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The Influence of the Induction Motor Rotor Geometry on the Higher Harmonic Index of the Zero-Sequence Current

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Abstract-- **Lately, a new diagnostic mean has been introduced for reliable fault diagnosis in delta-connected induction motors. This diagnostic mean is the zero-sequence current frequency spectrum. Since this diagnostic mean successfully answers to a variety of reliability demands, a thorough investigation of its harmonic index has to be performed as a function of the rotor geometry. In this work, FEM sinulations have been performed for motors of different rotor slot numbers and the zero-sequence current spectra are studied with the application of the FFT. Finally, experimental testing is applied to verify the simulations results.**

Index Terms—**Finite element analysis, Harmonics, Induction Motor, Zero-sequence current.**

I. Introduction

The scientific area of induction motor fault diagnosis, in its present form, has gained a great deal of interest in the last decade, despite the fact that it's fundamentals are about three decades old. Through the today's available large number of publications, as it can be seen in review papers [1]-[3], it occurs that, the fault diagnosis area is mainly divided into two sub-areas: The first sub-area deals with the fault impact on the machine and its electromagnetic or mechanical variables, while the second sub-area focused on the appropriate signal processing method aiming to extract the needed information from a selected signal.

The different rotor and stator faults create asymmetries in the motor's magnetic field. Those asymmetries are then expressed through the motor's operating variables [1]-[3] such as the magnetic flux density, the stator current, the electromagnetic/mechanical torque, the electrical power etc. Between all diagnostic methods, the MCSA (Motor Current Signature Analysis) is the most preferred because of its simplicity, low cost, non intrusiveness and the ability to be applied on-line.

The thorough and detailed knowledge of the harmonic index of the selected diagnostic mean in healthy operation is the key for reliable diagnosis. The saturation and load level impacts on the diagnostic mean's harmonic index are also of great importance. Despite the fact that, the MCSA is quite an old diagnostic method, one of the latest publications [4] has presented in detail the stator current harmonic index in healthy induction motors and its dependence on the pole pairs, slot numbers and operating conditions.

The zero-sequence current frequency spectrum has proved to be a valuable diagnostic mean lately. It reliably deals with a variety of delta-connected induction motor faults such as the static eccentricity (even when the motor is PSH), the broken bar fault, the supply imbalance and the stator inter-turn fault [4]-[7]. Although it requires three current sensors, instead of one needed with the traditional MCSA, it answers to more diagnostic problems. For example, it offers greater broken bar fault signatures than the stator current for the case of double-cage induction motors and it can detect the only-static eccentricity in PSH-induction motors. In both the above two problems, the MCSA has been reported to be unreliable [1].

In this work, the zero-sequence current and its frequency spectrum are studied in detail for healthy, 3-phase, 4-pole, 4kW, 400V, 50Hz, induction motors with 36 stator slots. Six different rotor slot number cases are examined with the use of the Finite Element Method (FEM). To allow for a fair comparison, the studied induction motors have equal rotor cage resistance, rotor bar shape, rotor bar depth and equivalent air-gap. The phase, line and zero-sequence current frequency spectra are calculated and studied with the application of the FFT. The work focuses on the rotor slot number impact on the higher harmonic index of the zero-sequence current. Finally experimental testing is carried out to verify the theoretical and simulation results.

II. Finite Element Analysis

In order to allow for a fair comparison, a parameterized induction motor model has been created and simulated with FEM under six different cases. All motor cases share identical stators, air-gap length and shaft radius. The rotor angular geometrical variables have been created parameterized in relation to the rotor slot number. On the other hand, the radial geometrical rotor variables are fixed. So, increasing the number of slots will mean decreasing the width of the bars and consequently their surface, as well as the rotor teeth openings accordingly. In this way all studied motors have equal DC rotor resistance and equivalent air-gap. Finally, in reality different rotor slot numbers under the same stator slot number automatically would imply different skew angle. So, it becomes evident that the skewing angle parameter will negatively influence a fair comparizon of the motor cases and this is why it will be neglected. All studied motor cases are considered un-skewed.

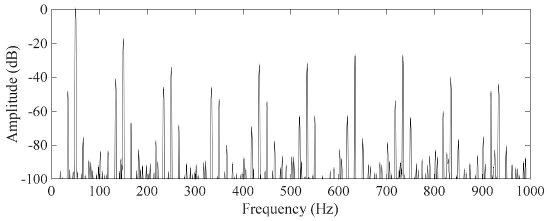
The induction motor prototype used to build the original FEM model has the following characteristics: 400V, 4kW, 4-poles, 3-phase, 36 stator slots and 28 rotor slots.

