Sensorless Control of Asynchronous Motor at Low speed

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Abstract. The subject of the submitted paper is to provide a detailed description of simulation control of rotor position sensing of an asynchronous motor by an injection method of high-frequency analogue signal on supply signal frequency of up to 5 Hz, i.e., at zero and low speed. In general, contrary to discrete signal injection, the implementation of the method appears to be simpler for continual signal injection aimed at monitoring of asymmetry of rotary electric machines, however, the process of information gathering related to position of monitored asymmetries during signal reaction processing is more complicated. Genuine verification of the method requires designing a mathematical model of a motor including asymmetries caused by rotor grooving and by magnetic core saturation. The asymmetries occurring in asynchronous motors considerably influence the instant value of a stator induction LS. Asymmetries caused by magnetic circuit saturation were identified and eliminated because of inducing the measured signal distortion. The elimination method LMDEM is the method proposed for repressing the asymmetries. The asymmetries caused by rotor grooving are intended to detect the rotor position. In final part, mathematical functions will be used for converting the signal to rotor position.

1. Introduction
As it is known, the asynchronous machines are more advantageous than the direct current ones, however, their use was rather limited until the first half of the 20th century. The difficulty rested in control of the asynchronous motor within entire range of rotations which was caused by rotation speed being dependent on frequency of supply voltage. The computing technique development contributed to elimination of the problem. Technological progress supported development of new control structures such as scalar control. It allowed controlling of the asynchronous motor from zero speed yet without nominal motor load and with high dynamics [4] [15] [16].

The advancement in the sphere of control of A/C rotary machines brought about the invention of vector control in the 70s of the twentieth century. The control allowed the direct current machines to be removed from majority of applications owing to possibility of achieving the drive control by means of vector control within the entire range of rotations with maximum torque. In the beginning, in case of vector control, the rotation sensor was needed which could be considered as the sole difficulty observed. In case of small motor drives, the sensor doubled the price. The price reduction of the whole drive could be achieved through removal of rotation sensor and installation of sensorless methods.

Monitors based on mathematical model of the motor were the most frequently applied rotor or coupled magnetic flux position estimators. The monitors require precise identification of motor
parameters which are subjected to specific operating effects such as motor heating or influence of magnetic core saturation in case of low speed. The change in parameters causes estimation errors which can be eliminated by adaptive on-line parameter estimation [5] [17].

Mathematical model-free method is more suitable to be used mainly due to unreliability of the methods at low or zero speed. The principle of methods rests in voltage or current impulses injection and in consequent measurements of impulse echoes. The rotor or magnetic flux position determination is assured by echo measurement the instant values of which depend on either magnetic or geometrical dissymmetry of motors. The methods are suitable for operation within the range of low speed values, starting even from the zero ones. The methods can be divided into two main groups based on type of signal being injected [6] [18].

The first method applied was the injection method of a pulse analogue current signal. The author of the method is Blaschke. The method employs the saturation effect of magnetic circuit. As the injection echo of the current impulse injection it would be suitable to measure echoes of rotor fluxes to detect the position of rotor precisely. However, in case of a squirrel cage it cannot be accomplished as to its design. According to Blaschke [7], it is possible to gain important information on flux vector with low frequencies and especially in case of zero frequency it is feasible by means of stator voltage and current.

The method of high-frequency signal injection is different for an injected signal being the voltage one, not the current one. It is due to the fact that voltage signals are easier to be injected than the current ones. The signal is performed in the αβ system bound with the stator and by means of an auxiliary voltage supply. This injected signal is superponated on a basic voltage with frequency ranging from 500Hz up to 2kHz. In his thesis, Sul describes the principle of the aforementioned method applied in case of an actual motor [8] at zero and low speed under different operating conditions.

