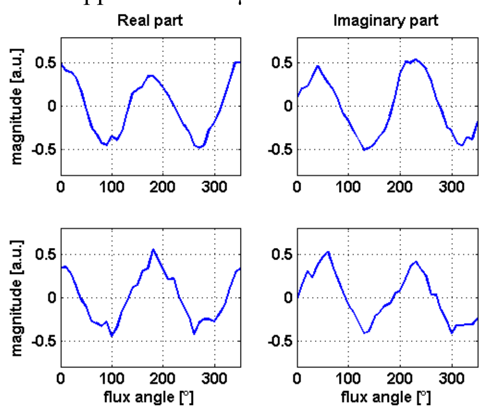

Fig. 4. Comparison of saturation signal using standard measurement approach (upper) and oversampling approach (lower) (observation window length: 2.5µs; sampling rate: 80MHz; a.u. arbitrary unit)

The slotting signal could be used for sensorless control. One period in Fig. 4 equals one rotor slot. Within that period the accuracy is in the range of ~25° what (for a machine with 28 rotor slots) results in a resolution of about one degree over a whole mechanical rotation.

Similar results can be obtained regarding the saturation saliency. Fig. 4 shows a comparison of saturation signal's real and imaginary part for the different approaches. The parameters set are again 50µs and 2.5µs at 80MHz (same as for the slotting saliency).

The saturation saliency is depicted over one electrical revolution of the main flux at rotor standstill. As only saturation can be detected and not its direction this results in a sinusoid with a period of two. The results for the saturation saliency show, that fundamental wave excitation hardly influences the quality of the saliency signal.

The signal-to-noise-ratio (SNR) can be used for a comparison of the different saliency identification methods as an indicator for signal quality. In this case the spectral component of the saliency signal associated with the asymmetry is defined as the wanted and all other components are defined as noise. Table 1 compares the SNR for the different saliency identification methods.

TABLE 1
COMPARISON OF SNR FOR DIFFERENT SALIENCY IDENTIFICATION METHODS; SAMPLING RATE: 80 MHZ, FILTER LENGTH: 2.5µS

Approach:	Standard	Oversampling
Slotting saliency	19.77 dB	21.74 dB
Saturation saliency	27.88 dB	26.8 dB

Table 1 points out that regarding the slotting saliency the signal quality is even increased by applying the new approach. On the other hand the signal quality for the saturation saliency only suffers a slight degradation. However the significant reduction of necessary pulse duration (2.5µs to 50µs) prevails over this disadvantage.

B. *Saliency information extraction using delta-sigma modulation and data processing*

The principle of delta-sigma data conversion is, that at first a modulator converts the measurement signal into a 1-bit-stream with high bit rate. By using a certain filter this bit stream is converted into a digital word with a high resolution and lower data rate.

This concept offers the possibility to separate the modulator and the filter part. The single bit stream is very robust against electromagnetic interference (EMI) and thus ideally suited for a harsh industrial environment. Furthermore the separation of filter and modulator offers the possibility to design the used filter – especially if realized in a FPGA (field programmable gate array) – according to the needs of the application.

To better understand the proposed strategy, a short explanation of delta-sigma modulator and related filters is given in the following. See for example [16] for a more detailed description.

As mentioned above, the first stage of a delta-sigma converter consists of a modulator, which converts the analog signal into a 1-bit stream. The density of 1's in this bit stream is proportional to the analog signal. The modulator is built up of a number of integrators equal to the order of the modulator, a comparator that converts the integrator output into a bit stream and a DAC (Digital-to-analog converter) that converts the bit stream into an analog signal. Finally, this signal is fed back and subtracted from the analog input.

The second stage consists of a digital filter, which by reducing the data rate and a concept denoted as noise shaping increases the resolution and reduces quantization noise. Sinc^k-filters are a suitable solution for this stage. As they do not need any multipliers, simple hardware realization in an FPGA is possible for example.

In the present investigation a 2nd order delta-sigma modulator is used. It is recommended to use a filter one order higher as the modulator. Thus a sinc^3-filter is applied.

As a single sampling value after the delta-sigma conversion is proportional to the signal contained in a single filter window, the parameters influencing signal accuracy and window length are the modulator's bit rate and the decimation factor of the sinc^3-filter.

For the following analysis the bit rate is chosen to 10 and 20MHz as these are specifications of commercially available modulators. The decimation factor is varied between 8 and 64 (in steps of 2^n) equaling a filter response from 2.4µs to 19.2µs at 10MHz and 1.2µs to 9.6µs at 20MHz. Doubling the decimation factor results in a doubling of the filter response.

