Using Switching Transients to Exploit Sensorless Control Information for Electric Machines

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***Abstract* -- Model-based control strategies of induction machines usually require a rotor speed sensor if operated around zero fundamental electrical frequency. Sensorless control based on the exploitation of the inherent saliencies can be applied in this operating range. To identify magnitude and position of these saliencies injected high frequency signals or the current reaction on transient voltage steps can be used. Current techniques need to apply specific switching pattern or modify the PWM (pulse width modulation) scheme to exploit the machine response. This results in a higher torque and current ripple as well as additional acoustic noise emission. The proposed new measurement overcomes these disadvantages by using oversampling techniques to extract the wanted information from the switching transients in the current signal. Therefore it is possible to apply standard PWM without modification to ensure accurate flux or rotor position estimation. Measurement results will be shown and compared for the standard and the proposed approach.**

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

I. Introduction

The application of inverter-fed induction machines in industry has been constantly increasing in the past decades. Sensorless control strategies offer the possibility to save cost and size or increase fail-safety if used as a back-up system for drives equipped with a mechanical rotor position or speed sensor. Especially the latter becomes more and more important as the application of electrical drive systems in safety critical devices like x-by-wire is gaining significance.

In industry sensorless control based on the exploitation of the machine's back-EMF (electro-motive-force) have been widely used. However, these methods cannot guarantee stable operation for low fundamental frequency due to the influence of measurement inaccuracy and parameter uncertainties. Furthermore the feedback from the fundamental wave is completely missing around zero frequency [1]. In this operating range so-called injection based methods are able to supply the necessary information needed for flux or position estimation. Basically two different strategies can be found in literature. They either apply a high frequency signal in addition to the fundamental wave [2]-[7] or evaluate the transient current change due to voltage steps resulting from a specific switching pattern that is applied in addition to the PWM-sequence to excite the machine with the fundamental wave [8]-[10].

The main focus in scientific research on sensorless control of AC machines so far has been the performance of the saliency extraction procedure. However, the side effects like acoustic noise emission, influence on switching frequency and efficiency, additional current ripple, or decreased maximum inverter output voltage, coming along with the additional signal injection should not be disregarded. To overcome these drawbacks in [11]-[13] efforts have been made recently to integrate the transient excitation sequences into the PWM-sequence applied to excite the machine with the fundamental wave.

As shown in [11]-[13] it is possible to directly exploit the SVPWM (space vector PWM) to gain the necessary saliency information as the switching sequence of the fundamental wave consists of two active and one zero switching state. Still a practical limit for all these methods exists. The applied voltage steps have to exceed a certain minimum length to ensure accurate saliency detection. Due to the mismatch of the machine cable's surge impedance and the machine impedance itself the application of steep voltage changes leads to reflections at the machine terminals, also influenced by the parasitic capacitances of inverter, machine, and the inductance of the cable. That results in transient signal ringing measureable in all electrical quantities, what represents the main limiter for integration into SVPWM. Consequently, for standard approaches the measurements for saliency information detection cannot be initiated until the transient signal ringing has decayed, what is in the range of 10 to 20μs and above.

For low modulation indices the minimum duration of the voltage pulses is under-run and the switching pattern for the standard PWM has to be modified. As two active switching states are needed for the evaluation, this occurs during each sector crossing and especially for voltage space phasor with small magnitude.

The proposed method uses oversampling and specific signal processing what makes it possible to finish the measurement procedure even before the sampling can be initiated when using standard pulse injection. The presentation of different signal processing algorithms and First measurement results for a machine that is not excited with the fundamental wave can be found in [14]. Further measurements for a machine excited with the fundamental wave and an analysis of the influence of sampling rate and window length of the signal processing algorithm is presented in [15]. However, the measurements were done with an external measurement system and offline signal processing and evaluation. This limited the analysis to a small range of operating points as the data collection was relatively time consuming. A new measurement and control system has been built-up that allows automatic data collection and preprocessing. The evaluation of the collected data is still done offline. A complete real time integration of the evaluation into the measurement and control system is currently on-going.