Consoli is the author of further method called Zero-Sequence Technique. The method is based on estimation of the position of magnetic flux in the air gap by means of the element of the third harmonic one of the stator voltage. The basis of the technology is measurement of zero voltage element which occurs in asynchronous motor during standard operation between star-connected node and fictive centre of the DC circuit of a transducer that represents a result of saturation phenomena of the motor and of injection of high-frequency voltage signal. Consoli presents the method in his thesis [9]. He uses voltage signal with frequency of 500 Hz superponated on main stator voltage. Generation of a zero voltage element is not speed-dependent due to which the estimation of the flux position in the air gap can be performed at any speed within the range from zero up to nominal value.

Further method referred to as Zero Sequence Voltage is experimentally verified by Holtz in his thesis. To estimate the rotor position, Holtz uses rotor asymmetry caused by rotor grooving. Measurement of voltage echoes and injection of voltage impulses must be synchronized to assure collection of correct information on asymmetry location. According to Holtz’s description, voltage impulse injection [10] results in increase of stator currents and in consequent changes of their derivation which induce zero voltage. The method is negatively influenced by the fact that if the motor is connected by longer supply conductors, the measured signal can be disturbed by high-frequency currents. Holtz’s thesis analyses the solution of this problem as well.

The Zero Sequence Current method is based on the same principle as the previous one. Injection uses voltage signal, too. Echo measurement is not implemented during voltage measurement but in the course of zero current measurement. Therefore, the method is limited to a triangle connection. Discrete voltage impulses cause abrupt increase of currents and change in their derivation due to motor asymmetry [11]. Analyses and proves more in a detail the measurement principle of derivations for the purpose of monitoring of motor asymmetry caused by magnetic core saturation or by rotor grooving.

The name of the method “INFORM” was derived from its fundamental principle as follows: INdirect Flux detection by On-line Reactance Measurement. The method was developed by an Austrian author Schroedl [12] and it serves as a base for any method working on the principle of injection of
discreet voltage signals and of measuring the impulse echoes in the form of current differentials or current derivations.

2. Asymmetry development for the rotor grooving
If a simplified version is taken into consideration, the air gap $\delta$ in asynchronous machine is constant and development of magnetic induction in air gap is proportional to development of magnetic voltage $U_{mag1}(\theta, t)$, i.e., it is of a sinusoidal shape.

$$B_{\delta1} = f(\theta, t) = \frac{\mu_0 U_{mag1}(\theta, t)}{\delta}$$ (1)

In fact, the air gap $\delta$ is not constant as it changes along with opening and shape of a groove therefore development $U_{mag1}(\theta, t)$ is multiplied by a periodical function the basic wave of which has a length of groove pitch $\tau_d$, i.e., $Q/p$ waves of the $B_{d}(\theta, t)$ grooving fall on a single wave of the basic harmonic one $[1] [13] [19]$

![Figure 1. Development of magnetic induction in the air gap [3]](image)

These groove harmonic ones cause the following:
- induction of harmonic elements in induced voltage of the AC machines
- interaction of stator and rotor groove harmonic ones causes occurrence of spurious torques in induction motors and the torques can considerably change the shape of torque characteristics of the induction motor (figure 2)
- they cause noise and vibration of the machine
- they increase iron losses through releasing high-frequency elements of magnetic field to stator teeth.
To reduce the groove harmonic ones, the following procedures are used:

- Fractional-slot winding
- Rotor with chamfered grooves

Although, rotor grooves negatively influence the motor run, it is inevitable for estimating the rotor position by means of signal injection and therefore, the rotor with repressed asymmetry must be taken into consideration. Frequency spectrum measured in [3] [14], depicts the amplitude of the asymmetry in case of both flat and chamfered grooves.

