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ESTIMATION OF INDUCTION MOTOR SPEED BY USING ROTOR SLOT HARMONICS FREQUENCY

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Abstract- A conventional approach to determine the speed of an induction motor (IM) involves using a mechanical speed sensor or tachometer. However, there's a growing trend towards sensorless speed control in IM electrical drives. No mechanical sensors are needed for estimating the rotor speed. Based on it, this paper introduces a straightforward and reliable method induction motors rotor speed estimation without using mechanical sensors. The proposed method's accuracy is validated by comparing rotor speed estimates derived from rotor slot harmonics with other speed measurement techniques. Experimental test results confirm the effectiveness of this method. The novelty of this methodology lies in its utilization of inherent characteristics of the motor itself rather than relying on external sensors.

Keywords: Induction Motors, Spectrals Analysis, Rotor Slot Harmonics, Electrical Drives, Frequency Voltage.

1. INTRODUCTION

Induction motors (IM) are ubiquitous in various industrial, commercial, and residential applications for their robustness, reliability, and cost effectiveness. Developed over a century ago, they remain one of the most widely used types of electric motors [1-7].

To achieve accurate operating speeds and precise torque control in IM electric drives, advanced methods are required. These methods utilize control techniques and high speed digital signal processors that rely on speed and other machine state estimation or identification [1]. Most of conventional methods such as Direct Current (DC) tachogenerators, Alternating Current (AC) tachogenerators, electromagnetic speed transducers or opto-electronic sensors have been used to carry out the speed measurement in adjustable IM control speed drives. These devices are typically added on the shaft of the rotor. A DC tachogenerator, specifically, operates as a separately excited DC generator for this purpose.

Hence, the quest for speed detection sensorless is paramount in most of the electric drives. Accurately determining instantaneous position and rotor angular speed is crucial in sensorless IM electric drives. Various techniques have been used to control and estimate IM drives through circuit models of the electrical motor [2]. While steady state equivalent circuit models suffice for some applications, high performance drives demand dynamic motor models. Numerous strategies, employing simplified version of the motor dynamic models, have been formulated to infer motor speed from measured terminal quantities like voltage and current [8-16].

A relatively recent approach to speed estimation, known as Model Reference Adaptive System (MRAS), utilizes the analytical dynamic model of the machine. This technique employs an IM as the reference, while an adjustable model based on a vector controlled IM model is utilized [3, 7, 8]. The adjustable model is fine tuned to minimize the speed error between the two models. Using voltage and current measurements of the motors in stationary reference frame will illustrate the convenience of aligning motor equations with this frame. With comprehensive knowledge of motor parameters and variables we can estimate the rotor's instantaneous speed through closed loop computations derived from motor equations. The most important parameters are as follows:

- electrical angular speed
- inductance
- stator voltages
- resistance
- poles
- current

Speed estimation techniques relying on rotor slot harmonics analysis are favored as they operate independently of knowledge concerning the electrical parameters of the machine [14-24].

In this research work, we introduce a straightforward and robust approach for estimating the speed of induction motors and leveraging spectral analysis of electrical quantities like the voltage variation [9]. This voltage exhibits non zero characteristics due to motor asymmetry stemming from geometry parameters of IM. The air gap magnetic flux of IM, influenced by the stator and rotor slot configurations, encompasses fundamental and higher order harmonics [9-18]. Rotor slot induced variations in air gap flux give rise to harmonics in the stator current, albeit with lower amplitudes compared to base harmonic [9, 16].

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To address this challenge, we have checked the voltage waveform signal through stator winding's neutral point (0) and neutral point (0') formed through resistive network as Figure 1. The harmonics of the air gap magnetic flux is dependent at rotor's rotational speed [9]. Determining this frequency voltage enables the calculation of the induction motor's rotor angular speed.

