

Induction Motor Speed Estimator and Synchronous Motor Position Estimator Based on a Fixed Carrier Frequency Signal

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Abstract—A speed and position estimator, based on the introduction of a constant-frequency carrier signal (400–1000 Hz) in the stator currents has been developed. Speed and position are estimated through the detection of irregularities in the rotor and, hence, the results are independent of machine parameters. These irregularities generate amplitude oscillations in the currents generated by the high frequency carrier, which are proportional to the rotor position. At the same time, the frequency of these amplitude modulations is proportional to machine speed. In induction machines, the amplitude of these signals is too low to estimate position accurately. However, special electronic circuits, designed and implemented with analog multipliers and filters, have permitted measurement of very low speeds with high precision. Computer simulations and some experiments have been carried out, and they have shown that it is possible to measure speeds as low as 20 r/min. In the case of salient-pole synchronous machines, the method is useful to measure rotor position due to the high irregularities produced by the poles, which are easily computed because of the important amplitude variations detected in the high frequency carrier.

I. INTRODUCTION

THE recent advances in power electronics have permitted the implementation of sophisticated methods of control for induction machines, such as vector control [1], [2], slip frequency control [3], flux oriented control [2]–[4], and others. All these drives require a precise estimation of rotor speed. Traditionally, mechanical tachometers have been used, but they have the disadvantage of having mechanical problems and maintenance requirements. Recently, numerous attempts to estimate the speed machine without tachometer are being developed, most of them based on the knowledge of the parameters of the machine [5]. With these methods, the flux, torque, or speed can be evaluated to control the motor. However, the parameters of the machine are not constant because they depend strongly on machine temperature and saturation of the magnetic circuit. Similar research in synchronous motor position estimators has been carried out using different methods [6], with similar problems in its implementation. In

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recent years, a novel method, based on detecting small rotor irregularities through the stator currents has been reported [7], [8]. This method has the advantage to be independent of the parameters of the machine. However, it cannot be used to compute rotor position in synchronous machines, because the method depends on rotor slip. On the other hand, in the case of sensing induction motor speed, the method is difficult to operate with variable frequency systems and inaccurate at speeds below 100 r/min [9].

This paper presents a different approach, based on the introduction of a fixed, small-voltage, high-frequency carrier (400 Hz–1000 Hz), which is superimposed to the normal inverter output. During operation, the inverter current is sensed, filtered to isolate the carrier current, and then multiplied by itself [10]. After this operation, amplitude modulations of the carrier, which are produced by the irregularities of the rotor, allows to detect the machine speed. This method allows to measure speeds as low as 20 r/min compared with other methods that only permit speeds above 100 r/min. By contrast with other induction motor speed estimators, this method is also useful for measuring rotor position in synchronous machines, particularly salient pole, permanent magnet and reluctance types. That is possible because of two facts: the slip between the rotor and the carrier does exist, and the irregularities given by the poles are extremely high and hence very easy to detect and compute.

The generation of the carrier excitation has no additional cost, because it is added in the software of the inverter control. The detection, filtering and isolation of the speed signals from the machine currents, are implemented with low cost, commercially available electronic devices.

II. SPEED AND POSITION ESTIMATION

A. Induction Motors

As it was already mentioned, the speed estimation method is realized adding to the output frequency of the inverter, a fixed frequency carrier signal. To avoid problems with the isolation of the speed signals, the carrier must not interfere with the inverter frequency. If the inverter works in the region 0–100 Hz, the carrier signal has to be bigger than 100 Hz. 400 Hz has been chosen for this carrier signal, which is far from the main frequency and allows to generate more than one left-side band frequency. This frequency neither interfere with the PWM pulsations which, with the actual semiconductor devices

such as IGBT's, are in the ten kilohertz region. However, it will be shown later on that the switching frequency does not affect the speed information, mainly because of the method proposed. In this form, the carrier frequency, and their side-bands generated by rotor eccentricities, can be isolated from the inverter current. The side-band frequencies move when the speed machine changes and, according with [8], they can be evaluated through the following equations:

$$f_{sb1} = f_i \cdot [(n \cdot R \pm n_e) \cdot (1 - s)/p \pm n_{ws}] \quad (1)$$

$$f_{sb2} = f_i \cdot [(n \cdot R \pm n_e \pm n_r \cdot p) \cdot (1 - s)/p \pm n_{wr}] \quad (2)$$

where

- i 1 (main frequency); 2 (carrier frequency);
- f_{sbi} side-band frequency generated;
- R number of rotor slots;
- n any integer = 0, 1, 2, 3, ...;
- n_{ws} order number of stator mmf time harmonic = 1, 2, 3, ...;
- n_{wr} order number of rotor mmf time harmonic = 1, 2, 3, ...;
- n_r rotor space harmonic number = 1, 2, 3, ...;
- n_e dynamic eccentricity number = 1, 2, 3, ...;
- f_i fundamental frequency;
- s_i slip relative to f_i ;
- p number of pairs of poles.

The magnitude of the side-band frequencies produced by the dynamic eccentricities is normally very low. On the other hand, the frequency separation from the carrier, Δf , is also small. For example, the first left side-band frequency, generated by the 400-Hz carrier ($n_e = 1$), varies between 350 Hz for 3000 r/min and 399 Hz for 60 r/min ($\Delta f = 400 - 350 = 50$ Hz for 3000 r/min, and $\Delta f = 400 - 399 = 1$ Hz for 60 r/min). The speed estimation is then based on the design of accurate filtering circuits, able to isolate the side-band frequencies from the carrier frequency. The filtering and isolation of the side-band frequencies have to be realized with special circuits because at low speeds, the difference between the carrier and the side-band frequencies, Δf , (which contains the speed information) can be smaller than one Hertz. Besides, the amplitude of the side-bands is very low compared with the carrier. This situation makes almost impossible to separate the side-bands from the carrier, using simple filters. The method used in this work to separate these frequencies is based on the principle of frequency multiplication. Fig. 1 shows the carrier signal isolated from the motor current, which is successively self-multiplied, to get the information of Δf in the envelope of the carrier. When the carrier is selfmultiplied, its frequency is duplicated and the amplitude is amplified. The figure shows three successive multiplications, which permit to see clearly how the magnitude of Δf increases. The rotor speed is obtained by multiplying Δf by a constant number, which depends on the side-band that has been isolated. In practice, this signal is highly distorted and then is not good for estimating the position unless some work is done in the rotor [11]. However, is enough for detecting highest and lowest values of Δf in each period, which can be counted to measure the speed.

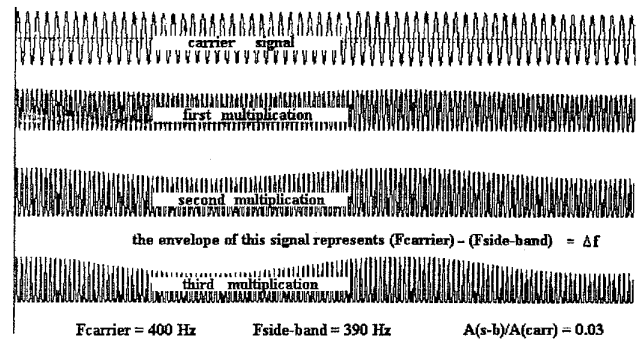


Fig. 1. Detection of Δf using analog multipliers.

B. Synchronous Motors

The amplitude modulation observed in Fig. 1 is a lot bigger in synchronous machines than in induction machines, particularly in the salient-pole type (wound rotor, permanent magnet or reluctance machines), and then it can be used to know where the machine poles are for position estimation purposes. The identification of which pole corresponds to North and which one corresponds to South is required only before starting, because after their identification, this information is stored in the control block. To identify which one of the poles corresponds to the North pole, a stator magnetomotive force, in quadrature with the poles, is applied. The direction of rotation of the machine, which is detected by the slope of the current envelope of the three carriers (one per phase), allows to identify the polarity of the poles of the machine. Another method is by applying a very low-frequency rotating field to align the machine rotor and then the poles can be automatically identified by the carrier. The amplitude modulation obtained with the carrier in synchronous machines is so big that selfmultiplication of this signal may not be required. The amplitude modulation can be processed using any AM detection method, able to demodulate the signal without shift angle delay. Taking the information of the three phases, it is possible to estimate the rotor position with high precision because there is one point known (zero crossing and equal magnitude) each 15 electrical degrees.

