A Slot Harmonic Detection with an Empirical Formula to Extend the Speed Range Control in 3-Phase IM Drives

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Abstract:- A lot of development has been made in the area of sensorless speed measurement in Induction Motor (IM) where the tachometer is discarded and the speed is measured from the magnetic characteristics of the machine itself. In IM there are slots of the surface of the stator and rotor iron cores. When the rotor rotates, harmonics are produced in the air-gap flux that induces slot harmonic voltages in the stator windings. By measuring either the magnitude or frequency of the slot harmonics the rotor speed can be determined. A method of improving the performance of a system using the rotor slot harmonic technique is investigated. This involves the use of an empirical formula to estimate the rotor speed, based on current and frequency readings. This is used in the speed range where the rotor slot harmonics become difficult to detect.

Key-Words:- Induction motor, sensorless control, slot harmonic.

1. Introduction

The induction motor is the most commonly used motor to date. The reason being that is requires practically no maintenance, is robust, can work in harsh conditions and is relatively cheap. As a result much attention has been given to induction motor control methods for starting, braking, speed changing, etc.

Also, because of advances in solid state power devices and digital signal processors, variable speed drives using switching power converters are becoming increasingly popular. Switching power converters offer an easy way to regulate both the frequency and magnitude of the voltage and current applied to a motor. As a result, much higher efficiency and performance can be achieved by motor drives with less generated noise.

The traditional method of closed loop motor control has been to use one or more sensors to provide feedback. A growing number of applications are now eliminating the sensor through one of several methods, such as back electromotive force (EMF) or inductance measurement, etc.

The traditional method of motor control has several disadvantages:

- In the low power range of drives the price of a speed sensor may be more than the motor itself.
- In some applications there is no space for them.
- Additional wiring is required, which can be prohibitive in applications such as hermetically sealed compressors.
- The wiring can also be vulnerable to electromagnetic interference.

Sensorless motor controls are best suited for applications where speed control is needed, but precise position control isn't needed. Typical applications include velocity control on conveyors, elevators, some pick-and-place applications, overhead gantries, appliance motors and centrifuges.

One type of sensorless control method involves using the rotor slot harmonics of an induction motor, which generate a frequency proportional to the speed of rotation [1]-[3]. This method is relatively easy to implement as it has few hardware requirements, and the software algorithm is relatively simple to implement. Previous studies have shown that this particular technique gives high speed accuracy in the steady state. At lower speeds, however, speed estimation becomes difficult as low frequency ripple occurs, due to the slow rotation of the rotor slots. This results in a distorted feedback signal.

A method of improving the performance of a system using the rotor slot harmonic technique is investigated. This involves the use of an empirical formula to estimate the rotor speed, based on current and frequency readings. This is used in the speed range where the rotor slot harmonics become difficult to detect.

The technique involved in isolating the rotor harmonic as well as the method used to derive the empirical formula is discussed. The new system will improve on the existing rotor harmonic technique of speed estimation by making the system more robust. The traditional weaknesses of the rotor slot harmonic technique is overcame by the introduction of an empirical formula to produce low speed estimation. This has the potential to improve on existing induction motor control by increasing the dynamic speed range of a system that uses rotor slot harmonic speed estimation in a direct field orientated control system.

A lot of development has been made in the area of sensorless speed measurement where the tachometer is discarded and the speed is measured from the magnetic characteristics of the machine itself. Sensorless motors are best suited for applications where speed control is needed but precise control isn't critical. The main reason being is that precise control is difficult to attain, due to the non-linear speed torque characteristics of the motor and its parameter variation with temperature, current and frequency.

The most versatile among motor control methods, a.c. variable speed drives (VSD)s are available using four basic methods: Open loop control, flux vector control, sensorless vector control and direct torque control provide an increasingly sophisticated command of induction motors.