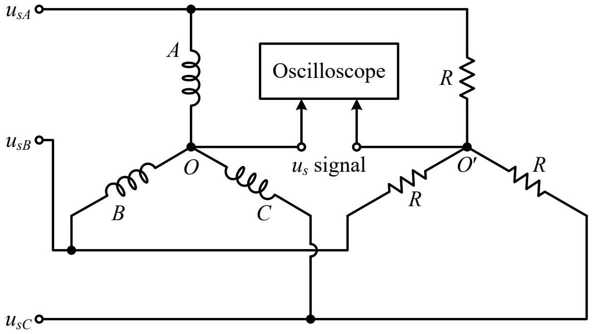


Figure 1. Rotor slot harmonics signal measurement

2. MAGNETIC FIELD EVALUATION OF THE INDUCTION MACHINES

The m.m.f. air gap in induction machines arises from the currents flowing through the windings of rotor and stator. At spatial arrangement of the windings of stator and rotor around the air gap, the resulting m.m.f. comprises not only the fundamental harmonic but also spatial harmonics. [9, 13, 16]. Furthermore, induction machine can be estimated by using Equations (1), (2) and (3) [9]:

$$f_s(\theta,t)=\sum_{\upsilon=1}^{\infty}\hat{f}_{s,\upsilon}\cos\left(\upsilon p\theta-\omega_1 t-\varphi_1\right) \tag{1}$$

where,

$$\upsilon=6\kappa\pm1, \quad \kappa=0,\ 1,\ 2,... \tag{2}$$

and $\hat{f}_{s,\upsilon}$ correspond to harmonic amplitude order υ. The estimation of harmonic amplitude will realized by using Equation (3) [5].

$$\hat{f}_{s,\upsilon}=\frac{3\sqrt{2}}{\pi}\frac{qN}{\upsilon}k_{p\upsilon}k_{y\upsilon}I_1 \tag{3}$$

where, N is one coil conductor numbers, φ_1 is initial phase of the stator current, ω_1 is angular electric speed of the fundamental harmonic, $k_{y\upsilon}$ is pitch coil harmonic order coefficient, I_1 is stator motor current and $k_{p\upsilon}$ is harmonic order distribution winding coefficient

Furthermore, in Equation (4) we can estimate the angular mechanical speed of the υ harmonic order (4):

$$\omega_\upsilon=\frac{\omega_1}{\upsilon p}=\frac{\omega_1}{\left(6k\pm1\right)p} \tag{4}$$

In the rotor winding current, induced by the magnetic field that has been generated from stator winding should include not only the fundamental harmonic but also higher harmonics. Consequently, the magnetomotive force of the winding of rotors will delineated as a composite of two elements. Equations (5)-(7) gives the determinations of the first component of magnetomotive force of the fundamental harmonic rotor current [9, 16].

$$f_{r,1}(\theta,t)=\sum_{\mu=1}^{\infty}\hat{f}_{r,1}\cos\left(\mu_1 p\theta-\omega_{\mu,1}t-\varphi_\mu\right) \tag{5}$$

where,

$$\mu_1=\kappa\frac{z_r}{p}+1, \quad \kappa=0,\ \pm1,\ \pm2,... \tag{6}$$

and, $\hat{f}_{r,1}$ is the amplitude for harmonic order □$_1$ and can be calculated as:

$$\hat{f}_{r,1}=\left(-1\right)^{\mu}\frac{3\sqrt{2}}{\pi}\frac{qN}{\mu}\xi_1\xi_\mu I_1\cos\varphi_1 \tag{7}$$

where, φ_u is respective harmonics initial phase, ξ_1 is distribution rotor winding coefficient, z_r is rotor slots number of the motor, and ξ_u is rotor pitch coil coefficient.

The angular speed denoted as $\omega_{\mu,1}$ in air gap magnetic field can be determined by using the Equation (8).

$$\omega_{\mu,1}=\left(\frac{\omega_r}{p}+\frac{s\omega_1}{\mu_1 p}\right)\mu_1 p=\omega_1\left[1+\frac{\kappa z_r\left(1-s\right)}{p}\right] \tag{8}$$

where, ω_r is the electric angular rotor speed, and s is the slip of IM.