The selected rotor slot numbers to be studied are: 24, 28, 30, 40, 41 and 48. Following past contributions [8]-[9] the motors with 24, 28, 40 and 48 are PSH induction motors. Moreover, 24 and 48 are multiples of 3. So, practically, this study will investigate significant representative cases of harmonics generation due to the rotor slot number. All motors are simulated to operate at 1460rpm.

For all cases, the spectra of phase current, line current and zero-sequence current will be illustrated and studied.

A. Case of 24 Rotor Slots

Fig. 1 shows the phase, line and zero-sequence currents' frequency spectra for the motor with 24 rotor slots. The phase current spectrum includes all odd multiples of the supply frequency, as well as harmonics related to the rotor slot number, pole pairs number and the slip. The rotr slot related harmonics exist as sidebands to all multiples of the supply frequency. On the other hand, the line current spectrum does not contain the odd triplets, multiples of the supply frequency, as well as any rotor slot related harmonics sidebands to the triplets. The analysis of the zero-sequence current spectrum reveals that the missing harmonics have been transferred from the phase to the zero-sequence current. Furthermore, it is obvious that the first triplet located at 150 Hz is the strongest harmonic in the zero-sequence current.



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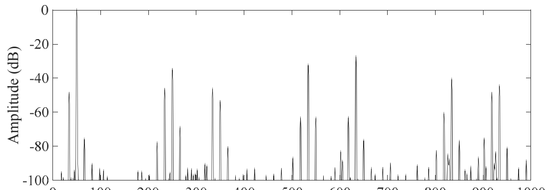

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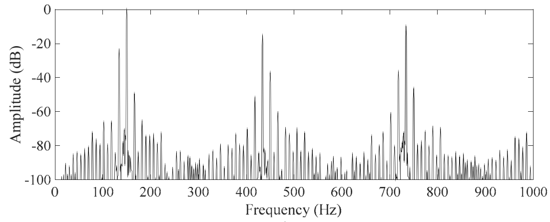

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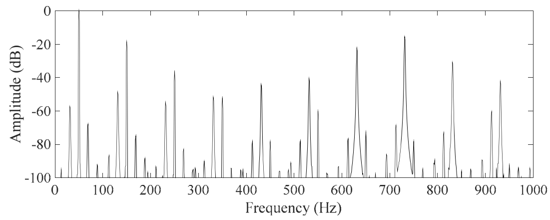
Fig. 1. a) Phase, b) line and c) zero-sequence current frequency spectra of the motor with 24 rotor slots.

B. Case of 28 Rotor Slots

The phase, line and zero-sequence current spectra are presented in Fig. 2. Generally, similarities exist between this motor and the one with 24 rotor slots. However, an interesting difference is observed. The 150Hz harmonic is not the strongest in the zero-sequence current, but the PSH located at 731Hz.



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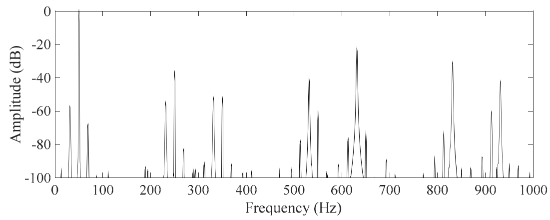

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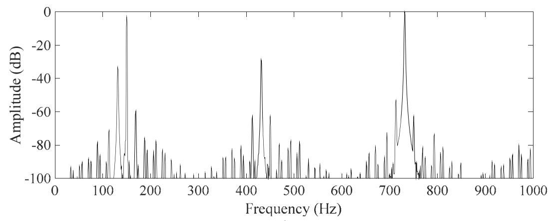

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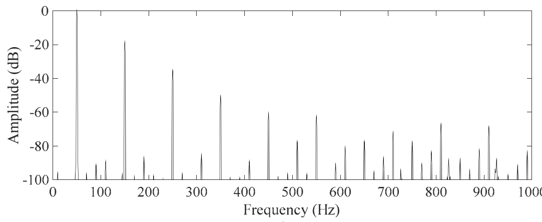
Fig. 2. a) Phase, b) line and c) zero-sequence current frequency spectra of the motor with 28 rotor slots.

C. Case of 30 Rotor Slots

The motor with 30 rotor slots is not a PSH induction motor case. Moreover, 30 is even number and multiple of 3. The phase, line and zero-sequence current spectra are presented in Fig. 3 for this motor case. It is evident that this motor type does not produce any significant rotor slot related harmonics. As a consequence, the phase current mainly consists of all odd multiples of the supply frequency. The odd triplets pass on to the zero-sequence current, whereas all the rest are observed in the line current frequency spectrum.