Furthermore the evaluation was limited to two active voltage pulses in the same phase with opposite direction. This pulse sequence is still applied in section III. . However, using the automatic data sampling and control system, a whole mechanical revolution could be analyzed.

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Therefore the measurement results of section III. are comparable to the ones gained in [14] and [15]. As this combination of active voltage pulses does not occur in SVPWM switching sequences the main focus of this paper is the calculation of saliency information signal from active switching patterns actually applied during excitation of the machine with the fundamental wave. This topic is discussed in section IV. Further measurement results for different load conditions will be presented. In addition a new signal processing algorithm and some challenges that come along with the novel procedure are discussed. All measurement results are compared with results of the standard pulse injection and measurement approach without oversampling to verify saliency detection capability of the proposed technique. Section V. discusses the detection of the actual switching instant what is crucial for most of the proposed signal processing algorithms.

II. SALIENCY TRACKING BASED ON VOLTAGE PULSE INJECTION

Saliency tracking based sensorless control techniques use the inherent machine asymmetries that are present due to the mechanical design (e.g. rotor slotting) and the machine's electromagnetic behavior (saturation). These asymmetries are not visible in the fundamental wave. However, they influence the phase value of the transient leakage inductance.

As already mentioned in the introduction two different approaches to identify the hf or transient inductance can be found in literature - the superposition of a high frequency voltage to the fundamental wave or the machine excitation with voltage pulses. The latter one is the applied procedure used in the following.

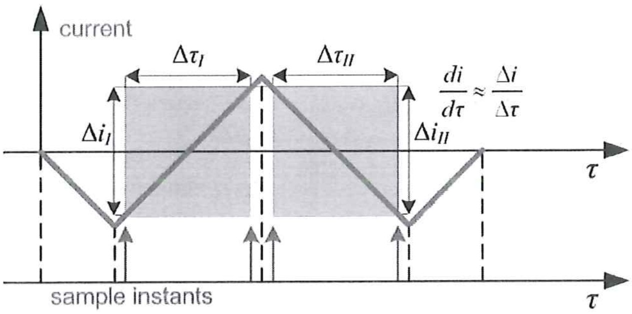

Fig. 1. Approximation of current derivative.

The transient leakage induction can be calculated by using the current derivative caused by a voltage pulse applied by the inverter. To eliminate the dependence on stator resistance (highly dependent on temperature) and the machine's back-EMF (depending on speed) the current reaction to two subsequent active inverter switching states can be evaluated. To excite the machine with the fundamental wave, the inverter is continuously applying voltage pulses. In some operating states the current response on these voltage pulses can be directly exploited to calculate the transient leakage inductance. Thus a theoretical integration of the pulse voltage injection for saliency tracking into the fundamental wave excitation can be achieved.

If standard industrial current sensors are used the current derivative is approximated by the difference of at least two sample values during each active switching state. This measurement scheme is shown in Fig. 1 for a voltage pulse pattern switching between the positive and negative state in one phase (i.e. +U/-U; 001, 110).

This measurement procedure limits the voltage pulse duration to a necessary minimum defined by the settling time of the current sensor signal (in the range of at least 10µs) and the time $\Delta\tau$ between the sampling instances. This time has to be long enough to ensure sufficient current difference for accurate saliency identification. For this approach the limit can be found at around 40–60 µs. This procedure will be denoted standard approach in the following.

Current derivative sensors (CDI) can be applied to further reduce the minimum necessary pulse duration. The application of current derivative sensors to further reduce the minimum necessary pulse duration is proposed in [16]. As then only one sample value during each active switching state is needed, the minimum pulse duration is just limited by the sensor signal's settling time. Thus a reduction for optimum condition to about 10-20µs (depending on the machine/cable/inverter configuration) can be achieved.

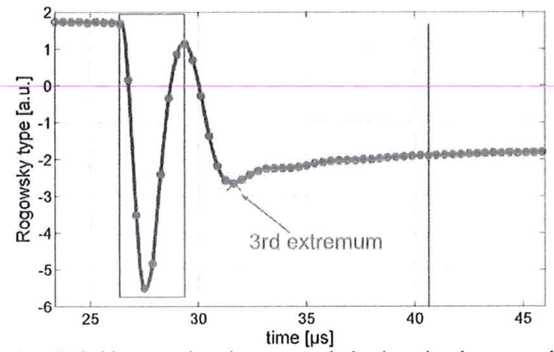

Fig. 2. Switching transient in current derivative signal measured with Rogowsky type sensors.

