

# An Improved Method to Measure Speed in Induction Motors, Based on Induced Irregularities

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**Abstract.-** This work presents a method of speed estimation for induction motors, based on the introduction of dynamic irregularities in the rotor. The method allows to increase the amplitude of the speed signals more than ten times with respect to normal eccentricities, without affecting the normal operation of the machine. With this method, and using only one eccentricity per pole, it has been shown that it is possible to measure speeds as low as 11 rpm. Adding more than one eccentricity per pole, it is possible to measure even lower speeds. Simulations and experimental results permit to compare this new method, with methods which use only normal eccentricities.

## I. INTRODUCTION

Power electronics has permitted the implementation of sophisticated methods of control for induction machines. Most of them need a precise speed information. Traditionally, mechanical tachometers have been used but, due to reliability problems, the research has been focused in methods of speed estimation based on machine parameters or based on rotor irregularities. These methods allow to estimate the speed through electrical variables, such as the machine current. The first method, based on machine parameters [1-3] (equivalent circuit), has the drawback of parameters variations with temperature and saturation. This drawback makes the method unaccurate, and then, some correction methods have to be implemented to have an acceptable degree of speed accuracy. Then, the method based on parameters machine becomes

complex, sophisticated, and unreliable. Recently, methods based on rotor irregularities, such as eccentricities, bars or slots, have been investigated [4,5]. These methods estimate speed through airgap variations and are independent of machine parameters. However, in the case of slots and bars, the method is not always practical because many machines are fabricated with helicoidal position of slots and bars. The second possibility, based on rotor eccentricities gives speed signals extremely low and noisy, limiting the range of speed estimation in 20 rpm as a minimum [6]. Even worst, some machines have very small eccentricities, and then the speed estimation becomes almost impossible.

The method proposed in this paper is based on the the addition of specific irregularities in the rotor, which will produce small airgap variations in the machine. These kind of irregularities will be called *induced irregularities*. These *induced irregularities* must be implemented taking in account three important requirements: 1) to avoid parasitic torque generation, and additional losses, they have to be made as small as possible (only a fraction of a milimeter); 2) to keep the rotor balanced, they have to be symmetrical with respect to shaft; and 3) they have to produce synchronized airgap variations on each pole of the machine, that means minimum (or maximum) airgap on each pole simultaneously. The last requirement is very important, because it keeps the rotor balanced and permits to obtain an excellent signal variation to measure speed. This also means that the number of induced irregularities is proportional to the number of poles of the machine.