Again slotting and saturation saliency signals are investigated and compared to the results using conventional saliency identification setup. The following Fig. 5 shows a comparison of the slotting signal for an optimum set of parameter.

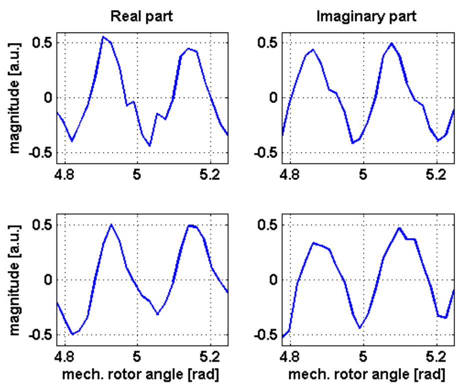

Fig. 5. Comparison of slotting signal using standard measurement approach (upper) and delta-sigma approach (lower) (decimation factor: 32 (4.8µs); modulator bit rate: 20MHz; a.u. arbitrary unit)

The upper diagrams show the real and imaginary part of the asymmetry phasor over the mechanical rotor angle if the standard saliency identification method is applied. The lower curves show the same signal when using the delta-sigma approach. The parameters are chosen to a modulator bit rate of 20MHz and decimation factor of 32 equaling a filter response of 4.8µs. Table 2 shows a comparison of SNR for this parameter set.

TABLE 2
COMPARISON OF SNR FOR DIFFERENT SALIENCY IDENTIFICATION METHODS; MODULATOR BIT RATE: 20 MHZ, DECIMATION FACTOR: 32

Approach:	Standard	Delta-sigma
Slotting saliency	19.77 dB	19.22 dB
Saturation saliency	27.88 dB	17.22 dB

As can be seen the slotting saliency can be detected without degradation in signal quality. However the accuracy of the saturation saliency signal declines when applying the delta-sigma approach. Further measurements and evaluations have to be done to analyze the influence of fundamental wave excitation on the discussed new saliency identification method. First evaluations show that fundamental wave excitation adds an extra harmonic to the spectrum of the asymmetry signal. This harmonic is related to the fundamental wave and can therefore be identified and eliminated feed forward. This procedure should then increase signal quality.

V. COMPARISON OF THE PROPOSED SALIENCY IDENTIFICATION METHODS IN DEPENDENCE OF PARAMETER CHOICE

The results presented in the section, indicate that the correct choice of sampling rate and observation window length strongly influence the signal accuracy. The aim of the proposed approaches is to reduce the minimal necessary pulse duration by oversampling and data processing techniques. Thus the optimum observation window length is a trade-off between minimized window length and signal accuracy compared to the conventional approach. Limitations regarding sampling frequency or modulator bit rate are given by the fast sampling a/d converter and delta-sigma modulator commercially available in the low to medium price range.

For all investigations regarding the delta-sigma conversion, a modulator of second order and a sinc^3-filter is used.

The sampling frequency of the fast sampling a/d converters is set to 10MHz, 20MHz, 80MHz and 100MHz. The window length is varied in the range between 0.5µs to 10µs for the different frequencies in the following comparison.

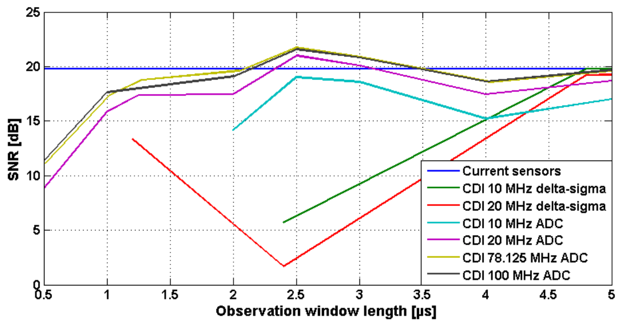

Fig. 6. Comparison of the slotting signal performance; SNR for different approaches over observation window length

For the delta-sigma conversion the modulator bit rate is chosen to 10MHz and 20MHz. The observation window length defined by the decimation factor is varied between 1.2µs and 19.2µs. In Fig. 6a comparison of the SNR for the slotting signal identified with the proposed oversampling approaches over the observation window length is depicted. The blue line represents the SNR achieved by using standard industrial current sensors in combination with the approach illustrated in Fig. 1 as a reference.

The optimum observation window length can therefore be identified to around 2.5µs when using fast sampling a/d converters and mean value calculation for all investigated sampling rates. Fig. 6 illustrates that an increase of the sampling rate results in an increase in signal quality to a certain point (around 70MHz). Above this a further augmentation doesn't improve SNR.