The trace of a Rogowsky type current derivative sensor (CDI) signal during the transition between two active switching states is shown in Fig. 2. The red vertical line marks the sampling instant after the settling of the sensor signal ringing.

A detailed description on the signal processing to gain the saliency information from the current derivative measured or calculated during two active switching states that are applied subsequently can be found in [8].

III. SALIENCY IDENTIFICATION EXPLOITING CURRENT REACTION DURING SWITCHING TRANSIENTS

The sensor signal in Fig. 2 depicts that the current derivative caused by inverter switching follows the behavior of a second order delay. As the transient effects are correlated with the final value and only relative relationships are needed for saliency extraction, it is sufficient to calculate signal characteristics during the transient proportion of the current derivative. These signal characteristics already imply, as well as the final value, the wanted saliency information. By using oversampling and signal processing it is possible to calculate such signal characteristics permitting to further reduce the minimum necessary voltage pulse duration. Thus the measurement is finished before other approaches start the sampling process. The integration of the switching pattern necessary for saliency tracking into the fundamental wave PWM is then possible in a much wider range of operating points.

To prove the saliency identification capabilities of the proposed procedure measurements were carried out on a 2-pole standard 5,5kW squirrel cage induction machine with an unskewed rotor cage. However, the proposed procedure is not limited to induction machines.

All measurements and control tasks are carried out on a setup consisting of a real-time rapid prototyping system programmable under Matlab/Simulink (dSpace 1103) responsible for machine control and a FPGA (Field Programmable Gate Array) for PWM-generation, measurement and signal preprocessing. The high frequent sampling is realized with a custom-built circuit board with 16bit, 40MS/s A/D-converters. Due to the high sampling rate during a short time window only, the communication between ADC and FPGA is realized with data buffers.

A comparison of different signal processing algorithms to the standard approach and to the measurement approach using CDI-sensors and one sampling instance during a voltage pulse of 20µs (further denoted as standard approach with CDI-sensors) shows, that similar signal accuracy can be reached, although the minimum pulse duration is reduced significantly.

In this paper three different signal processing approaches using oversampling of the current derivative signal will be presented and discussed:

1) Detection of actual switching instant and mean-signal-slope-calculation during specific time window
2) Detection of actual switching instant and mean-value-calculation during specific time window
3) Detection of sample value at extrema of high frequency signal during switching transient

The sensors applied for all three approaches are of Rogowsky-type (current derivative sensors). The basic idea of the first two signal processing approaches was presented in [14] and [15]. However, there the analysis was limited to a small range of operating points as the measurements were done off line with an external system. The results presented in this paper have been gained with a system integrated in the control scheme as stated in the introduction. Furthermore the second detection approach is applied on switching patterns that actually occur as switching sequences during SVPWM.

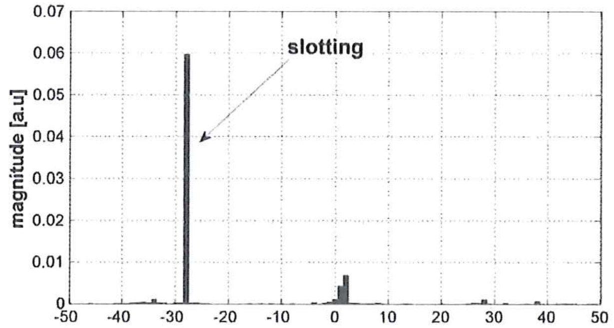

Fig. 3. Frequency spectrum of the saliency information signal over one mechanical revolution for the standard approach.

The most challenging part for the first and second approach is the identification of the actual switching instant that is strongly dependent on the delay of the gate driving circuitry, the jitter of the inverter's gate drive signal and of course inverter-dead-time. Fig. 3 and Fig. 4 show the Fourier-spectra (magnitude) of the saliency signal over one mechanical revolution for the standard (pulse duration of 60µs) and the mean-signal-slope-calculation approach, respectively.