The subsequent part of the rotor's magnetomotive force originates from the higher order harmonics through the rotor current. This parameter is characterized by using Equations (9)-(11).

$$f_{r,2}(\theta,t)=\sum_{\mu=1}^{\infty}\hat{f}_{r,2\mu}\cos\left(\mu_2 p\theta-\omega_{\mu,2}t-\varphi_\mu\right) \tag{9}$$

where,

$$\mu_2=\kappa\frac{z_r}{p}+\upsilon, \quad \kappa=0,\pm1,\pm2,... \tag{10}$$

$$\hat{f}_{r,2,\mu}=\left(-1\right)^{\mu}\sqrt{2}I_{r\upsilon}\frac{\upsilon}{\mu}\xi_\upsilon \tag{11}$$

and, $I_{r\upsilon}$ is amplitude of the rotor current for harmonics υ, and ξ_υ is coefficient rotor winding distribution for harmonics υ.

The sum of rotor and stator winding can give us a air gap m.m.f. resultant of IM, as Equations (1), (5), and (9) [9, 16, 18].

$$\begin{aligned}
&f(\theta,t)=f_s(\theta,t)+f_{r,1}(\theta,t)+f_{r,2}(\theta,t)=\\
&\quad=\hat{f}_1\cos\left(p\theta-\omega_1 t-\varphi_1\right)+\\
&\quad+\hat{f}_{6\kappa+1}\cos\left[\left(6\kappa+1\right)p\theta-\omega_1 t-\varphi_1\right]\Big|_{\kappa=1,2,3...}+\\
&\quad+\hat{f}_3\cos\left[\left(z_s-p\right)\theta-\omega_1 t-\varphi_1\right]+\\
&\quad+\hat{f}_4\cos\left[\left(z_s+p\right)\theta-\omega_1 t-\varphi_1\right]+\\
&\quad+\hat{f}_5\cos\left[\left(z_r-p\right)\left(\theta-\omega_r t\right)+s\omega_1 t\right]+\\
&\quad+\hat{f}_6\cos\left[\left(z_s+p\right)\left(\theta-\omega_m t\right)-s\omega_1 t\right]
\end{aligned} \tag{12}$$

where, ω_m is mechanical rotor speed of IM.

From Equation (12), it becomes evident where resulting air gap m.m.f. in induction machine comprises various harmonics.

By using Equation (12), the air gap flux density will be expressed as follow [9]:

$$\begin{aligned} b(\theta,t) = {} & \hat{b}_1 \cos(p\theta - \omega_1 t) + \\ & +\hat{b}_5 \cos(5p\theta + \omega_1 t) + \\ & +\hat{b}_7 \cos(7p\theta - \omega_1 t) + \\ & +\hat{b}_{1-s}^{(+)} \cos\left[(z_s - p)\theta + \omega_1 t\right] + \\ & +\hat{b}_{1-s}^{(-)} \cos\left[(z_s + p)\theta - \omega_1 t\right] + \\ & +\hat{b}_{1-r}^{(+)} \cos\left[(z_r - p)(\theta - \omega_m t) + s\omega_1 t\right] + \\ & +\hat{b}_{1-r}^{(-)} \cos\left[(z_r + p)(\theta - \omega_m t) - s\omega_1 t\right] \end{aligned} \tag{13}$$

where, $\hat{b}_1, \hat{b}_5, \hat{b}_7, \hat{b}_{1-s}^{(+)}, \hat{b}_{1-s}^{(-)}, b_{1-r}^{(+)}, \hat{b}_{1-r}^{(-)}$ represent all the flux density amplitudes to the whole related harmonics. The indices (–) and (+) denote negative and positive waves generated by slots in rotor and stator of IM. It is clear, that the Equation (14) gives the air gap flux.