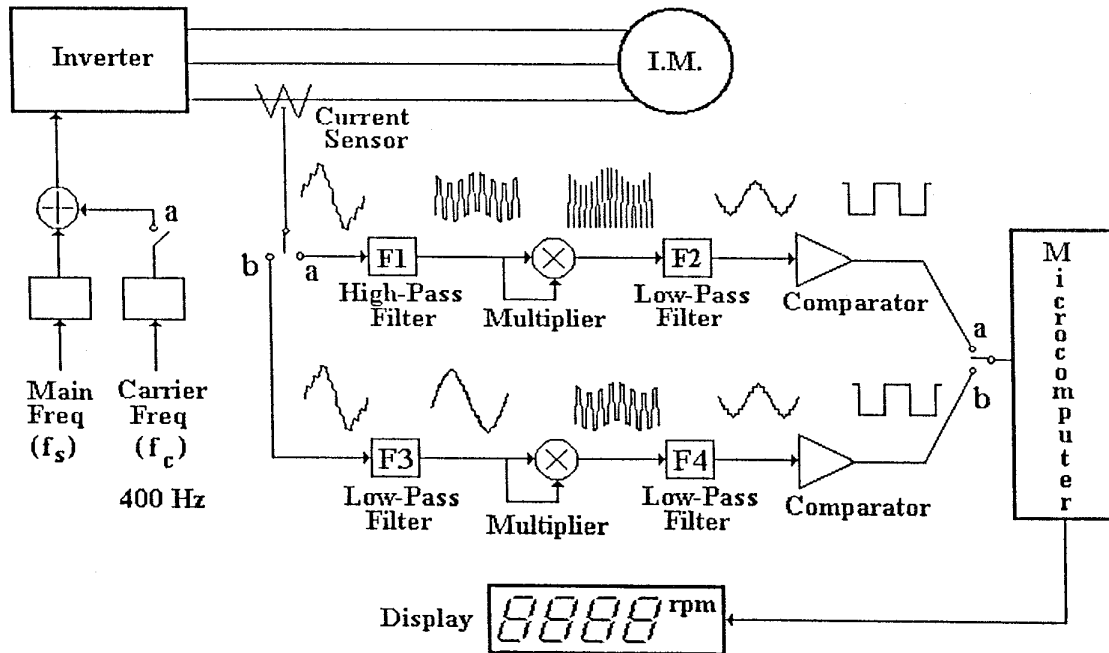


Fig. 1 Block diagram of the speed estimator circuit

The detection of irregularities (normal or induced) is based on the introduction of a fixed, high frequency carrier, superimposed on the normal inverter frequency which feeds the machine. The high frequency carrier (400 Hz), is sensed and isolated from the normal inverter frequency, and then multiplied by itself. Then an amplitude modulated signal, produced by rotor irregularities is obtained. This amplitude modulated signal contains side-band frequencies which are proportional to the speed of the machine. The block diagram of figure 1, shows the circuit implemented in laboratory for speed estimation [7].

The method based on induced irregularities generates signals which are a lot bigger than the signals generated with normal rotor eccentricities. To demonstrate that, an analytical study, to compare the methods, will be developed. The methods will also be compared experimentally.

## II. NORMAL ECCENTRICITIES

The figure 2 shows a schematic of normal eccentricities in an induction machine. When only exists eccentricity of the shaft with respect to stator, no side-band frequencies are generated. When the

eccentricity is only with respect to rotor, the rotation of the shaft will produce a reactance variation each time the rotor passes through a pole. For example, in a four-pole machine, one complete rotation will produce four amplitude pulsations in the machine current, which represents a particular side-band.

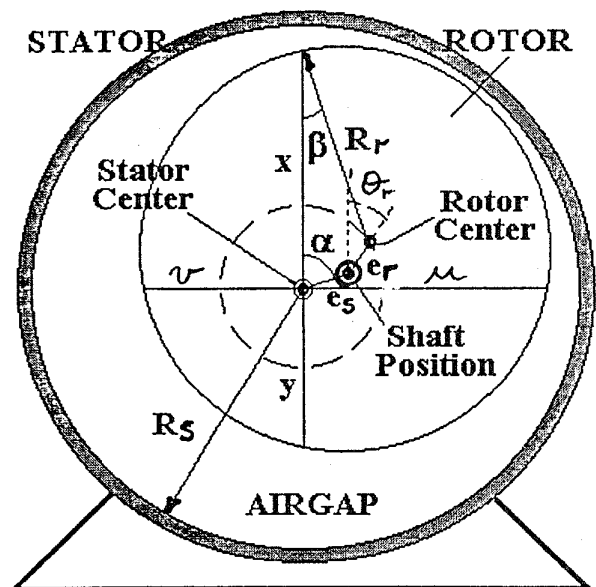


Fig. 2 Normal eccentricities in an induction machine

Now, when both, rotor and stator have eccentricities, which is the normal case encountered in experiments, a second couple of side-band frequencies, which produces one pulsation per rotor turn (independent of the number of poles), superimposed to the first one, is generated. Then, in a four-pole machine, eccentricities of order 4 and 1 will be present ( $n_e=4$  and  $n_e=1$ ). In figure 2, the eccentricities  $e_r$  and  $e_s$  have been defined, and  $R_r$  y  $R_s$  are the external rotor radius and the internal stator radius respectively. From this figure, the distance  $x$  can be defined as:

$$x = R_r \cdot \cos\beta + e_r \cos\theta_r + e_s \cos\alpha \quad (1)$$

Where  $\alpha$  and  $\beta$  are defined in fig. 2. Also:

$$R_r \cdot \cos\beta = \sqrt{R_r^2 - (e_r \cdot \sin\theta_r + e_s \cdot \sin\alpha)^2} \quad (2)$$

from (1) and (2):

$$x = e_r \cos\theta_r + e_s \cos\alpha + \sqrt{R_r^2 - (e_r \cdot \sin\theta_r + e_s \cdot \sin\alpha)^2} \quad (3)$$