The machine was operated at zero flux to ensure that the most dominant asymmetry is caused by rotor slotting. As the rotor under test has 28 rotor slots the slotting results in a -28th harmonic. For the mean-signal-slope-calculation the current derivative signal is sampled using standard A/D-conversion at 40MHz. The instant of the actual switching transition is determined (triggering) and the signal's mean slope during one period of the high-frequent signal ringing (about 2.5µs) is calculated. That is the difference between two subsequent sample values is calculated for a constant time window. It is averaged over all these differences. This mean value is proportional to the current derivative after settling of the switching transients and is further processed to identify the inherent machine saliency as described in [8]. The time window used for the mean-slope-calculation is highlighted by the green rectangle in Fig. 2. The applied switching sequence is between positive and negative state in one phase. The difference between the current derivative or the value proportional to the current derivative for the novel approaches during each of the two switching states is calculated for all phase values. These values are then combined to one space phasor denoted as current derivative space phasor. A linear combination of the current derivative space phasors gained from switching sequences in all three phases (+U/-U, +V/-V, +W/-W) eliminates the offset of the single current derivative space phasor's trajectory and represents the signal for saliency information extraction. In the frequency spectrum of Fig. 4 an additional harmonic can be seen. This is caused by sensor nonlinearity and has to be compensated in a future task.

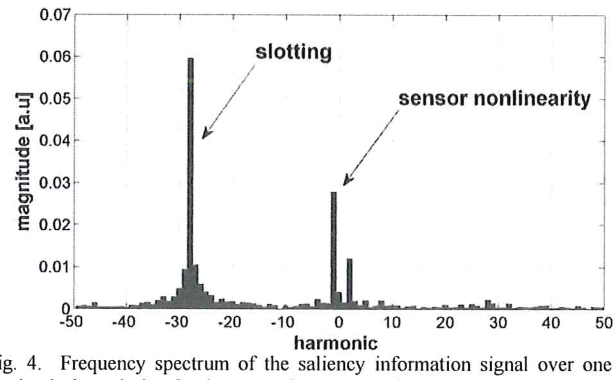

Fig. 4. Frequency spectrum of the saliency information signal over one mechanical revolution for the mean-slope-approach.

To show the performance of the proposed saliency identification procedure for a machine excited with the fundamental wave additional measurements were carried out. The machine under test is excited with rated flux and zero torque. The direction of the rotor flux is kept constant in the rotor frame of reference. The saliency signal is captured over one half mechanical revolution. The flux causes an additional harmonic in the saliency signal. For a 2-pole machine, as used in this investigation, this results in a 2nd harmonic as only saturation is detected and not its direction.

Fig. 5 depicts the saliency signal's real part. The blue trace shows the results for the standard approach with CDI-sensors, the green for the new proposal. The signal processing technique used here is the detection of the 3rd extremum in the high frequency ringing of the current derivative signal (marked with a green X in Fig. 2). With this approach minimum necessary voltage pulse duration of under 5μs can be realized, to ensure accurate saliency detection. The applied switching sequence is the same as for the measurement results in Fig. 3 and Fig. 4 and as described above.

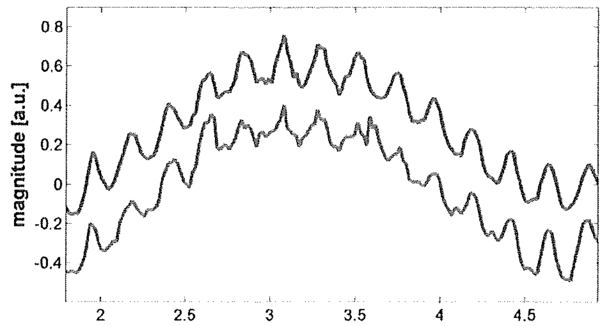

Fig. 5. Real part of saliency information signal gained by using standard approach with CDI-sensors (upper/blue) and proposed (lower/green) approach over one half mechanical revolution (offset added for better visual separation).