III. CIRCUIT DESIGN FOR SPEED DETECTION

The voltage amplitude of the carrier signal has been set in 15% of the nominal value of the fundamental. In this form, parasitic torque are small enough and then they will not produce pulsation problems. As the amplitude of the carrier is only 15% the nominal voltage of the machine, the side-band frequencies become extremely small. As an example, the Fig. 2(a) shows the frequency spectrum of the stator current obtained when a four pole machine is fed with a fundamental of 55 Hz and rotates at 1640 r/min ($\Delta f = 27.33$ Hz). The fundamental and the 400-Hz carrier with their respective first side-bands frequencies, according to (1), can be observed. The side-band frequencies are located symmetrical with respect to the corresponding fundamental. The first step is then to increase the amplitude of the carrier with respect to the main frequency of the inverter.

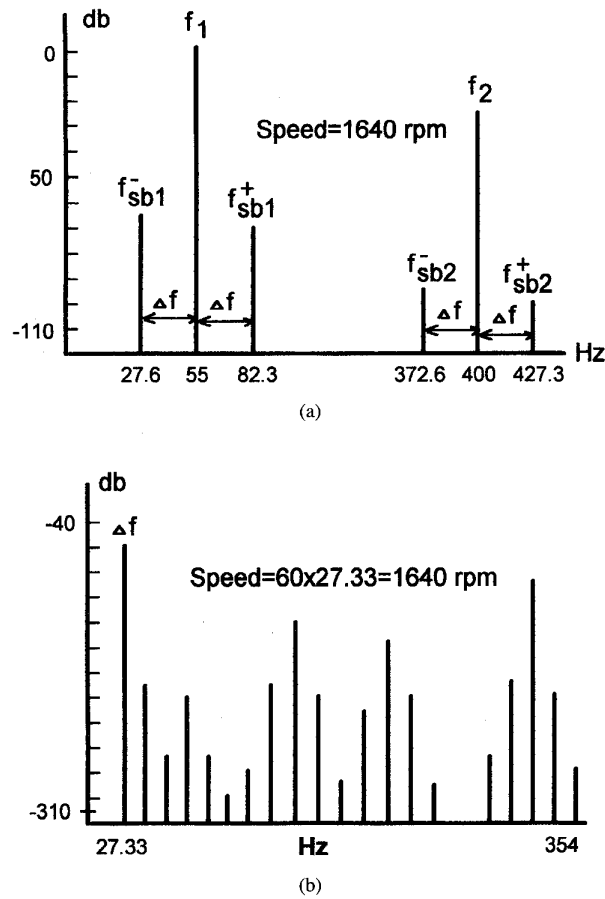


Fig. 2. Frequency spectrum for 1640 r/min. (a) The stator signal. (b) After multiplication and filtering. (The highest amplitude corresponds to Δf).

To increase the amplitude of the carrier signal with respect to the fundamental, the signal is filtered and amplified with respect to the mains frequency current and then multiplied by itself. This multiplication allows the separation of the main frequencies from the side-band frequencies through the sum, difference and double frequencies which appear in this operation. After the multiplication of the signal, another filtering through a low-pass filter is required from where the frequency spectrum shown in Fig. 2(b) is obtained. In the process, the biggest amplitude (without considering the dc component which is easily filtered) corresponds to Δf , which is the basis of the speed evaluation. The large magnitude of Δf is due to the addition of four amplitudes: $A[f_{sb1}^+ - f_1]$, $A[f_1 - f_{sb1}^-]$, $A[f_{sb2}^+ - f_2]$, and $A[f_2 - f_{sb2}^-]$, which correspond to the difference between the fundamental with their first-sidebands and the carrier with their side bands, respectively. The high magnitude reached by Δf allows the computation of the rotor speed. The switching frequency of the inverter, which has neither been mentioned nor been taken in account, also contributes to increase the value of Δf and for this reason it is not required to filter it. After all these computations, the mechanical speed can be evaluated from