In a similar form, expressions for the distances  $y$ ,  $u$  and  $v$  from fig. 2 can be obtained. Then, the next step should be to get the total airgap of the machine. For the particular case of a four pole machine:

$$eh_T = \frac{e_x \cdot e_y}{e_x + e_y} + \frac{e_u \cdot e_v}{e_u + e_v} \quad (4)$$

where  $e_x$ ,  $e_y$ ,  $e_u$  and  $e_v$ , are the airgaps which correspond to  $x$ ,  $y$ ,  $u$  and  $v$  respectively.

$$e_{x,y,u,v} = R_s - x, y, u, v \quad (5)$$

The equation (4) represents the airgap variations as a function of eccentricities  $e_r$ ,  $e_s$ ,  $\alpha$  (constant numbers for a particular machine), and also as a function of rotor position  $\theta_r$ . This airgap variation with rotor position can be detected through stator current variations to get the speed information.

However, due to the effect of compensation in  $e_x$ ,  $e_y$ ,  $e_u$  and  $e_v$  in eq.(4), the airgap variation becomes very small, and hence difficult to measure. Besides, the eccentricities  $e_r$  and  $e_s$  of the machine become more and more negligible with the advances in factory machine assembly, and hence the estimation of speed could result almost impossible. To illustrate this situation, the figure 3 shows graphically the airgap variation  $eh_T$  vs  $\theta_r$ , for three different situations: a) eccentricities  $e_s=0.5$  [mm] (large), and  $e_r=10^{-4}$  [mm] (negligible); b)  $e_s=10^{-4}$  [mm] (negligible) and  $e_r=0.5$  [mm] (large); and c)  $e_s=0.1$  [mm] and  $e_r=0.1$  [mm] (the both normal values). In the three cases  $R_s=251$  [mm],  $R_r=250$  [mm] and  $\alpha=45^\circ$ . It can be noticed that in the two first cases the magnitude of airgap variation is extremely low (in the order of  $10^{-5}$  mm). Besides, in the case b) the eccentricities  $n_e=1$  and  $n_e=4$  are clearly present. By contrast, the case c) shows a magnitude variation of  $eh_T$  100 times bigger than in a) and b), even considering that in this case the two eccentricities are relatively small.

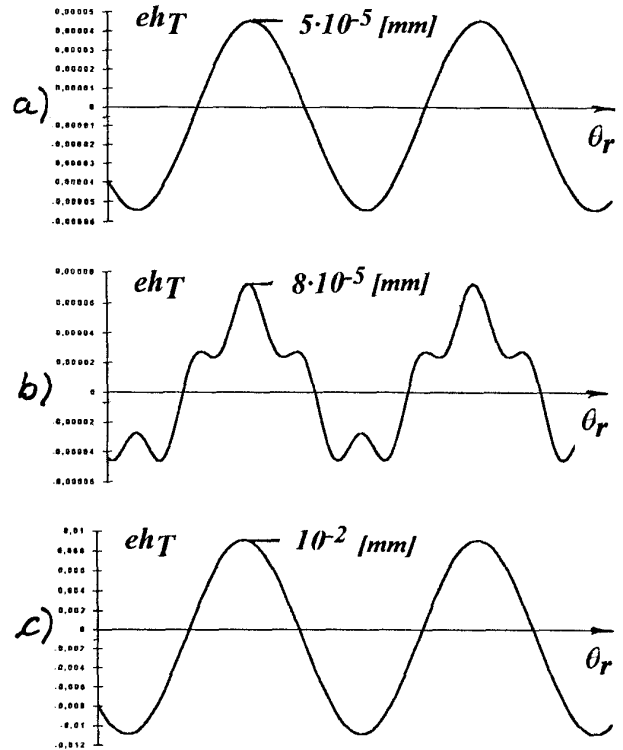


Fig. 3.- Airgap variation  $eh_T$  vs  $\theta_r$   
a) eccentricities  $e_s=0.5$  [mm] and  $e_r=10^{-4}$  [mm]  
b)  $e_s=10^{-4}$  [mm] and  $e_r=0.5$  [mm]  
c)  $e_s=0.1$  [mm] and  $e_r=0.1$  [mm]

Then, it becomes very clear that the airgap variation  $eh_T$ , is strongly dependent on the eccentricities  $e_r$  and  $e_s$ , and it can become negligible with factory assembly improvements. To avoid that, a new method, based on induced irregularities is proposed.