IV. Integration of the Saliency Identification into the Fundamental PWM-Sequence

In section III. the identification of the saliency signal based on a classical switching pattern with reduced voltage pulse width is described. By applying the described oversampling and signal processing approach to the voltage pulses already generated to excite the machine with the fundamental wave it is possible to employ sensorless control without alteration of the PWM-excitation in almost all operating points. In the following this integration is established and the saliency detection performance is tested for the mean value calculation 2).

As the inverter is only capable of applying seven (or eight when short circuit is separated between upper and lower; 111 and 000) different switching states, the PWM modulation has to be used to generate a voltage phasor with magnitude and angle. A PWM-modulated switching pattern consisting of three different switching states is thus applied to excite the machine with the pulse voltage space vector demanded by the machine control loop. The used space vector PWM approach can be found in [17] and is of asymmetrical type (saw-tooth counter).

The following Table 1 shows the different switching patterns that are applied during a PWM-cycle to excite the machine with a voltage space vector demanded by the control. SC stands for short circuit U,V,W for the corresponding phase directions.

Table 1. Applied switching pattern during SVPWM

Sector	Switching pattern
I	SC/+U/-W/SC
II	SC/-W/+V/SC
III	SC/+V/-U/SC
IV	SC/-U/+W/SC
V	SC/+W/-V/SC
VI	SC/-V/+U/SC

Measurements showed that the qualitative shape of the transient signal ringing is independent of the operating state if the switching state is changed in one phase only. A change from +U to –W represents such a switching transition as only phase V is switched from the lower to the upper transistor (001 to 011). In the description of the switching states a "1" equals upper and "0" lower transistor active. For a combination of active switching states in one phase and opposite sign, for example +U to –U (001 to 110) all 6 transistor change their state. If this transition takes place the qualitative shape of the transient signal ringing is strongly dependent on the operating point - that is the different current directions in the three phases. One reason for this is that – depending on the current direction in the corresponding phase – inverter interlock dead time has an effect in for example one phase whereas it hasn't in the others.

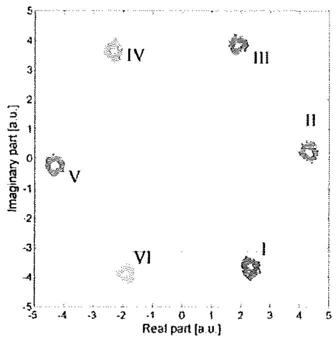

Fig. 6. Saliency information signal (current derivative space phasor) over one mechanical/electrical revolution gained from evaluating the two active switching states in all six PWM-sectors by applying the standard approach witch CDI-sensors; machine excited with rated flux, zero torque.

For a first investigation the saliency signals gained from exploiting switching sequences as summarized in Table 1 are analyzed. In order to enable a comparison of the saliency extraction performance with the standard approach it is necessary to allow minimum pulse duration for each active switching state of 20μs. This is done by interrupting the standard PWM-cycles applying the demanded voltage with this special test voltage pointing in the direction of the center of each sector (30°, 90°,...). If all switching sequences of Table 1 are evaluated over one electrical revolution – that is to say the current derivative space phasor is calculated and collected for every SVPWM-sequence – six different trajectories one for each of the sectors can be found. The number of the sectors in Table 1 is changed every 60° of the demanded voltage with sector I starting from 0° till 60°. The trajectories of the resulting current derivative space phasors are depicted in Fig. 6 for the standard approach using CDI-sensors. The machine was excited with rated flux and zero torque. Data was collected over one mechanical equal one electrical revolution as the machine has one pole pair. The six different trajectories are tagged in the figure with the corresponding sector number in roman numerals.

As each sector shows an individual offset depending on the switching pattern applied, these values have to be identified and compensated using signal processing like that presented in [18].

In the following, measurement results for the mean-value-approach will be depicted and compared to the classical approach using CDI-sensors. The used switching patterns to calculate the current derivative space phasor are the ones of Table 1.

