A NEW SENSORLESS SPEED DETECTION METHOD BY FLUCTUATION OF ZERO CROSSING TIME SIGNALS IN INDUCTION MOTORS

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ABSTRACT

Several works have been done to detect the rotor speed without tachometers, encoders and resolvers. This study proposes a new sensorless speed measurement method based on stator current harmonics by using fluctuation of zero-crossing time signals acquired from three-phase stator currents of an induction motor. Three Hall effect current transducers are used to measure degraded values of three-phase stator currents which are employed to a circuit composed of zero-crossing time signal detectors and logical calculators. The square-wave signal obtained from the circuit shows time interval between adjacent current zero crossing time points. A 16-bit time counter on 87C51 is used to measure this time interval. These zero crossing time signals then are sent to a PC by serial connection to be saved in a file. The FFT spectral analysis of the signals by MATLAB package is used to extract the rotor speed and the other frequencies interested. A speed detection with 0.61% error is achieved with experimental data. Being independent of any time-varying parameters, such as stator winding resistance, this method provides a suitable off-line measurement system for steady-state operations of an induction motor. Zero-crossing time signals can also be used to detect the induction motor failures like rotor bar faults, unbalanced stator winding failure and bearing failure.

Key Words: Zero crossing time signal, sensorless speed detection, FFT spectrum analysis.

1. Introduction

Induction motors are widely used as the
workhorse of industry and public corporations, etc. because of its roughness and versatility. Progress in semi-conductor devices and their applications on induction motors to variable frequency supplies have introduced sophisticated control techniques have been making it possible to develop various induction motor drives with high performance. These control techniques such as slip frequency control, flux control, vector control, phase locked loop control, etc. require detection of rotational speeds of induction motors and are dependent on fast and accurate speed sensing for optimum operation. In real industrial world, speed sensors are expensive, the cables are connected to motor and speed sensors need extra maintenance work. So speed monitoring sensorlessly is more attractive in real industrial world. The speed feedback could increase the benefit of induction machine drive applications but shaft mounted speed transducers reduce the reliability and increase the cost and size of drive [1]. Numerous observer based adaptive schemes estimating rotor slip from the back emf are parameter dependent and fail under some continuous low speed operation. This paper presents a new sensorless monitoring induction motor speed.

Sensorless speed estimation permits robust, field oriented torque control without a tachometer. Many works have been done to replace conventional speed transducers in adjustable drives, by sensing the speed from the electrical quantities applied to the induction motor such as current and voltage are available for the drive assessment and control. An early effort of the sensorless speed measurement was made by Abbondanti and Brenner who designed in 1975 an analog slip calculator based on the processing of the motor input quantities, voltages and currents [2]. Later Ishida et al., in 1979 [3], who used rotor slot harmonic voltages in slip frequency control. This technique in [4] is endorsed by Ishida and Iwata without any further progress in improving the speed range. Another method was presented by Hammerli et al., in 1987, based on detecting the speed in the range 20–100% of nominal speed from the rotor slot harmonics. In this method, in the range under 30% of nominal speed, by injecting an additional signal of constant frequency into the machine to produce rotor slot modulation and therefore enhance the speed detection at low frequencies. Beck and Naunin reported a different approach describing a sensorless speed control of a squirrel-cage induction motor, based on the calculation of the rotor frequency from the phase angle between the stator voltage and current [1].

A Sensorless speed detection method based on the FFT spectral analysis is presented by Ferrah [1]. The work is mainly concerned with the extraction of the speed information contained in the rotor slot ripple harmonics created in the airgap of the induction motor using digital signal processing. Hurst proposes an algorithm which employs DSP
techniques to filter and manipulate speed related current harmonics from rotor slotting and eccentricity [5]. Hurts later contributed to determine the optimal method for accurately extracting the speed related harmonics in the least amount of time by using digital filtering [6].

This paper proposes a new method of determining rotor speed from current harmonics by using fluctuation of zero crossing times of three phase of stator currents. Three phase AC source supplying induction motor has two zero values per cycle, since current reverses twice per cycle. If a load is supplied with a 50 Hz balanced sinusoidal source, the period of one phase of load current becomes \( T = 0.02 \) s and each time interval between zero crossings is \( T/2 = 0.01 \) s. Zero crossing time is defined as the time difference between two adjacent zero-crossing time (ZCT) of line current subtracted by the time for 60° as shown in figure 1.

Figure 1. The definition of ZCT points in three phase currents.