$$\begin{aligned} \phi(\theta,t) = {} & \hat{\phi}_1 \cos(p\theta - \omega_1 t) + \\ & +\hat{\phi}_5 \cos(5p\theta + \omega_1 t) + \\ & +\hat{\phi}_7 \cos(7p\theta - \omega_1 t) + \\ & +\hat{\phi}_{1,s}^{+} \cos\left[(z_s - p)\theta + \omega_1 t\right] + \\ & +\hat{\phi}_{1,s}^{-} \cos\left[(z_s + p)\theta - \omega_1 t\right] + \\ & +\hat{\phi}_{1,r}^{+} \cos\left[(z_r - p)(\theta - \omega_m t) + s\omega_1 t\right] + \\ & +\hat{\phi}_{1,r}^{-} \cos\left[(z_r + p)(\theta - \omega_m t) - s\omega_1 t\right] \end{aligned} \tag{14}$$

where, $\phi_\upsilon = b_\upsilon S_\upsilon = b_\upsilon S_1/\upsilon$ and S_1 denotes the outer boundary periphery surface corresponding to a pole of the fundamental harmonic.

From the Equation (14), it is clear that magnetic flux in air gap comprise numerous harmonics. Every harmonic in air gap flux would generate the corresponding electromotive force (e.m.f.) in both windings of stator and rotor [9]. This induced e.m.f. for a single phase can be represented through Equations (15).

$$\begin{aligned} u_{sA} = \frac{\partial \hat{\phi}}{\partial t} = {} & \hat{u}_1 \cos(p\theta - \omega_1 t) + \\ & +\hat{u}_5 \cos(5p\theta + \omega_1 t) + \hat{u}_7 \cos(7p\theta - \omega_1 t) + \\ & +\hat{u}_{1,s}^{(+)} \cos\left[(z_s - p)\theta + \omega_1 t\right] + \\ & +\hat{u}_{1,s}^{(-)} \cos\left[(z_s + p)\theta - \omega_1 t\right] + \\ & +\hat{u}_{1,r}^{(+)} \cos\left[(z_r - p)(\theta - \omega_m t) + s\omega_1 t\right] + \\ & +\hat{u}_{1,r}^{(-)} \cos\left[(z_r + p)(\theta - \omega_m t) - s\omega_1 t\right] \end{aligned} \tag{15}$$

where, $\hat{u}_{1,s}^{(+)}$, $\hat{u}_{1,s}^{(-)}$, $\hat{u}_{1,r}^{(+)}$, $\hat{u}_{1,r}^{(-)}$ are the amplitudes for negative and positive components due to slots in the rotor and stator and $\hat{u}_1$ represent the amplitude of e.m.f. The phase voltages for phase B and C will be derived directly through Equation (15), differing only in their phase displacement by 120° and 240° electric degrees from phase A. From the Equation (15), it is clear that the voltage signal between stator winding's neutral point (0) and the neutral point (0') can be expressed as follow:

$$\begin{aligned} u_s = {} & u_{sA} + u_{sB} + u_{sC} = \\ & = \frac{1}{2}\kappa_{\upsilon 1}(N_r\omega_r + \omega_1)\left\{1 + 2\cos\left[2(N_r+1)\frac{\pi}{3}\right]\right\} \times \\ & \times \cos\left[(N_r\omega_r + \omega_1)t - (N_r+1)f_{h1}\right] + \\ & + \frac{1}{2}\kappa_{\upsilon 2}(N_r\omega_r - \omega_1)\left\{1 + 2\cos\left[2(N_r-1)\frac{\pi}{3}\right]\right\} \times \\ & \times \cos\left[(N_r\omega_r - \omega_1)t - (N_r-1)f_{h2}\right] \end{aligned} \tag{16}$$

where, N_r represents the number of pole pairs rotor slots ($N_r = Z_r/p$) and $k_{\upsilon 1}$, $k_{\upsilon 2}$, f_{h1}, f_{h2} are different coefficient's which varies from electromagnetic and mechanical structure of the IM [9, 18-23].