Fig. 7 shows the magnitude of the frequency spectrum of the current derivative space phasor's trajectory over one fundamental wave period (comparable to the blue trajectory in Fig. 6 but at different operating condition) for the switching sequence of sector I – that are the switching states +U and -W (001, 011). The applied approach is the standard one using CDI-sensors and 20μs pulse width. The machine was operated at rated flux and 10% load. The dominant saliencies in the frequency spectrum are caused by saturation and rotor slotting. The saliency detection technique used can only detect the level of saturation and not its direction. Therefore saturation results in a 2^{nd} harmonic over one fundamental wave period. The saliency caused by slotting results in a -10^{th} harmonic for this specific operating condition and varies depending on the slip frequency. It is equal to the number of rotor slots that are passed during one fundamental wave period.

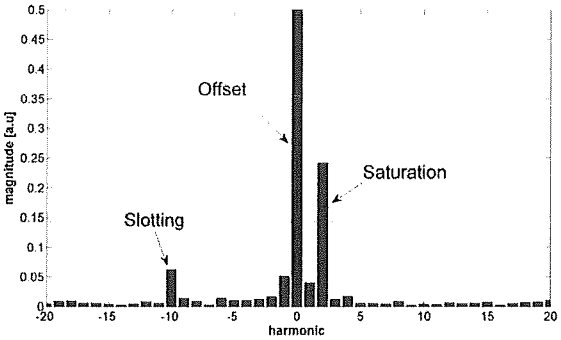

Fig. 7. Frequency spectrum of the saliency information signal over one electrical revolution for the standard approach with CDI-sensors; machine excited with rated flux and 10% load.

The results for the oversampling approach using mean-value calculation are depicted in Fig. 8. Now only the switching transitions from inactive to +U and from +U to -W (000 > 001 > 011) are exploited. The same operating conditions and switching sequence as in Fig. 7 are applied. The signal processing steps to be performed are described in the following:

- Determination of actual switching instant (triggering)
- Averaging of sample values over a time window of ~3μs in both active switching states (values proportional to current derivative) in all three phases
- Subtracting both values for each phase
- Calculation of current derivative space phasor

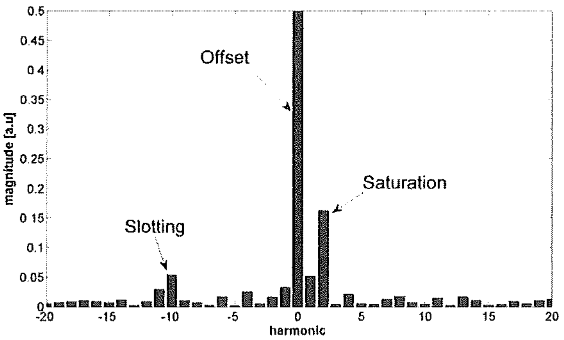

Fig. 8. Frequency spectrum of the saliency information signal over one electrical revolution for the mean-value-approach with window length of 3μs; machine excited with nominal flux and 10% load.

When comparing the measurement results of the two approaches, the expected saliencies are visible in both results. The offset in both cases is an outcome of the symmetrical portion of the transient leakage induction what is proportional to the current derivative space phasor. A more detailed description can be found in [8].

TABLE 2. COMPARISON OF SALIENCIES EVALUATED WITH BOTH APPROACHES

Harmonic number	Standard approach with CDI-sensors	Mean-value-approach
0 (Offset)	4.33	4.04
$+2^{nd}$ (saturation)	0.242	0.163
-10^{th} (slotting)	0.0625	0.054

TABLE 1 summarizes the comparison of the three saliencies present in the results of Fig. 7 and Fig. 8. As can be seen the saliencies can be detected with both approaches with only a slight degradation of signal to noise ratio (SNR). However, the minimum necessary pulse duration could be significantly reduced from 20μs to around 3μs.

V. DESCRIPTION OF THE APPLIED TRIGGERING ALGORITHM

As mentioned before a very important task in the signal processing chain is to accurately identify the actual switching instant where to start with the evaluation of the current derivative signal. The actual switching instant can strongly deviate from the instant of the switching command due to the delay of the gate driving circuitry, the jitter of the inverter's gate drive signal and of course inverter-dead-time. If this instant is not accurately identified the error in the calculation of the mean-value rapidly increases with the deviation of the detected trigger instant from the actual switching transition instant.