$$\omega_m = k \cdot \Delta f \quad [\text{r/min}] \quad (3)$$

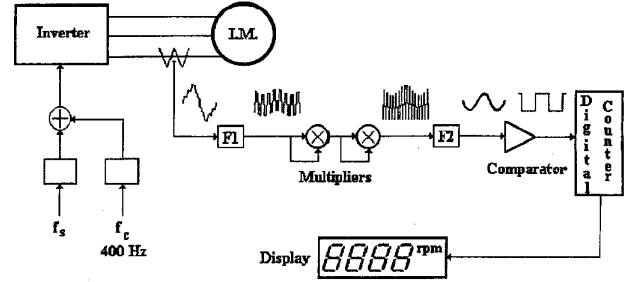


Fig. 3. Block diagram of the speed estimator circuit.

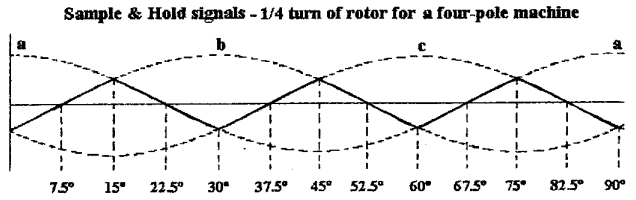


Fig. 4. Position detection using the quasi-triangular waveform.

where $k = 60/n_e$ is a constant whose value depends on the side-band frequency being isolated. The first side-band, $n_e = 1$, generates one period per rotor turn, and hence Δf turns per second. That means $60 \cdot \Delta f$ rpm. The eccentricity order $n_e = 4$, which is important in a four-pole machine, gives $k = 15$. The value of Δf is evaluated through

$$\Delta f = f_{sbi}^+ - f_i = f_i - f_{sbi}^- \quad [\text{Hz}]. \quad (4)$$

The Fig. 3 shows a functional block diagram of the overall system described, which comprises a high-pass filter, $F1$, to increase the magnitude of the carrier with respect to the main inverter frequency, and a couple of multipliers connected in cascade. From the second multiplier, the envelope, which corresponds to Δf , is isolated through a low-pass filter, $F2$. Then, it is compared with a dc signal to get a square waveform of Δf , which is proportional to the machine speed. In the very low speed region, a high order frequency side-band ($n_e = 4, k = 15$).

IV. CIRCUIT DESIGN FOR POSITION ESTIMATION

The information of rotor position can be obtained directly from the filtered carrier envelopes. The values of the envelopes are isolated by eliminating the dc components of these signals. Subsequently, the three signals are digitally computed using analog-to-digital converters and a microprocessor. The microprocessor allows the estimation of the position from the relative amplitude of these signals. As it was already mentioned, the position information can be estimated with precision through zero crossing of each signal and also when two signals have the same magnitude, as shown in Fig. 4. In between, the position is estimated using the value of the envelope with the highest slope, which corresponds to a quasi-triangular waveform shown in full line in Fig. 4. A functional block diagram of the detector is shown in Fig. 5.

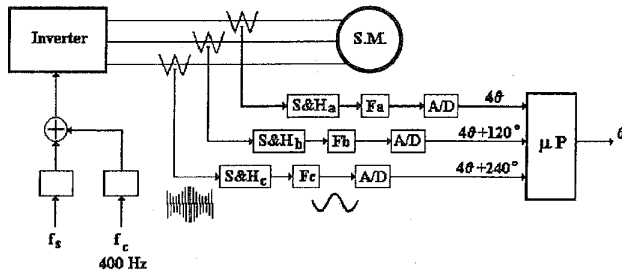


Fig. 5. Block diagram of the position estimator circuit.