Open loop a.c. drives employ the simplest motor control, the so-called volts-per-hertz (V/Hz) method [5]. Also known as "scalar" control, to differentiate it from vector control methods [4]. V/Hz runs in open loop without a formal feedback device. However, current and voltage sensing are done for current limit and slip estimation. This lower cost method is basically a speed control, providing relatively low speed and torque response. It offers no torque control or high torque values at low speeds. The principle of constant V/Hz for a.c. induction motors begins by assuming that the voltage applied to a three-phase a.c. induction motor is sinusoidal and neglects the voltage drop across the stator. At the steady state we have the following:

$$\hat{V} \approx j\omega\hat{\Lambda} \tag{1}$$

i.e.

$$V \approx \omega\Lambda \tag{2}$$

where $\hat{V}$ and $\hat{\Lambda}$ are the phasors of stator voltage and stator flux, and V and Λ are their magnitudes, respectively. Thus, we get

$$\Lambda \approx \frac{V}{\omega} = \frac{1}{2\pi}\frac{V}{f} \tag{3}$$

From which it follows that if the ratio V/f remains constant with the change of f, then L remains constant too, and the torque is independent of the supply frequency. In actual implementation, the ratio between the magnitude and frequency of the stator voltage is usually based on the rated values of these variables, or motor ratings. However, when the frequency and hence also the voltage are low, the voltage drop across the stator resistance cannot be neglected and must be compensated. At frequencies higher than the rated value, the constant V/Hz principle also has to be avoided. This is necessary to avoid insulation break down, hence the stator voltage must not exceed its rated value. This principle is illustrated in figure.1.

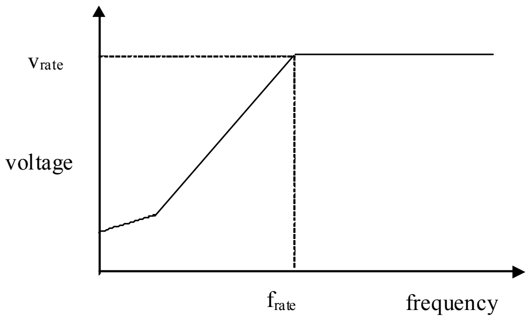

Fig.1 Voltage vs Frequency under the Constant V/Hz Principle

Since the stator flux is maintained constant, independent of the change in supply frequency, the torque developed depends on the slip speed only, this is shown in figure. 2.

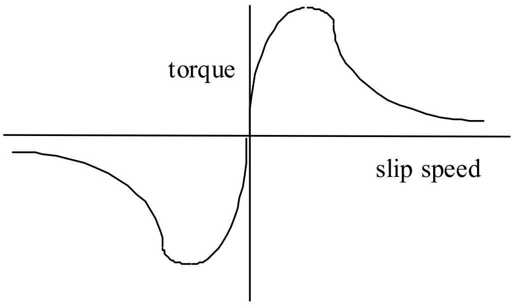

Fig. 2 Torque vs Slip Speed of an Induction Motor with Constant Stator Flux

The V/Hz control method is still used in most a.c. drive types. This type of drive is used when accuracy in speed response is not a concern, such as powering pumps, fans, HVAC (heating, ventilation and air conditioning) and other continuous process applications. In this case, the supply frequency is determined based on the desired speed and the assumption that the motor will roughly follow its synchronous speed.

The error in speed resulting from the slip of the motor is considered acceptable. One notable advantage is the ability to control several motors from one drive. Various V/Hz characteristics are also possible in addition to the common linear V/Hz relationship.

At the other end of the variable speed drive spectrum is flux vector control (FVC), also known as field orientated control [5]. In field orientation, the motor input currents are adjusted to set a specific angle between fluxes produced in the rotor and stator windings in such a manner that follows the operation of a d.c. machine. More formally, the approach applies direct-quadrature (D-Q) two-axis analysis methods directly to the torque control problem. When the dynamic equations for an induction motor are transformed by means of some well known rotating transformation methods into a reference frame that coincides with rotor flux, the results become similar to the dynamic behaviour of a d.c. machine. This allows the a.c. motor's stator current to be separated into a flux-producing component and an orthogonal torque-producing component, analogous to a d.c. machine field current and armature current. The key to field-orientated control is knowledge of the rotor flux position angle with respect to the stator. Approaches in which rotor flux is sensed are now generally termed "direct field orientation" methods. Another approach is to compute the flux angle from the shaft position information, provided other motor parameters are known. This is known as "indirect field orientation".