Fig. 9 shows a zoomed current derivative signal for a switching transition from lower short circuit (000) to +U (001). The sample instants are marked in the figure with a red circles.

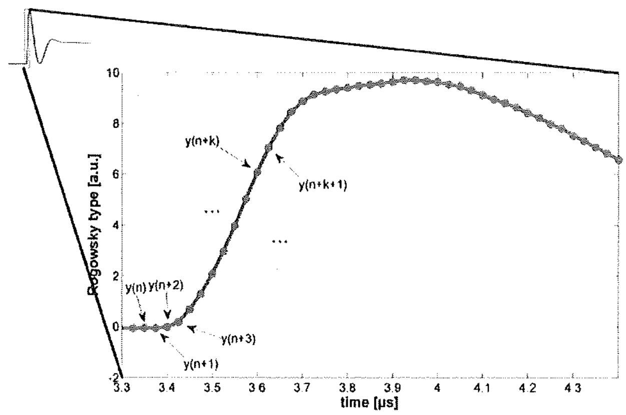

Fig. 9. Zoomed current derivative signal; Sample instants marked with red circle

The requirements for the applied trigger detection algorithm are, first of all, simplicity for real time implementation in i.e. an FPGA, reliability and robustness in terms of independence of the current machine's operating state. As the qualitative shape of the current derivative signal is independent of the operating point if changing the switching state of one phase only, the last requirement is relatively easy to reach. Furthermore the slope of the current derivative signals changes quite abruptly what is advantageous for trigger detection. To be independent of the current derivative's sign the absolute value of the signal can be used.

As a first pre-trigger the instant of the switching command can be used (i.e. $y(n)$). From this time instant onwards the current derivative signal is collected. As the signal has to be collected for a relatively short time of some µs only, the trigger instant can be determined from the collected data as sufficient calculation time after data collection is still available. Beginning with the instant of pre-triggering the difference between two subsequent sample values can be calculated ($y(n+1)-y(n); y(n+2)-y(n+1);\ldots$). If this difference – proportional to the derivative of the signal – is above a certain threshold value d_{thresh} this first of the two sample values is a possible trigger instant ($y(n+3)-y(n+2)>d_{thresh}$). If the overall trend of the next sample values is rising the trigger instant is found.

This results in the fact that two parameters have to be tuned for the trigger detection algorithm – the threshold value and the number of sample values that have to follow a rising trend. The tuning of these two parameters represents the most challenging part of the triggering. The whole triggering algorithm consists of additions, subtractions and comparisons only, what makes it very attractive for FPGA-implementation.

As the switching results in a steep change of the current derivative signal's slope a hardware implementation of the triggering using differentiators would be a possible solution as well. But then one has to be careful as also measurement noise is boosted. The switching would reflect in this signal as a peak that could be detected.

VI. Discussion

The present paper discusses the quality of the saliency information signal gained with the proposed oversampling approach. A future step will be online tracking of the flux angle and then implementation of the actual senorless control scheme. As the development and assembling of the laboratory control and measurement system to allow a profound analysis of the proposed oversampling approach is relatively time consuming, these three steps are separated into three tasks. However, the pending tasks will be performed in near future.

Although the SNR might be reduced in comparison to standard approaches the possibility to generate angle information with high update rate – as the evaluation is possible in most PWM-cycles – overcomes this drawback.

Furthermore the application of the oversampling approach to standard industrial current sensors and the investigation of signal processing algorithms to realize this combination are currently under development.

VII. Conclusions

A new approach to identify inherent machine asymmetries by using oversampling and data processing techniques was proposed. The information gained can be used for saliency tracking based sensorless control. Current injection based techniques need to apply additional switching patterns or modify the standard PWM to realize saliency identification.

Measurement results showed that the proposed technique allows accurate saliency detection by exploiting the switching transients only. This permits the integration of the excitation sequence needed to identify the machine's asymmetries into the fundamental wave PWM for most operating points.

Three different signal processing approaches were presented all using current derivative sensors. The last section discussed the most important issue in the signal processing chain – the detection of the actual switching instant (triggering). A relatively simple software realization of this task – well suited for real time calculation in an FPGA – was described.

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