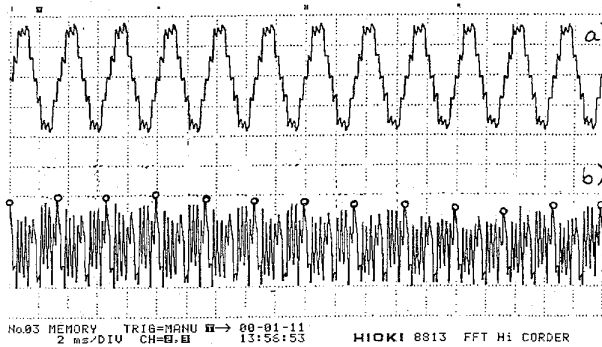


Fig. 6. (a) Frequency carrier waveform. (b) Selfmultiplication of the carrier.

V. EXPERIMENTAL RESULTS

A. Induction Machines

In the experiments, it has been found that the method based on the detection of side-band frequencies can measure speeds as low as 20 r/min, due to a good separation between Δf and the others frequencies. However, the utilization of the first-side-band at these low speeds, becomes unpractical, because the electronic counter has to wait at least half turn of the rotor to determine Δf . If a higher-order side-band is used, which is possible with the 400-Hz carrier, these speeds in a shorter time can be measured.

Some experiments have been carried out using four different induction machines: i) a 2-hp, 4-pole, 220-V, 50-Hz; ii) a 2-hp, 4-pole, 380-V, 50-Hz; iii) a 5-hp, 4-pole, 380-V, 50-Hz; and iv) a 12-hp, 6-pole, 380-V, 50-Hz. From all of them, the speed estimation using the proposed method was successful. The following figures shows the experimental results obtained with the first aforementioned machine.

The Fig. 6(a) shows the current waveform of the frequency carrier and Fig. 6(b) shows the output signal obtained after the carrier is multiplied by itself. The envelope which contains the information of Δf has been marked with circles in 6(b), allowing to see almost one period of this frequency. The signal obtained from Fig. 6(b) is filtered to get the envelope (Δf), which is shown in Fig. 7. The frequency of this envelope corresponds to 250 r/min and $k = 15$ (see (3)). This envelope is then compared with a constant signal to get a square waveform which is proportional to the speed machine. The Fig. 8 shows now the envelope Δf with its square waveform, for a speed

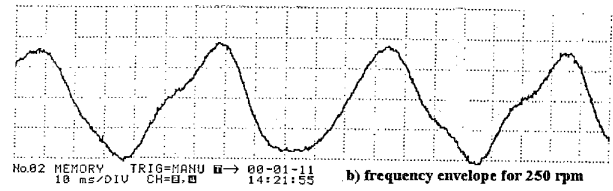
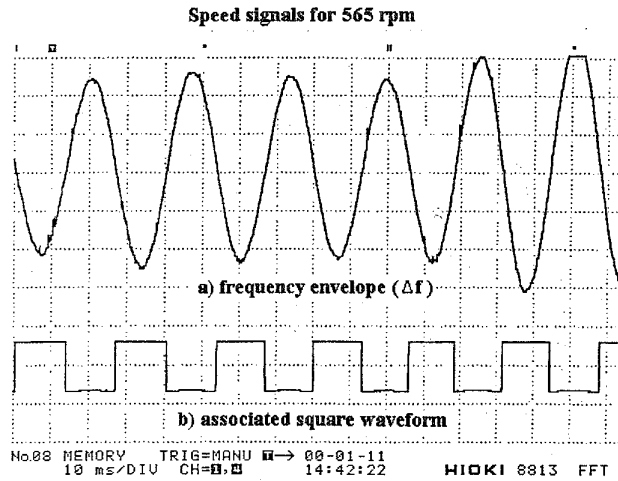
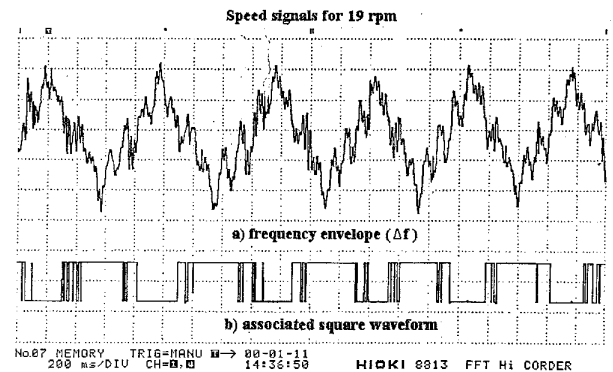


Fig. 7. Frequency envelope for 250 r/min.