Whatever the field-orientation approach, once the flux angle is known, an algorithm performs the transformation from three phase stator currents into the orthogonal torque and flux-producing components. Control is then performed in these components and an inverse transformation is used to determine the necessary three phase currents or voltages.

Sensorless vector control provides another alternative for speed regulation and starting torque over V/Hz drives [6]. The enhancements come at relatively small additional cost. Most of these schemes depend on integrating the back emf voltage, which by Faraday's Law produces the stator flux. At high speeds, the back emf is approximately equal to the terminal voltage, since the stator voltage drop is negligible, and integration of the stator voltage accurately estimates the field orientation angle. At low speeds, however, back emf-based schemes fail for two reasons.

Direct vector control is another sensorless method of directly controlling torque by independent control of an induction motor's magnetic field (flux) and torque using only voltage and current information from the motor [7]. The induction motor voltages or currents are set to values as close as possible to the ones needed to generate a desired torque. This method depends on a very accurate motor model and a processor that can compare instantaneous torque and flux with reference values as fast as 25ls.

2. Speed Estimation Methods

In order to develop a reliable system of sensorless control, an accurate model of the system is needed, in particular accurate speed estimation. Various methods of sensorless speed control were investigated.

In an induction motor there are slots of the surface of the stator and rotor iron cores. When the rotor rotates, harmonics are produced in the air-gap flux that induces slot harmonic voltages in the stator windings. By measuring either the magnitude or frequency of the slot harmonics the rotor speed can be determined. In [2] an early attempt at using rotor slot harmonics is undertaken. The motor is connected in star and the phase voltages summed up. Tapped stator windings are used for flux measurement and rotor slot ripple measurement. The frequency of the rotor slot harmonic is isolated by using a analogue phase locked loop. A switched capacitor is also used to allow easy adjustment of the centre frequency.

Using analog devices has some disadvantages, the first being that extra hardware is needed for the application, which adds to the cost of the system. Factors, such as time constants and variations by temperature, become important. The phase locked loop requires careful choice of parameters, such as lock-in-frequency and capture frequency for correct operation. The need for tapped stator windings limits the application from using general off-the-shelf induction motors.

The results showed good speed control at higher speeds with regulation deteriorating at lower speeds, this is a common problem with using rotor slot harmonic measurements.

An improvement in the technique can be seen in [8]. The rotor slot harmonics are used to determine the speed by using the frequency of the harmonics. A parameter adaptation scheme is used to eliminate the speed estimation error by on-line tuning of model parameters. The estimation error is caused by rotor resistance changes caused by temperature, the changes in stator inductance, caused by changes of magnetization and the variation of leakage inductance due to saturation of stator teeth. The harmonics are extracted by using a digital bandpass filter, the centre frequency is tuned to the harmonic frequency. This offers an improvement as all the filtering can be done on the digital signal processor (DSP), thus reducing the hardware needed and reducing the overall cost.

Improving the speed estimation error is done by comparing the rotor harmonic frequency to the estimated rotor frequency, based on the rotor resistance model. This results in a signal, which can be used for direct feedback with enough accuracy to be used in high performance drives.
Speed errors were reduced to 0.002p.u. and fast dynamic response was observed. This system however, would not be able to function and was not tested at sustained low speed, which showed the fundamental disadvantage of using rotor slot harmonics for speed estimation. As the speed decreases, eventually the signal becomes an a.c. ripple and no information can be extracted.

A method known as spectral analyses can be used at low speed [9]. Speed related harmonics from the rotor slotting and eccentricities are used to determine the speed. Since current harmonics are sampled and exist at any non-zero speed, the rotor speed can be determined at very low frequencies. The algorithm uses current harmonics, which are independent of motor parameters, and magnitude independent of source frequency.