Theoretical principle formed the base for forming the change of induction by the effect of rotor grooving in a simulation model of asynchronous model of motor. The value of stator induction \( L_s \) represents periodical function sine (cosine) of rotor position with frequency dependent on number of rotor teeth \( N_r \). The following represents the voltage equations for stator winding of matrix shape:

**Figure 2.** Torque characteristics ASM with seats of asynchronous torques [2]

**Figure 3.** Harmonic analysis of motor signal with 56 grooves a) chamfered grooves b) flat grooves [3]
With $L_1$ expressing difference between maximum and minimum value of stator induction in dependence on rotor position

$$L_1 = \frac{L_{s\text{max}} - L_{s\text{min}}}{2}$$

(3)

Furthermore, it is inevitable to take into account the fact that asymmetry implementation in the motor results in electromagnetic torque ripple.

3. Estimation of rotor position based on high-frequency signal injection

The method or rotor position estimation based on external high-frequency signal injection is suitable for synchronous and asynchronous machines although in practice, the method application is more or less related to synchronous machines which is caused mainly by more precise magnetic expression of rotor. Eventually, magnetic expression of rotor becomes evident either by a change in electromagnetic field or by losses, in dependence on rotor position. Consequently, these are directly related to change in induction or resistance of stator winding [19] [20].

Correct determination of position at low or zero rotations requires external voltage actuating signal in the form of rotating vector with constant amplitude $V_s$ which rotates at constant speed $\omega_i$ and matrix shape of which can be expressed as follows:

$$v_{aB,i} = \begin{bmatrix} v_{a,i}^s \\ v_{\beta,i}^s \end{bmatrix} = V_s \begin{bmatrix} \cos \omega_i t \\ -\sin \omega_i t \end{bmatrix} = V_s e^{-j\omega_i t}$$

(4)

Based on the premise of asynchronous motor with flat grooves actuated by high-frequency signal, according to equation (4), it is possible to discuss a high-frequency motor model in which case the mathematical model of stator voltage will be modified as follows:
\[ u_{a\beta,i} \approx L \frac{di_{a\beta,i}}{dt} \]  

(5)

With \( L \) standing for matrix of induction from equation (2) which includes asymmetry caused by motor grooving. Integration of the equation (5) results in the following:

\[ \int u_{a\beta,i} \, dt = L_i i_{a\beta,i} \]  

(6)

Which, in case of rotating vectors and the actuating signal according to (3) including modification, leads to the following:

\[ \frac{V_{si,\omega_i}}{\omega_i} \begin{bmatrix} \sin \omega_i \\ \cos \omega_i \end{bmatrix} = \begin{bmatrix} L_s + L_1 \cos(N_r \theta_r) & L_1 \sin(N_r \theta_r) \\ L_1 \sin(N_r \theta_r) & L_s - L_1 \cos(N_r \theta_r) \end{bmatrix} \begin{bmatrix} i_{\alpha,i} \\ i_{\beta,i} \end{bmatrix} \]  

(7)

Consequent expression of currents allows detection of the motor current echo to respective high-frequency signal.

\[ i_{\alpha,i} = \frac{(L_s - L_1 \cos(N_r \theta_r))(V_{si,\omega_i,\sin \omega_i}) - (L_1 \sin(N_r \theta_r))(V_{si,\omega_i,\cos \omega_i})}{(L_s - L_1 \cos(N_r \theta_r))(L_s + L_1 \cos(N_r \theta_r)) - (L_1 \sin(N_r \theta_r))(L_1 \sin(N_r \theta_r))} \]  

(8)

\[ = \frac{V_{si,\omega_i} (L_s \sin \omega_i - L_1 \sin(N_r \theta_r + \omega_i))}{L_s^2 - L_1^2} \]

The same is applicable in case of \( i_{\beta,i} \):

\[ i_{\beta,i} = \frac{(L_s - L_1 \cos(N_r \theta_r))(V_{si,\omega_i,\cos \omega_i}) - (L_1 \sin(N_r \theta_r))(V_{si,\omega_i,\sin \omega_i})}{(L_s - L_1 \cos(N_r \theta_r))(L_s + L_1 \cos(N_r \theta_r)) - (L_1 \sin(N_r \theta_r))(L_1 \sin(N_r \theta_r))} \]  