The line current ZCT can be detected easily by using current transducers or transformers, logic circuits and a microcontroller. If both the motor is balanced and the supply is perfect, the ZCT should be equally spaced with increments of 60° and each ZCT is zero. In reality, it is impossible to assume an ideal supply and a complete symmetrical induction motor, and the ZCT is never always to be zero. In fact, it was experienced that the ZCT signal was found to be carrying rich information reflecting both internal conditions of the induction motor being monitored and external conditions such as supply. In each phase, the current does zero-crossing twice per cycle as it passes through zero and tries to reverse. Since this happens in each of the three phases, there are therefore \((2 \times 3)\) 6 instants when currents cross zero per cycle of the mains supply, 360°. If everything is balanced, these ZCTs occur at equal intervals of 60 degrees or one sixth of a cycle. So they occur at 6 times the supply frequency. Unbalance, whether in the rotor, or in end ring, or in the stator, or in the supply, causes small deviations from 60° in the interval between the crossings. If ZCTs are subjected to Fourier Analysis, it is found to contain many frequency components containing information about the state of the motor and of the supply. A great advantage of the method of sampling at the ZCT points is that the normally dominant fundamental component is absent as expected. Thus only deviations from ideal behaviour are seen, so that the method seems much more sensitive than normal speed detection methods.

2. Obtaining Zero Crossing Time Signal From One Phase of Stator Current
ZCT signals are obtained from zero crossings of stator current as seen in figure 2. Figure 3. shows block diagram of obtaining ZCT signals and sending to a PC. Usual current transducer or transformer is used to get one phase of stator current. The current passes through resistor and its voltage is then fed into LM339 based zero voltage comparators as seen in figure 4(a). Output of a comparator is a square wave as seen in figure 4(b). By logical calculation using logic circuits 7408 and 7427, these square waves produce a pulse signal to activate the interrupt mechanism of 87C51 single chip micro-controller. Since the time duration of two adjacent interrupts represents the time difference between two adjacent current zero crossing time, a high precision 16 bits time counter on 87C51 is used to measure the time interval of any two adjacent interrupts dynamically. ZCT signal is then sent to master PC in real time through 87C51 serial port via TXD pin and IC chip MAX232 is used for serial communication to convert ZCT signal from TTL level to RS232 level. The ZCT signals sent to PC are saved in a file for FFT spectrum analysis.

Figure 2. Zero crossing time signals of stator current converted to digital signals.

Figure 3. Block diagram for obtaining ZCT signals.

Figure 4. (a) LM339 based zero voltage comparator circuit for one phase, (b) Electronic Workbench oscilloscope screen with sinusoidal input and final digital output.

3. Obtaining Zero Crossing Time Signals From Three Phase of Stator Currents

The ZCT signals obtained from one phase
of stator current are sampled with $2f_1$ frequency. If supply frequency is $f_1=50$ Hz, sampling frequency will be 100 Hz and the frequency to be sampled becomes 50 Hz. In order to increase the frequency to be observed, the sampling frequency should be increased. In addition, a high resolution of frequency needs longer sampling interval. Another method of having longer sampling interval is to use the sampling of signals of 3 phase currents. Figure 5. shows block diagram of obtaining ZCT signals of the 3 phases.

For a three-phase AC supply there are six stop times per cycle, since current reverses twice per cycle in each of the three phases. A ZCT value is calculated for each stop time, so that a sequence of ZCT values is generated, with 300 measurements per second for a 50 Hz supply. This is equivalent to digital sampling at a rate of $6f_1$ points per second, where $f_1$ is the supply frequency as seen in figure 6. This time the frequency to be observed becomes 150 Hz. The ZCT values are transferred to a PC via a serial link. These values are then saved in a file for FFT spectrum analysis. Figure 7. shows LM339 based zero voltage comparator circuit for 3 phase and Electronic Workbench oscilloscope screen with one phase’s digital input and final digital output.

![Figure 5(a) Block diagram of obtaining ZCT signals from 3-phase stator currents.](image)

![Figure 5(b) Circuit connections of MAX232 IC.](image)
Figure 6. ZCT signals of 3 phase stator currents.

Figure 7. (a) LM339 based zero voltage comparator circuit for 3 phase, (b) Electronic Workbench oscilloscope screen with one phase’s digital input and digital output.