Regarding the delta-sigma approach the observation window can be chosen to 4.8µs corresponding to a decimation factor of 16 at 10MHz and 32 at 20MHz with only a slight decrease of SNR in comparison to the standard method.

Similar results can be achieved regarding the saturation signal (see Fig. 7).

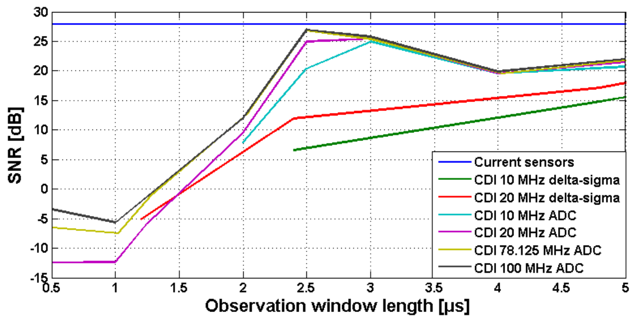

Fig. 7. Comparison of the saturation signal performance; SNR for different approaches over observation window length

Again 2.5µs can be regarded as the optimal observation window length for the oversampling approach using standard a/d converters. The SNR is only slightly below the reference value (blue line) for sampling rates around 80MHz and higher.

The results for the delta-sigma approach at an observation window length of 4.8µs are worse. However an analysis of the spectrum of the asymmetry phasor shows that the saliency harmonic is the one related to saturation (2nd harmonic over one electrical revolution). Increasing the decimation factor to 64 at 20MHz and 32 at 10MHz modulator bit rate results in a significant increase to 35.89 dB and 32.42 dB respectively, a clear augmentation of signal accuracy at only 9.6µs minimum pulse duration in comparison to the standard method.

The optimum observation window length for the oversampling approach using high speed a/d converters and mean value calculation can be determined for every drive system without performing this analysis if the signal of the current derivative sensors for voltage pulse excitation is known. The identified window length of 2.5µs equals one period of the switching transient when considering the high-frequency signal superposed to the current derivative signal as a negative cosine function. The value of 2.5µs then exactly equals the time from the actual switching transition to the 2nd peak – one period respectively.

Especially when using high speed a/d converters the proposed methods show a clear improvement for the integration of saliency identification into the PWM without further modification. The minimum pulse duration can be significantly reduced from 10µs as a minimum value for the approach using CDI-sensors and standard sampling to 2.5µs at the same signal accuracy.

The delta-sigma approach – not as efficient as the other – also shows a clear improvement concerning the minimum pulse duration or at the same pulse duration a significant improvement in signal accuracy.

VI. IDENTIFICATION OF THE TRIGGER INSTANT

The knowledge of the exact instant to start the measurement is essential for a correct calculation of the asymmetry phasor using the proposed oversampling techniques. It has to be guaranteed for every single switching transient that the position of the observation window is the same with respect to the actual switching operation.

Due to inverter interlock dead-time the switching command and the actual switching transition are time-delayed depending on the point of operation. The switching command itself thus cannot be used as trigger event.

Many different techniques to realize accurate triggering of the measurement are conceivable. A promising method however, is to use the switching command as a pre-trigger to set the measurement system to wait state. A differentiator can now be used to identify the actual switching transition. Before a switching operation the current slope and therefore the signal of the current derivative sensor is constant. By changing the switching state the current derivative signal experiences a steep change. If the sensor output signal is differentiated, this results in a pulse-like signal that can be used to trigger the measurement.

This identification of the trigger instant is used for the experimental results presented in this paper.

CONCLUSIONS

Every machine shows some inherent asymmetries. These saliencies can be extracted to estimate the rotor or flux position without additional mechanical sensors. To achieve this, a high frequency or transient excitation is necessary. Due to parasitic effects in the whole system conventional signal injection methods are unable to deliver saliency information useable for sensorless control for a certain time after the switching transition.

The presented method overcomes this drawback by applying oversampling techniques to current derivative signals. This enables an effective elimination of the disturbing signal components caused by the inverter switching.

Two methods to implement this approach are described – standard fast sampling a/d conversion and delta-sigma conversion. Experimental results are given for the extraction of slotting and saturation saliency of an unskewed induction machine. The investigations proofed that both methods are able to extract these saliencies with similar signal accuracy as the conventional approach. At the same time the minimum duration of a single pulse can be significantly reduced.

The presented methods thus offer the possibility to integrate the saliency information extraction into the PWM without modification or additional injection of specific switching patterns.

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