(9)

\[ = \frac{V_{si,\omega_i} (L_s \cos \omega_i - L_1 \cos(N_r \theta_r + \omega_i))}{L_s^2 - L_1^2} \]

Modifying and converting the equation to the matrix form results in the following:

\[ \begin{bmatrix} i_{\alpha,i} \\ i_{\beta,i} \end{bmatrix} = \begin{bmatrix} I_0 \sin \omega_i - I_1 \sin(N_r \theta_r + \omega_i) \\ I_0 \cos \omega_i + I_1 \cos(N_r \theta_r + \omega_i) \end{bmatrix} \]  

(10)

with

\[ I_0 = \frac{V_{si,\omega_i}}{\omega_i} \left( \frac{L_s}{L_s^2 - L_1^2} \right) \]  

(11)

\[ I_1 = \frac{V_{si,\omega_i}}{\omega_i} \left( \frac{L_1}{L_s^2 - L_1^2} \right) \]  

(12)

According to 9, the final high-frequency current consists of two elements mutually spinning at different speed and in different direction. The first element is directly proportional to the value of stator induction \( L_s \). It expresses the value of current which would flow through the stator winding if the asynchronous motor without magnetic asymmetry was taken into consideration. The other element of high-frequency current, which rotates in opposite direction to voltage vector of high-frequency actuating signal, carries the information on position of detected asymmetry and is in due proportion to difference between maximum and minimum change of induction \( L_i \), for the influence of magnetic asymmetries of
the motor. Following the aforementioned, it is clear that both elements must be separated and the element carrying the information on respective asymmetry position must be repressed [21].

**Figure 5.** Block scheme of the vf signal injection

Based on the aforementioned information, the external signal is injected in the αβ system with frequency of 1000Hz and with amplitude of 2V and in opposite rotation direction to space vector of stator magnetic field. Selection of signal requires being particular about avoiding influence of amplitude and frequency of high-frequency signal on machine function. Following the principle of the method, it is clear that echo of high-frequency signal of stator current was measured in the αβ stator-bound system (fig. 6).

**Figure 6.** Stator currents ASM in αβ with stressed echo of vf signal

Figure 7 shows amplitude modulation of high-frequency signal which is caused by change in stator induction under the influence of NSDR. Consequently, filtration of positive element is needed with the use of a high-pass filter. The adequate mathematical operation must be used for transformation of the position signal to the system of injected signal rotating at speed \( \omega_i \) (13) in case of which the changes of stator induction caused by NSDR can be detected and the rotor position can be consequently determined according to the measured signal.

\[
\begin{align*}
    i_{vf.d} &= i_{vf.a} \cos(\theta_i) - i_{vf.b} \sin(\theta_i) \\
    i_{vf.q} &= i_{vf.a} \cos(\theta_i) + i_{vf.b} \sin(\theta_i)
\end{align*}
\]  

(13)
4. Conclusion
The paper presented a detailed description of sensorless methods of rotor position estimation of asynchronous motor based on injection of voltage or current signals. Closer attention was paid to the analysis of the estimation method of rotor position of asynchronous motor called INFORM. The subchapters focused on explanation of existence of two types of magnetic asymmetries in case of asynchronous motors during operation. These asymmetries influence instant value of stator induction $L_S$. These asymmetry types were included in the mathematical model of asynchronous motor.

Consequently, the asymmetries were detected by the method of high-frequency signal injection in the $\alpha\beta$ system with frequency of 1kHz and with amplitude of 2V. Asymmetries caused by saturation of magnetic circuit led to deformation of the measured signal and therefore their identification and modification is inevitable. The method LMDEM could be used as the elimination method through which the asymmetries would be repressed. Consequently, the signal carrying the information on asymmetry position caused by rotor grooving must be converted to rotor position by the $\text{arctan}$ function and multiplied by number of rotor teeth.