This algorithm makes up for the rotor slot harmonic's failure at low speed. However the algorithm is more computationally intensive combining several filtering steps and fast fourier transform. Due to the discrete nature of the speed detector the system must be in steady state for a minimum period, required by the algorithm. Thus, applications like fans, pumps and conveyors are recommended.

The best solution in the quest for creating a universal sensorless controller would be to incorporate more than one traditional control method. This way creating a system that draws from the strengths of the individual models, and also creating a truly robust system.

A technique of speed estimation where there were relatively few hardware costs and which, also incorporates a simple control algorithm was sought. It was found that sensorless speed estimation based on rotor slot harmonics matched the mentioned criteria. This technique yielded high speed accuracy in the steady state [10]. However, as also mentioned in [11], this particular method had the disadvantage in that at low rotor velocities, the rotor slot signals deteriorate and speed estimation was difficult. A method of improving on this technique is investigated and simulated.

3. Experimental Setup

Readings were needed for the lookup table, below 300rpm where the rotor slot harmonics start to degrade. The voltage, frequency and current readings were taken for motor loads ranging from no load up to full load. Load was adjusted by varying the resistance of a d.c. brake attached to the induction motor. The motor being tested had the following specifications; 0.33hp, 400/230Volt (Star/Delta), 0.9Amp, and 1400rpm.

From the measurements a mathematical relationship was developed using minitab 13 for the speed in terms of current and frequency.

$$Speed = 287 + 8.89\, frequency - 969\, current \quad (4)$$

Harmonic measurements were taken at various speeds in an attempt to locate the rotor slot harmonics. According to theory the rotor slots produce slot harmonics in the airgap field, which

modulate the stator flux linkage at a frequency proportional to the rotor speed. The slot harmonic voltages comprise two components of frequencies:
$N_r f_r + f$ and $N_r f_r - f$
Where;
N_r = number of rotor slots per pole pair
f_f = rotor revolutions per second
f = supply frequency
Spectrum harmonic components were identified for different speeds as can be seen in figures 3 and 4.

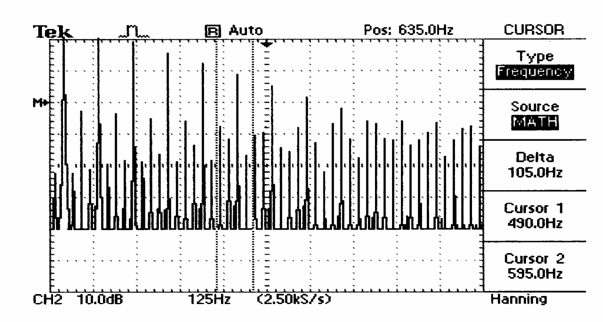

Fig. 3 Spectrum at 1470rpm

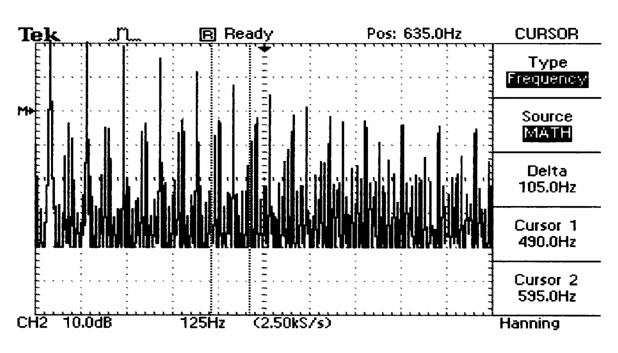

Fig. 4 Spectrum at 1314rpm

The next step will be to filter out the desired rotor slot harmonic and use it to determine the rotor speed. The induced rotor slot harmonics along with other third harmonic components are separated from the much larger fundamental emf. The rotor slot harmonic components exhibit the dominating frequency in the vicinity of $(N_r + 1)f_{rotor}$. They are to be extracted by a band-pass filter, the center frequency of which is adaptively tuned to the rotor slot harmonic frequency. The evaluation of the rotor slot harmonics offers a signal which is equivalent to that of an incremental speed sensor having a resolution of $p(N_r + 1)$.
Where;
p= number of pole pairs
N_r = number of rotor slots per pole pair

This gives 46 counts per revolution. Once the harmonic is filtered, the signal will be digitized, by detecting its zero crossing instants. A software counter will be incremented by one count at each zero crossing, thus giving the rotor position angle. The rotor speed will then be calculated by digital differentiation.