3. MEASUREMENT SETUP

Figure 2 illustrates the validation process of this method for estimating speed in three phase IM. This method utilizes Fourier spectral analysis to examine the voltage across both the neutral point at the windings of stator and 3-phase resistive network depicted in Figure 1. This voltage signals u_s exist because of rotor slot harmonics. The measurements have been performed on a three-phase squirrel cage IM. All the IM parameters which have been used in this experimental research work are shown in Table 1.

This particular induction motor which is used for the experiments has 46 rotor slots ($z_r = 46$). It was supplied by grid symmetrical 3-phase voltage system through rated frequency (f_1 = 50 Hz). Adjustments to the motor's load torque were made using a DC generator coupled to the induction motor. The spectral analysis of voltage u_s, utilizing Fast Fourier Transform (FFT), was performed using an oscilloscope.

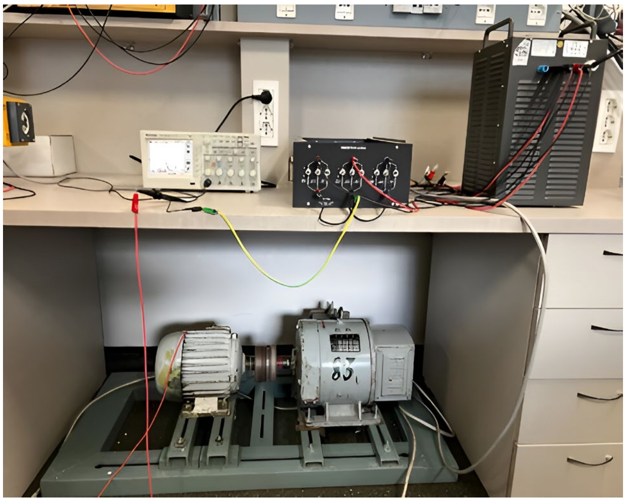


Figure 2. Experimental setup in three phase IM, electric machinery laboratory at Faculty of Electrical Engineering, Polytechnic University of Tirana, Tirana, Albania

Table 1. Parameters of the induction motor

n [rpm]	I [A]	P [kW]	U [V]	f_1 [HZ]	cos φ
1430	6.9	3	380	50	0.82

From above Equation (15) and (16) it is clear that the voltage u_s correspond to sinusoidal shape. In case of N_r it is a natural number, then we can evaluate Equations (17)-(21), as follow:

$$u_s = 0 \tag{17}$$

for $N_r = 3N_t$, $N_t = 1, 2, \ldots$

$$u_s = \frac{3}{2}\kappa_{\upsilon 1}\left(N_r\omega_r + \omega_1\right)\times \\ \times\cos\left\{\left(N_r\omega_r + \omega_1\right)t - \left(N_r + 1\right)f_{h1}\right\} \tag{18}$$

for $N_r = 3N_t - 1$, $N_t = 1, 2, \ldots$

$$u_s = \frac{3}{2}\kappa_{\upsilon 2}\left(N_r\omega_r - \omega_1\right)\times \\ \times\cos\left\{\left(N_r\omega_r - \omega_1\right)t - \left(N_r - 1\right)f_{h2}\right\} \tag{19}$$

for $N_r = 3N_t + 1$, $N_t = 1, 2, \ldots$

Furthermore, as per Equation (16), it becomes evident that if N_r correspond to natural number we have the rotor slot harmonics frequency given in Equation (20).

$$f_s = \frac{N_r\omega_r \pm \omega_1}{2\pi} = \\ = \frac{\left[N_r(1-s) \pm 1\right]\omega_1}{2\pi} = \\ = \left[\frac{z_r\left(1-s\right)}{p} \pm 1\right]f_1 \tag{20}$$