4. Theory of ZCT Method and Processing ZCT Signals

It is well known that stator line current has components $f_t \pm f_r$, where $f_t$ is the supply frequency and $f_r$ is the frequency of rotor speed. ZCT method samples the current zero crossing time and analyse the fluctuation of the zero crossing times. ZCT frequency spectrum introduces $f_r$ component used to detect rotor speed sensorlessly by the current transducers.

The frequency resolution of FFT spectrum analysis depends on the sampling period over which data is collected [6,7]. For a period $T$, the frequency resolution will be $1/T$. As far as the ZCT signal is concerned, the sampling frequency is fixed at $6f_t$. If a
frequency resolution of 0.05 Hz is desired, ZCT data values must be collected for \((1/0.05=)\) 20 seconds, and then subjected to spectrum analysis by FFT. This would require \((6\times50\times20=)\) 6000 sampled values to be stored for a 50 Hz system, and the FFT to be applied to these values. However, during the 20 second time, if the motor speed has changed the speed component would smear out. Rotation of squirrel cage rotor causes fluctuations on the ZCT signals of squirrel cage induction motor under different loads as shown in figures 8 to figure 12. The dotted guide lines are drawn for a comparison with increments of 3.333 msn.

Figure 8. Ideal ZCT signals for the rotor speed, \(f_r = 25\) Hz, 1500 rev/min.

Figure 9. Fluctuation of ZCT signals for the rotor speed, \(f_r = 24\) Hz, 1440 rev/min.

Figure 10. Fluctuation of ZCT signals for the rotor speed, \(f_r = 23.83\) Hz, 1430 rev/min.

Figure 11. Fluctuation of ZCT signals for the rotor speed, \(f_r = 23.5\) Hz, 1410 rev/min.

Figure 12. Fluctuation of ZCT signals for the rotor speed, \(f_r = 23.17\) Hz, 1390 rev/min.

Sensorless motor speed monitoring and motor failure prediction requires mostly the motor voltage and current. Firstly, the highly accurate A/D converter is required for accurate sampling of motor currents or voltage values and it is very difficult to sample three phase currents or voltages simultaneously. There is an unavoidable delay between two adjacent phase current or voltage. However, it is relatively easier
if only the current or voltage zero crossing time is measured instead of sampling every value of current or voltage. Meantime, sampling ZCT could get rid of the frequency of fundamental which is dominant in FFT of current or voltage. But since the measurements are taken at the zero crossings, the sample frequency is locked to six times of mains supply and is only affected by drift or fluctuation in the supply frequency. But the distortion in supply and harmonic currents has no effect on the motor speed.

5. Off-line Speed Computation by ZCT Signals

For a 4-poles motor, \( f_r \) is at 25(1-s) Hz, where \( s \) is the fractional slip of the motor. There is a clear component in the ZCT spectrum at the same frequency just below 25 Hz, which may be used to measure the motor speed. The following results show that the speed frequency obtained by the ZCT method is in very good agreement with speed measurement by a shaft encoder or tacho as shown in table 1 and figure 13.

<table>
<thead>
<tr>
<th>Load Torque (Nm)</th>
<th>Measured rotor speed (rev/s) ( M )</th>
<th>Computed rotor speed (rev/s) ( C )</th>
<th>Error % ((C-M)/M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>25.00</td>
<td>25.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1</td>
<td>24.83</td>
<td>24.90</td>
<td>0.28</td>
</tr>
<tr>
<td>2</td>
<td>24.50</td>
<td>24.65</td>
<td>0.61</td>
</tr>
<tr>
<td>3</td>
<td>24.33</td>
<td>24.25</td>
<td>-0.33</td>
</tr>
<tr>
<td>4</td>
<td>24.16</td>
<td>24.15</td>
<td>-0.04</td>
</tr>
<tr>
<td>5</td>
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<td>0.00</td>
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<td>-0.33</td>
</tr>
<tr>
<td>7</td>
<td>23.50</td>
<td>23.50</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 1. Measured and computed speeds and % error, frequency resolution = 0.05 Hz.

Figure 13. Off-line speed computation with 1 kW, 380 V, 4 poles induction motor at 50 Hz. A comparison of between measured and computed speeds.

Figures 14 to 17. show the graphs of time - ZCT values and FFT spectrum analysis - related speed frequencies with different loads. If the motor speed varies during the 20 second sampling period, the spectral peaks are smeared out and reduced in amplitude and may be hard to observe as seen Figure 18.