The observed harmonics differed from the calculated rotor slot harmonics by a maximum of 38Hz. However, based on the data obtained, since each revolution corresponds to 46 zero crossing counts, a maximum 38Hz difference corresponds to 76 zero crossing counts per revolution. This translates to a 1.65rpm error.

4. Simulation

The simulation is done in Simulink 4 and is done to test the performance of the system and various parts thereof. This will help to determine if the system has any shortcomings that would need to be addressed.

The complete model of the system incorporating the phase locked loop and empirical formula for the speed estimation can be seen in figure 5.

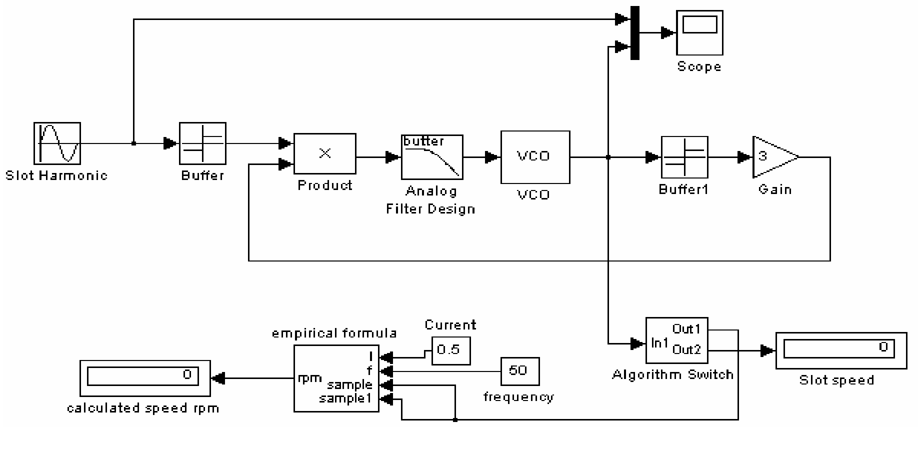

Fig. 5 Complete System Model

The final system model performs as expected with the VCO frequency locking onto the input slot harmonic and producing speed results exactly as predicted. When the speed fell to 500rpm and below, this resulted in the empirical formula immediately taking over the speed estimation from the rotor slot harmonic, producing a speed output in accordance with the input current and frequency.

The algorithm switch will be a software implementation in the final system as well as using a PLL with an adjustable VCO frequency to follow the harmonic as it changes with rotor speed.

The simulation demonstrates that this type of model using two algorithms interchangeably works, and is a viable proposition in extending the range of a slot harmonic speed control system.

5. Conclusion

In an induction motor there are slots of the surface of the stator and rotor iron cores. When the rotor rotates, harmonics are produced in the air-gap flux that induces slot harmonic voltages in the stator windings. By measuring either the magnitude or frequency of the slot harmonics the rotor speed can be determined. This method is relatively easy to implement as it has few hardware requirements, and the software algorithm is relatively simple to implement. At lower speeds, however, speed estimation becomes difficult as low frequency ripple occurs, due to the slow rotation of the rotor slots. A method of improving the performance of a system using the rotor slot harmonic technique was investigated in this paper. This involved the use of an empirical formula to estimate the rotor speed, based on current and frequency readings. This was used in the speed range where the rotor slot harmonics become difficult to detect. The technique involved in isolating the rotor harmonic as well as the method used to derive the empirical formula was discussed and the results were shown. The complete simulation of the system was presented in this paper.

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