Pursuant to the aforementioned knowledge and mathematical models, a simulation model of asynchronous motor control can be designed with the application of scalar control approach. To obtain the most authentic information, the simulations should be performed in modes, with start at defined rotations, with reverse and with drive loading with rated torque.

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References
[1] Hrabovcova V, Rafajdus P, Franko M, Hudak P. 2004 Meranie a modelovanie elektrických strojov, EDIS ZU
[2] Heier S. 2006 Grid Integration of Wind Energy Conversion System, Wiley Chichester
[3] Dobrucky B, Filka R. 2002 Sensorless rotor position determination of PMSM focusing on hf signal injection method, AEEE Vol 1, No 2
[4] Krejci, F. 2010 Asynchronní elektromotory, Profi Elektronika
[5] Dobrucky B, Filka R, Abdalmula M.A.R, Holeck R. 2006 A new optimisation algorithm of position estimation for zero and low speed range using magnetic saliency method, EPE-PEMC’02
[6] Degner M.W, Lorenz R. D. 2000 Position estimation in induction machines utilizing rotor bar slot harmonic and carrier-frequency signal injection, IEEE Transactions on IA Vol. 36 No. 3
[7] Blaschke F, Burgt J, Vandenput A. 1996 Sensorless Direct Field Orientation at Zero Flux Frequency, Conference Record of the IEE – IAS Annual Meeting
[8] Sul S, Ha J. 2000 Physical Understanding of High Frequency Injection Method to Sensorless Drives of an Induction Machine, IEEE - Industry Applications Conference
[9] Consoli A, Scarcella G, Testa A. 2000 A New Zero-Frequency Flux-Position Detection Approach for Direct-Field-Oriented-Control Drives, IEEE Transactions on Industry Applications, Vol. 36, No. 3
[10] Holtz J, Pan H. 2003 Acquisition of Rotor Anisotropy Signals in Sensorless Position Control Systems, IEEE
[11] Caruana C, Asher G. M, Clare J. 2003 Sensorless Flux Position Estimation at Low and Zero Frequency by measuring Zero-Sequence Current in Delta Connected Cage Induction Machines, IEEE IAS Annual Meeting
[12] Schroedl M. 1996 Sensorless control of AC machines at low speed and standstill based on the INFORM method, IEEE – IAS Annual Meeting, Vol.1
[13] Mital G, Dobransky J, Ruzbarsky J, Olejarova S. 2019 Application of laser profilometry to evaluation of the surface of the workpiece machined by abrasive waterjet technology, Applied Sciences, Vol. 9, No. 10
[14] Coranic T, Gaspar S, Pasko J. 2021 Utilization of optimization of internal topology in manufacturing of injection moulds by the DMLS technology, Applied Sciences, Vol. 11, No. 1
[15] Pavlenko S, Kacalova M, Fackovec R, Coranic T. 1019 Analysis and computation method of torsional compliance of worm gear, Technical Gazette : TV-TG, Vol. 26, No. 2
[16] Mascenik J, Pavlenko S. 2020 Determination of stress and deformation during laser welding of aluminium alloys with the PC support, MM Science Journal
[17] Mascenik J, Pavlenko S. 2018 Innovative broad - spectrum testing and monitoring of belt transmissions, MM Science Journal
[18] Mascenik J. 2017 Monitoring of parameters directly influencing performance transfer by belt gear, MM Science Journal
[19] Kascak Jakub, Torok J, Torokova M. 2021 Utilization of the ultrasonic diagnostic method in rail status on a defined railway section, TEM Journal, Vol. 10, No. 1
[20] Matiskova D, Balog M, Husar J. 2018 Criteria for the optimization of production processes in machining of metallic materials, Management systems in production engineering, Vol. 26, No. 4
[21] Dyadyura K, Hrebeny L, Krenicky T, Zaborowski T. 2021 Modeling of the manufacturing systems state in the conditions of the lean production, MM Science Journal