A NEW SENSORLESS SPEED DETECTION METHOD IN INDUCTION MOTORS

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Abstract

The speed detectors attached mechanically to the induction motors like tacho-generators have been improvements considerably but this type of product must be installed on the driving shaft of the machine. Therefore it is desirable to detect the rotor speed without tacho-generators. This study proposes a sensorless speed measurement based on speed-related using zero-crossing time signal acquired from 3-phase induction motor. Zero-crossing time signal can be also used to detect rotor bar fault and predict unbalanced stator winding failure. Three Hall effect current transducers are used to get degraded values of 3-phase stator currents. The degraded currents signals are employed to a circuit composed of zero-crossing time signal detectors and logical calculators. The square-wave signal obtained from this circuit shows time interval between adjacent current zero crossing time. A 16-bit time counter on 87C51 is used to measure this time interval. Then this signal is sent to a PC by serial connection, and for Fast Fourier Transform (FFT) spectral analysis the signal on PC is saved in a file. Being independent of any time-varying parameters, such as stator winding resistance, this schema provides a suitable off-line measurement system for steady-state operations of an induction motor. A speed detection with 0.61% error is achieved with an experimental machine.

Key Words: Zero crossing time, sensorless speed detection.

1. Introduction

Induction motors are widely used in industry and public corporations, etc. Progress in semi-conductor devices and their applications on induction motors to variable frequency supplies have introduced sophisticated control techniques. 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. 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.

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). It was followed by the work of Ishida et al., in 1979 (3), who used rotor slot harmonic voltages in slip frequency control. Ishida and Iwata endorsed this technique in (4). Hammerli et al. (1) presented a method, 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. A different approach was reported by Beck and Naunin in which they described 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 employs DSP techniques to filter and manipulate speed related current harmonics from rotor slotting and eccentricity (5).

This paper proposes a new method of determining rotor speed from current harmonics by using zero crossing times of three phase of stator currents. The 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 load current becomes $T=0.02$ s and each time interval between zero crossings is $T/2=0.01$ s. If the load is a induction motor, zero crossing times are experienced a defection by having a shift in zero crossing times. Rotation of squirrel cage changes the zero points on the current wave. A number of these defected zero crossing points are FFT spectrum analysed and speed of rotor is extracted from the analysis. It may also be possible to get an idea of rotor bar faults, stator windings failure and the other unbalanced quantities of motor. The current harmonics mentioned are independent of time-varying parameters, such as stator winding and rotor bar resistance.

2. Obtaining Zero Crossing Time Signal From One Phase Of Stator Current

Zero Crossing Time (ZCT) signals are obtained from zero crossings of stator current as seen in figure 1. Figure 2 shows block diagram of obtaining ZCT signals and sending to a PC. Usual current 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 3. Output of a comparator is a square wave. 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 or in fact defected 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 1. Zero crossing time signals of stator current converted to digital signals.

Figure 2. Block diagram for obtaining ZCT signals.

Figure 3. (a) LM339 based zero voltage comparator circuit for one phase, (b) Electronic
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 4. shows block diagram of obtaining ZCT signals of the 3 phases and sending to a PC.

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 5. 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 (Fourier) spectrum analysis.
Figure 4. (a) Block diagram of obtaining ZCT signals from 3 phase stator currents, (b) Circuit connections of MAX232 IC.
Figure 5. Zero crossing time signals of 3 phase stator currents

Figure 6. (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. Processing ZCT Signals

The frequency resolution of FFT spectrum analysis depends on the sampling period over which data is collected. 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 $6f$, where $f$ is the supply frequency. If a frequency resolution of 0.05 Hz is desired, ZCT data values must be collected for 20 seconds, and then subjected to spectrum analysis by FFT. This would require 6000 sampled values to be stored for a 50 Hz system, and the FFT to be applied to these values. FFT spectrum analysis has been done by MATLAB software. The frequency resolution in FFT depends on sampling period (6). Frequency resolution, $df$ for a $T$ period is given by (1):

$$df = \frac{1}{T} \quad (1)$$

The sampling period, $dt$ is given by (2):

$$dt = \frac{T}{n_t} \quad (2)$$

where $n_t$ is number of samples. The sampling frequency, $f_s$ is given by (3):

$$f_s = \frac{n_t}{T} \quad (3)$$

and maximum (Nyquist) frequency (6), $f_{max}$ is

$$f_{max} = \frac{n_t}{2} d_f \quad (4)$$

As seen, in this paper a frequency of 6 times supply frequency is sampled.