### III. INDUCED IRREGULARITIES.

As it was already mentioned, the airgaps  $e_x$ ,  $e_y$ ,  $e_u$  and  $e_v$  in eq.(4) tend to cancel, and then the airgap variation can become very small. The reason of that is because when  $e_x$  is increasing,  $e_y$  is decreasing and viceversa. The same happens with the couple  $e_u$ ,  $e_v$ . By contrast, the *induced irregularities* are implemented in such a way that allow a simultaneous and synchronized airgap variation. That means, the four airgaps increase and/or decrease simultaneously, reaching maximum and/or minimum values at the same time. In this form, the airgaps will reinforce instead of try to cancel. To reach that, the number of induced irregularities has to be proportional to the number of poles of the machine. The figure 4 shows a four-pole machine, in which four induced irregularities have been introduced in the rotor.

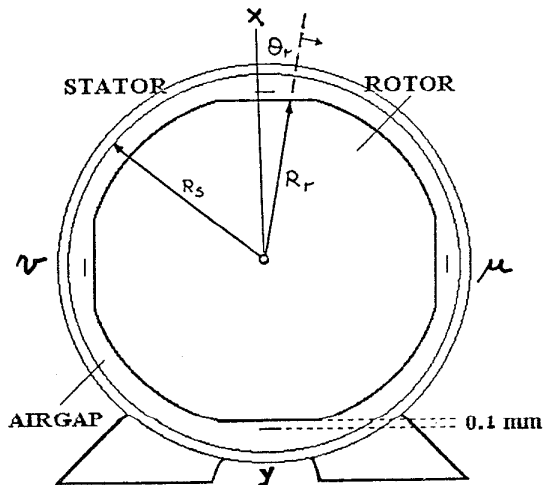


Fig. 4. Induced irregularities in the rotor

To simplify the mathematical analysis, let assume that the induced irregularities produce a variation in the rotor radius  $R_r(\theta_r)$ , given by the following expression:

$$R_r(\theta_r) = R_0 + e_r \cdot \text{sen}(n \cdot p \cdot \theta_r) \quad (6)$$

where  $e_r$  is the amplitude variation of rotor radius,  $n$  an integer (1,2,...n),  $p$  the number of poles of the machine and  $\theta_r$  the angular position of the rotor. Then, for a four pole machine, assuming  $e_1=e_2=0$  (rotor perfectly centered), and taking  $n=1$ , the following values for  $e_x$ ,  $e_y$ ,  $e_u$  and  $e_v$  can be expressed:

$$e_x = R_s - R_r(\theta_r) = R_s - R_0 - e_r \cdot \text{sen}(4\theta_r) \quad (7)$$

$$e_y = R_s - R_r(\theta_r + \pi) = R_s - R_0 - e_r \cdot \text{sen}(4\theta_r + 4\pi) \quad (8)$$

$$e_u = R_s - R_r(\theta_r + \frac{\pi}{2}) = R_s - R_0 - e_r \cdot \text{sen}(4\theta_r + 2\pi) \quad (9)$$

$$e_v = R_s - R_r(\theta_r + \frac{3\pi}{2}) = R_s - R_0 - e_r \cdot \text{sen}(4\theta_r + 6\pi) \quad (10)$$

From (7), (8), (9) and (10):

$$e_x = e_y = e_u = e_v = e(\theta_r) \quad (11)$$

and from eq.(4),  $eh_T$  becomes:

$$eh_T = \frac{e_x \cdot e_y}{e_x + e_y} + \frac{e_u \cdot e_v}{e_u + e_v} = e(\theta_r) \quad (12)$$

Plotting  $eh_T$  from eq.(12), for  $R_s=251$  [mm],  $R_r=250$  [mm], eccentricities  $e_1$  and  $e_2$  equal to 0 and  $e_r=0,1$  [mm], the following oscillogram, shown in figure 5, is obtained:

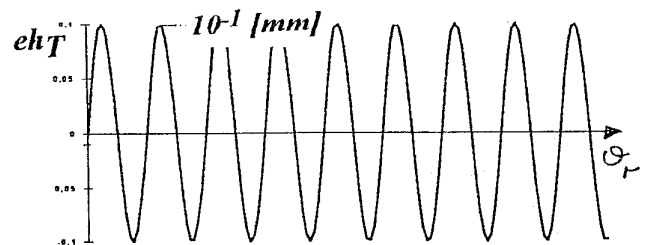


Fig. 5. Airgap variations for induced eccentricities.