Figure 14. FFT spectrum analysis and related speed frequencies, motor with no
The method applied is also suitable to motor with different number of poles. In figure 19. FFT spectrum analysis of 2-poles motor with load is shown. The rotor frequency interested is changed to near 50 Hz, 49.6 Hz as expected. If the load is 3 lamps on the three-phases instead of an induction motor, FFT spectrum analysis does not give any speed frequency information related to speed, because there is no information on the lamps related to speed as shown in figure 20. The method is also applicable to motors supplied by V/F controlled inverter as shown in figure 21.
If the rotor is made of solid iron without aluminium bars and also slip is very high, a comparison of between measured and computed speeds with frequency resolution = 0.1 Hz is shown in figure 22. In this experiment, under low slips it is very difficult to observe the frequency related to speed as the high magnitude of the other harmonics. Under high slips, there is frequencies related to speeds but with very low magnitudes. All these explains there is close relation with the physical structure of the rotor like presence of bars.

6. On-line Speed Computation by ZCT Signals

The method discussed is not suitable for real time on-line speed determination. On-line speed determination requires the
ZCT values continuously FFT analysed rather than be stored in a file. This problem can be solved by a small change in the software. For a FFT frequency resolution of 0.05 Hz, 6000 ZCT data values must be collected for 20 seconds for a 50 Hz system. This long duration of process is not suitable for real time speed determination. A new approach with advantage of the limited frequency region of interest and incorporates digital filtering techniques for real-time speed measurement with high accuracy should be developed. There are different band-pass filters to filter out the speed component in real world. The ZCT signal may be passed through Butterworth digital band-pass filter with bandpass frequencies from 23 Hz to 25 Hz for the 4-poles motor or from 47 to 50 Hz for the 2-poles motor. Instead of processing the ZCT signal in frequency domain, the frequency of the ZCT component emerging from the filter may be measured by observing its ZCT points in time domain. Both magnitude and frequency may be obtained and displayed as a moving average, whilst ZCT sampling is still going on. So the 20 second data collecting time delay would be reduced to 1-2 second which is still very useful as one monitoring signal with the advantage of its simple method, sufficient accuracy and low cost.

7. Induction Motor Faults Prediction by ZCT Method

The workhorse of industry, squirrel-cage induction motor is designed, manufactured and applied to function as intended for many years. However, if its limitations are exceeded, will result in premature failure of stator or rotor. An unexpected failure of induction motor may result in a loss of production and often the cost production far exceeds the cost to replace the failed component. Induction machines convert electrical to mechanical energy and they achieve this by magnetically coupling electrical circuits across an air gap that permits rotational freedom of one of these circuits. The transfer of energy inevitably involves the dissipation of heat, by ohmic losses in the electric circuits, and by eddy current and hysteresis losses in the magnetic circuit. An electrical or mechanical fault is always preceded by deterioration of one of the electrical, mechanical, magnetic, insulation or cooling components of the machine. If that deterioration takes a significant period of time and can be detected by measurement then that detection may be a valuable means of monitoring the machine before failure. With advances in digital technology over last several years, adequate data processing capability is now available on cost-effective hardware platforms to monitor motors for a variety of abnormalities on a real time basis.

It is expected to be the variation of ZCT predicts the induction motor failure. From the current waveform spectrum after holes or cracks appear in the rotor bars, it is straightforward to explore the component in current ZCTs spectrum due to asymmetry causing a pulsating component in the rotor. Stator winding
failure as a short circuit of some turns or an open circuit would cause an unbalanced phase currents which is also expected to be predicted by ZCT method. Induction motor faults prediction by ZCT method is out of scope of this paper as the work is still continuing.

8. Conclusions

A new method of FFT spectrum analysis based off-line sensorless speed detection of 3 phase induction motor driven by mains supply and \( V/F \) controlled inverter is presented. A speed detection with 0.61% error is achieved with an experimental machine. The speed extracted from FFT spectrum analysis depends the fluctuation on ZCT signals by rotation of squirrel cage rotor. ZCT signals do not depend on the number of rotor bars but presence of rotor bars increases the sensitivity. The method presented here can be easily made suitable for real-time on-line speed determination by using the advantage of the limited frequency region of interest and incorporates digital filtering techniques. It may also be possible to get an idea of rotor bar faults, stator windings failure, bearing failures and the other unbalanced quantities of motor. The current harmonics are independent of time-varying parameters, such as stator winding and rotor bar resistances. The future work may include a microprocessor based motor controller with measuring ZCT signals for FFT analysis and predicting the speed, rotor and stator and bearing failures.

9. References