Respectively, s represents the IM slip. As indicated in Equation (20), it's notable where frequency of the rotor slot harmonics relies solely on f_1 and s. Thus, the rotor speed of the induction motor can be determined as follows [9-17]:

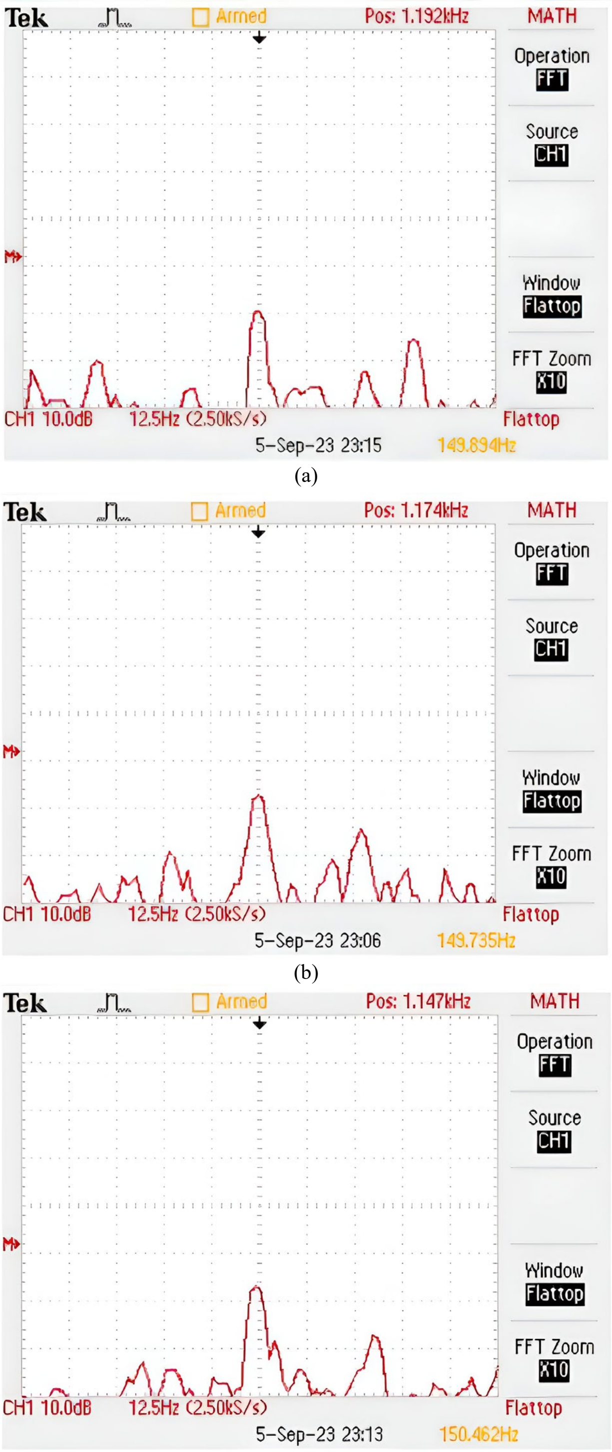
$$n = 60\frac{f_1}{z_r}\left(\frac{f_s}{f_1} \pm 1\right) \quad \text{[rpm]} \tag{21}$$

4. EXPERIMENTAL RESULTS

Figure 3 depicts the spectral analysis of voltage u_s for three distinct rotor speed values: 1491 rpm, 1468 rpm, and 1431 rpm. The corresponding values of rotor speed of the induction motor, both evaluated and measured by using rotor slot harmonics, have been presented in Table 2. Notably, from Table 2, it is evident that the speed error is minimal, and importantly, it remains consistent regardless of variations in motor load and temperature conditions.