5. Off-line Speed Computation by ZCT Signals

For a 4-pole motor, the rotor (shaft) speed 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 7.

<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>
</tbody>
</table>
Table 1. Measured and computed speeds and % error, frequency resolution = 0.05 Hz.

<table>
<thead>
<tr>
<th></th>
<th>Measured</th>
<th>Computed</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>24.16</td>
<td>24.15</td>
<td>-0.04</td>
</tr>
<tr>
<td>5</td>
<td>24.00</td>
<td>24.00</td>
<td>0.00</td>
</tr>
<tr>
<td>6</td>
<td>23.83</td>
<td>23.75</td>
<td>-0.33</td>
</tr>
<tr>
<td>7</td>
<td>23.50</td>
<td>23.50</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Figure 7. Off-line speed computation with 1 kW, 380 V, 4 pole induction motor at 50 Hz. A comparison of between measured and computed speeds.

Figures 8. shows the graphs of time - ZCT values and FFT spectrum analysis - related speed frequencies with different loads. In figure 8(e) FFT spectrum analysis of 2 poles motor with load is shown. The method applied is also suitable to motor with different number of poles. If the load is 3 lamps on the 3 phases instead of an induction motor, FFT spectrum analysis does not give any frequency related to speed, because there is no information on the lamps related to speed. 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 9(a). The method is also applied to motor supplied by V/F controlled inverter. FFT spectrum analysis is shown in figure 9(b), the results still give reasonable answer.
If the rotor is made of solid iron without aluminium bars and slip is very high, a comparison of between measured and computed speeds with frequency resolution = 0.1 Hz is shown in figure 10. In this experiment, under low slips it is very difficult to observe the frequency related to speed as the high magnitude of 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.

(a) motor with no load, \( f = 25 \) Hz.  
(b) motor with rotor blocked, \( f = 0 \) Hz.  
(c) motor with load, \( f = 23.3 \) Hz.  
(d) motor with load, \( f = 24 \) Hz.
(e) 2 poles motor with load, $f=49.6$ Hz.  
(f) load as lamps, $f=0$ Hz.

Figure 8. FFT spectrum analysis and related speed frequencies.

Figure 9. FFT spectrum analysis with load, (a) motor with variable load, (b) motor supplied by $V/f$ controlled inverter, $f_1=75$Hz.
Figure 10. Off-line speed computation with 2 pole induction motor at 50 Hz. Rotor is made of solid iron without aluminium bars and slip is very high. A comparison of between measured and computed speeds, frequency resolution = 0,1 Hz.

6. On-line Speed Computation by ZCT Signals

Up to now all our discussion is not suitable for real-time on-line speed determination. For a frequency resolution of 0.05 Hz, ZCT data values must be collected for 20 seconds, and then subjected to spectrum analysis by FFT. This would require 6000 sampled values to be stored for a 50 Hz system. In addition, 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.

A new approach for real-time speed measurement with high accuracy should be developed, which takes advantage of the limited frequency region of interest and incorporates digital filtering techniques. The ZCT signal may be passed through Butterworth digital band-pass filter with bandpass frequencies from 23 Hz to 25 Hz. Instead of processing the ZCT signal in frequency domain, the frequency of the ZCT component emerging from the filter is measured by observing its zero-crossing points in time domain. Both magnitude and frequency are obtained, and may be displayed as a moving average, whilst ZCT sampling is still going on.

7. Conclusion

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 in this paper. A speed detection with 0,61% error is achieved with an experimental
machine. The speed extracted from FFT spectrum analysis depends on ZCT signals defected by rotation of squirrel cage rotor. ZCT signals do not depend on the number of rotor bars.

The method presented is not suitable for real-time on-line speed determination. A new approach for real-time speed measurement with high accuracy should be developed, which takes 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 and the other unbalanced quantities of motor. The current harmonics are independent of time-varying parameters, such as stator winding and rotor bar resistances.

8. References