It can be noticed that the amplitude variation of  $eh_T$  is **ten times bigger** than the best previous case, in which we used  $e_r=e_s=0.1$  [mm]. The comparison is valid considering that the amplitude variation of the airgap in the case of *induced irregularities* has also been set to  $e_r=0.1$  [mm], with  $e_r=e_s=0$ . The speed estimation becomes less difficult with the new method. The induced irregularities are so small that their effect in parasitic torque or additional losses are negligible.

#### IV. EXPERIMENTAL RESULTS.

The rotor of a four-pole, induction machine, was modified in laboratory, resulting a machine similar to the drawing shown in figure 4. The speed signals were isolated with the circuit of figure 1, and compared with estimations obtained with the same machine, before the induced irregularities were introduced.

The figure 6 shows the signals obtained for a speed of  $98$  [rpm], before and after the introduction of *induced irregularities*. It can be observed that the signals have increase more than ten times with the new method. The frequency spectrum for each case is also displayed. The signals are cleaner with the new method.

Going to lower speeds, the figure 7 shows the results obtained with a speed of  $11$  [rpm], which is compared with a speed of  $14$  [rpm] obtained with the conventional method. Again, the signals become larger and cleaner with the proposed method.

#### V. CONCLUSIONS

A different method to estimate speed without mechanical sensors, and independent of machine parameters, has been proposed. The method is based on the introduction of small irregularities in the rotor surface. The method allows to get speed signals at list ten times larger than with normal rotor eccentricities, keeping the rotor balanced, and allowing to measure lower speeds. This idea can be applied during factory assembly of machine rotors, creating an oval matrix to make the rotors. This solution will allow the speed evaluation directly from stator current information, without the knowledge of machine parameters. The

induced irregularities are so small that their effect in parasitic torque or additional losses remain negligible.

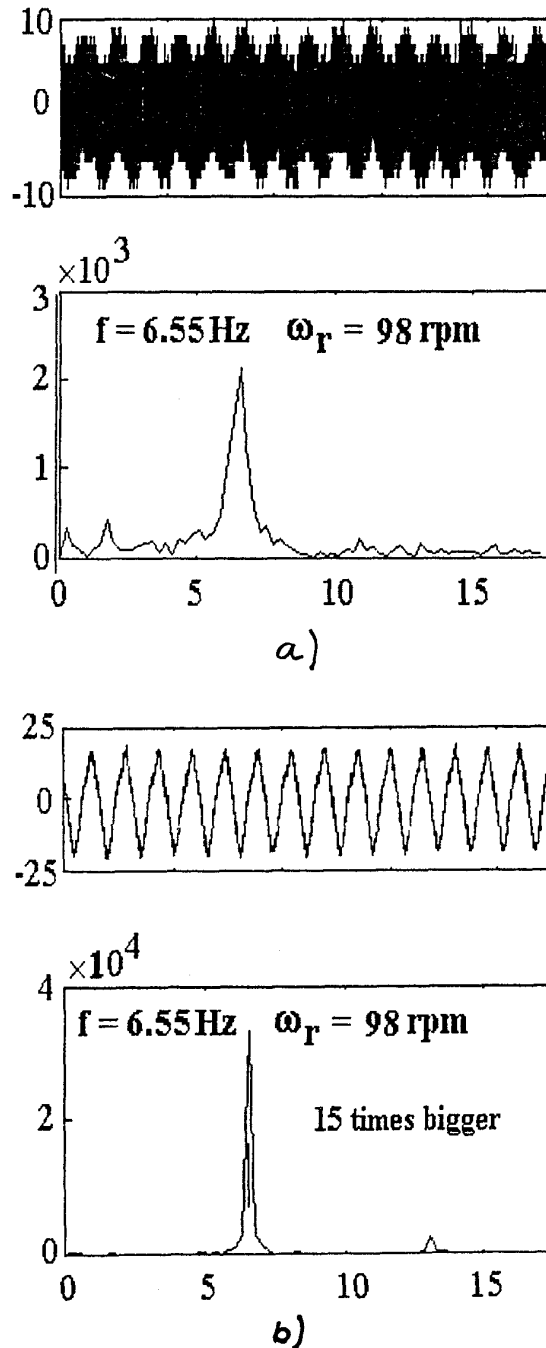
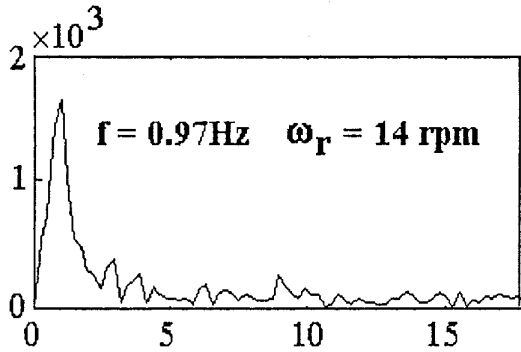
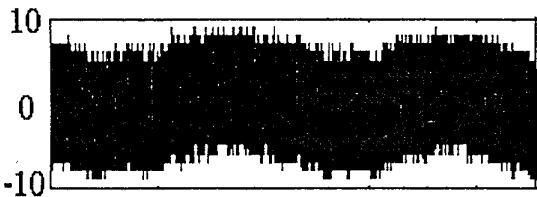
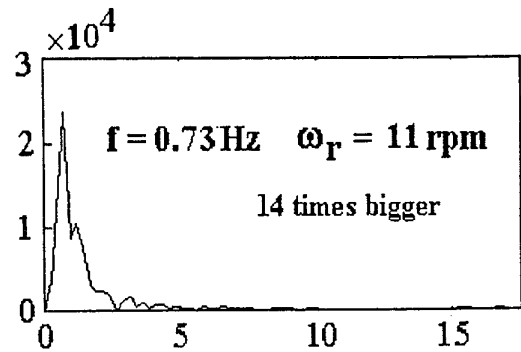
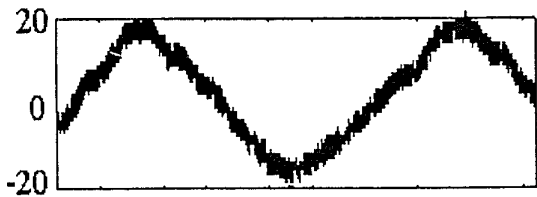