Fig. 8. Speed signals for 565 r/min. (a) Frequency envelope (Δf). (b) Associated square waveform.Fig. 9. Speed signals for 19 r/min. (a) Frequency envelope (Δf). (b) Associated square waveform.

of 565 r/min. Finally, the Fig. 9 shows Δf and its associated square waveform for a speed of 19 r/min. At this speed the waveforms are very distorted but the speed is still recognized. However, lower speeds become practically impossible because of the distortion observed in Fig. 9. In this figure, it is also possible to see another frequency superimposed over Δf , which corresponds to a frequency generated by rotor slots.

It can also be mentioned that with the 12-hp, 6-pole machine tested, a speed of 2 r/min was computed with the circuit. This was possible because the harmonics generated by the rotor slots were large enough in amplitude to be measured and they produced 40 periods of Δf with just one turn of the rotor.

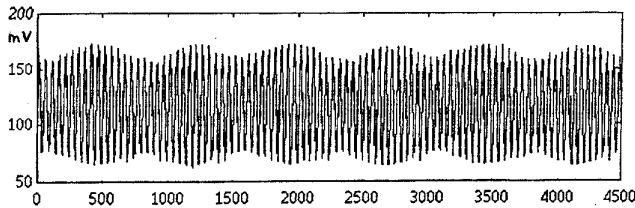


Fig. 10. Carrier envelope for a synchronous machine.

B. Synchronous Machines

Simulations and some experiments have shown that the rotor position can be measured through the processing of the carrier envelope signal. Fig. 10 shows the modulation of one of the carrier signals, for a four-pole, 7.5-hp, synchronous machine, when the rotor turns at very low speed. The amplitude variation of the envelopes is big enough to be used to determine the machine poles position. The North pole can be identified by comparing the slopes of the current envelopes of the three carriers.

VI. CONCLUSION

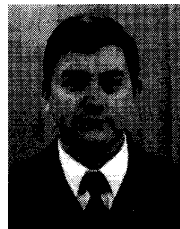
A different method to estimate the speed of induction motors and the position of synchronous motors is proposed. The method is based on the addition of a fixed carrier frequency signal to the PWM modulation. This carrier permits the detection of side-band frequencies generated by rotor eccentricities, which are subtracted from the carrier to obtain Δf . Depending on the order of the side-band which has been computed, Δf is multiplied by a constant to get the speed of the machine in r/min. The speed detection is independent of the electromagnetic parameters because the induced harmonics are based on the mechanical eccentricities of the rotor. It has also been verified that with some kind of induction motors, high-order side-band harmonics, produced by rotor slots, can be detected, making it possible to measure speeds as low as 2 r/min. However, with the motors tested in laboratory this was feasible in only one machine. Despite it, 20 r/min as a lowest speed limit for the other machines was possible by isolating the fourth-order side-band frequency. The measurement of smaller speeds become impractical because of the time required to count one period of Δf . The signal also becomes very noisy, and the presence of slot harmonics distort the information of the side-band. One drawback of the system is that it depends on rotor eccentricities, and hence, when machine is perfectly balanced, no speed information is attainable. However, an interesting experiment was done with one machine, in which small rotor surface irregularities were made. The results were very promising, because high amplitude speed signals were generated.

On the other hand, the application of the method in synchronous machines is simpler than in induction machines because of the high reluctance variation produced by the poles. This characteristic allows to get accurate information of the rotor position, particularly at standstill and at very low speeds, through the information obtained from the three phases.

Computer simulations and experiments with different induction machines have permitted to verify the feasibility of practical implementation. Experiments in a four-pole synchronous machine have also demonstrated the simplicity of the method to detect rotor position for this kind of motor.

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