Table 2. The measurement and estimated speed results

No.	f_s [Hz]	f_1 [Hz]	$n_{estimated}$ [rpm]	$n_{measured}$ [rpm]	Error [%]
1	1192	50	1490	1491	0.067
2	1185	50	1480	1477	0.203
3	1174	50	1466	1468	0.136
4	1168	50	1458	1454	0.275
5	1162	50	1450	1450	0
6	1155	50	1441	1442	0.069
7	1147	50	1431	1431	0
8	1137	50	1418	1418	0
9	1131	50	1410	1408	0.142



(a)

(b)

(c)

Figure 3. Spectral analysis of voltage signal for rotor speeds, (a) 1491 rpm, (b) 1468 rpm and (c) 1431 rpm

The results have demonstrated the accuracy of the speed estimation method for IM that focuses on rotor slot harmonics frequency.

The rotor speed values obtained through the rotor slot harmonics frequency method, when compared to traditional sensor-based techniques or model-based approaches, offer several important benefits and limitations, as discussed in prior research works which are mentioned as follows [25-31]:

- The accuracy of rotor speed estimation is notably improved with the rotor slot harmonics frequency method, resulting in minimal speed errors compared to traditional methods. This heightened accuracy is critical in ensuring precise motor control and performance.
- Comparisons of the variability or scatter in rotor speed values obtained from the rotor slot harmonics frequency method with traditional methods provide valuable insights into the precision, consistency, and reliability of speed estimation techniques. This aids in informed decision-making for various engineering and industrial applications, allowing for optimized motor control and predictive maintenance strategies.
- The cost-effectiveness of the rotor slot harmonics frequency method surpasses traditional methods, taking into account factors such as computational complexity, calibration procedures, hardware requirements, and maintenance considerations. This affordability makes the method more accessible and practical for widespread implementation in industrial settings.
- However, one of the main limitations of the rotor slot harmonics frequency method arises from the presence of harmonic noise, particularly in scenarios where the voltage is too small. This can pose challenges in obtaining reliable signals for accurate speed estimation, highlighting the need for further research to address such issues and enhance the method's robustness.

5. SUMMARY AND CONCLUSIONS

In this research work we have briefly described the evaluation of IM speed by using rotor slot harmonics frequency. The results have demonstrated the accuracy of the speed estimation method for IM that focuses on rotor slot harmonics frequency. The novelty of this methodology lies in its utilization of inherent characteristics of the motor itself rather than relying on external sensors. Rotor slot harmonics are natural frequencies that occur due to the shape and construction of the motor rotor. By analyzing these harmonics, the paper suggests that it's possible to infer the speed of the motor accurately.

Through this methodology for evaluation of the rotors speed it has been investigated some advantages in comparison of the conventional methods. It doesn't require speed transducers mounted on the rotor shaft, remains unaffected by its operational environment, is adaptable for various power ranges of induction motors, and requires no maintenance. It is clear, when the rotor speed is low we have very small amplitude of voltage signal u_s. In case that the voltage amplitude u_s becomes too small, obtaining a reliable signal becomes challenging due to the presence of harmonic noise. Moreover, detecting the rotor slot harmonic frequency becomes difficult under these circumstances. This drawback stands out as one of the primary limitations of the method.

In forthcoming research work, we aim to address this challenge by injecting an additional sinusoidal three phase signal through the stator windings of the IM.

NOMENCLATURES

1. Acronyms

IM	Induction Motor
MRAS	Model Reference Adaptive System
FFT	Fast Fourier Transform

2. Symbols / Parameters

f: Magnetomotive force

θ : Air gap periphery

p : Number of pole pairs

υ : Harmonic order

ω : Angular speed

q : Number of coils

N : Number of conductors in one coil

s : Induction motor slip

z_r : Number of rotor slots

z_s : Number of stator slot

b : Flux density

ϕ : Magnetic flux

f_1 : Fundamental frequency

f_s : Fundamental slot harmonic frequency

n : Rotational speed of induction motor

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