Fig. 6. Speed signals for a speed of  $98$  [rpm]  
 a) natural irregularities  
 b) induced irregularities



a)



b)

Fig.7. Speed signals for 11 [rpm]  
 a) natural irregularities (14 rpm)  
 b) induced irregularities (11 rpm)

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## REFERENCES

- [1] J. Pontt, J. Rodriguez and P. Pavez, "Control Analógico de un Motor de Inducción con Inversor PWM sin empleo de Tacómetro", VIII Congreso Chileno de Ingeniería Eléctrica, 1989, pp. 14-18.
- [2] C. Ilas, A. Bettini, L. Ferraris and G. Griva, "Comparison of Different Schemes without Shaft Sensor for Field Oriented Control Drives", IEEE - IPEC'94, pp. 1579-1588.
- [3] T. Chin, "Approaches for Vector Control of Induction Motors without Speed Sensor", IEEE - IPEC'94, pp.1616-1620.
- [4] T.C. Green, B.W. Williams and D.S. Schramm, "Non-Invasive Speed Measurement of Inverter Driven Induction Motors," IEEE Industry Applications Society, Annual meeting 1990, pp. 395-398.
- [5] M. Ishida and K. Iwata, "Steady-State Characteristics of a Torque and Speed Control System of an Induction Motor Utilizing Rotor Slot Armonics for Slip Frequency Sensing," IEEE Trans. on Power Elect., vol. PE-2, N°3, pp. 257-260, July 1987.
- [6] J. Dixon y J. Rivarola, "A Precise Induction Motor Speed Estimator, Based on a fixed Carrier Frequency Signal", IEEE International Symposium on Industrial Electronics, ISIE'94, 23-25 de Mayo de 1994, Santiago, Chile, pp. 109-203.
- [7] J. Dixon y J. Rivarola, "A Wide Range Sensorless Speed Estimator, Based on Rotor Irregularities for Induction Motors", IEEE Applied Power Electronics Conference, APEC'95, March 5-9, 1995, Dallas, Texas, pp. 204-210.