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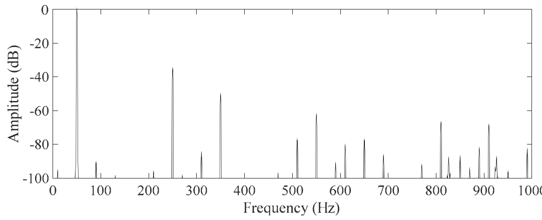

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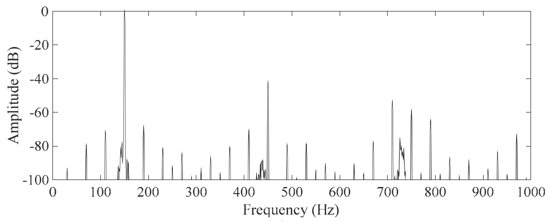

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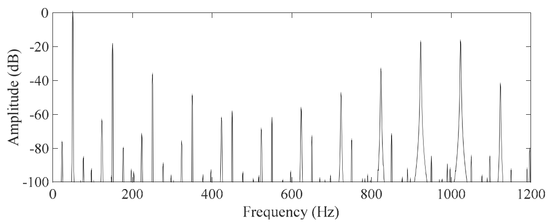
Fig. 3. a) Phase, b) line and c) zero-sequence current frequency spectra of the motor with 30 rotor slots.

D. Case of 40 Rotor Slots

It is expected that the motor with 40 rotor slots will present similar behaviour to the one with 28 rotor slots. That is because they are both PSH induction motor cases and their rotor slot numbers are not multiples of 3. The analysis results for this case are illustrated in Fig. 4 and seem as expected. One interesting point is that the PSH are now located close to 1000Hz and with significant amplitudes. On the other hand, the rotor slot related harmonics at lower frequencies exist but are characterized by weak amplitudes.



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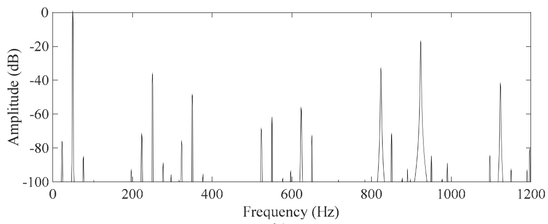

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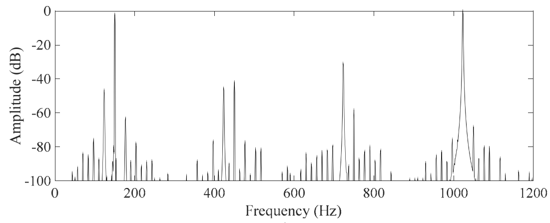

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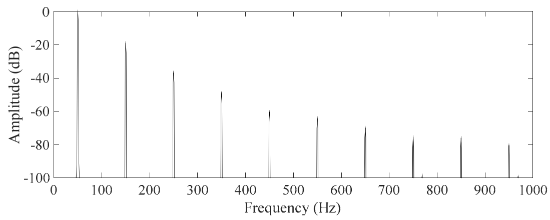
Fig. 4. a) Phase, b) line and c) zero-sequence current frequency spectra of the motor with 40 rotor slots.

E. Case of 41 Rotor Slots

This case is difficult to happen in real machines and is studied out of academic interest. It is a case of an odd rotor slot number not multiple of 3. The analysis results are shown in Fig. 5. It can be seen that the harmonic index of all signals is very similar to the one of the motor with 30 rotor slots (Fig. 3). The only difference is the complete absence of rotor slot related harmonics at higher frequencies of the phase and line currents.



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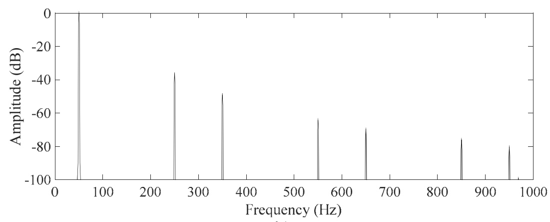

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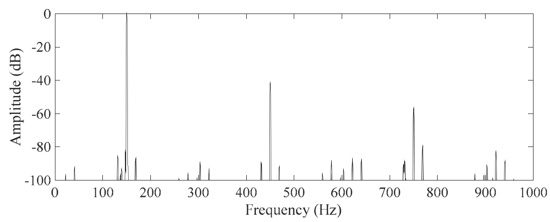

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Fig. 5. a) Phase, b) line and c) zero-sequence current frequency spectra of the motor with 41 rotor slots.

F. Case of 48 Rotor Slots

The final rotor slot number case to be studied in this paper is the one of 48 rotor slots. This number implies that the analyzed induction motor is a PSH induction motor. Moreover, the rotor bars number is a multiple of 3. The results are presented in Fig. 6. The harmonics' pattern resembles the one of the motor with 24 rotor slots (Fig. 1). However, the amplitudes of rotor slot related harmonics at low frequencies are insignificant whereas at high frequencies (>700Hz) they are very strong.

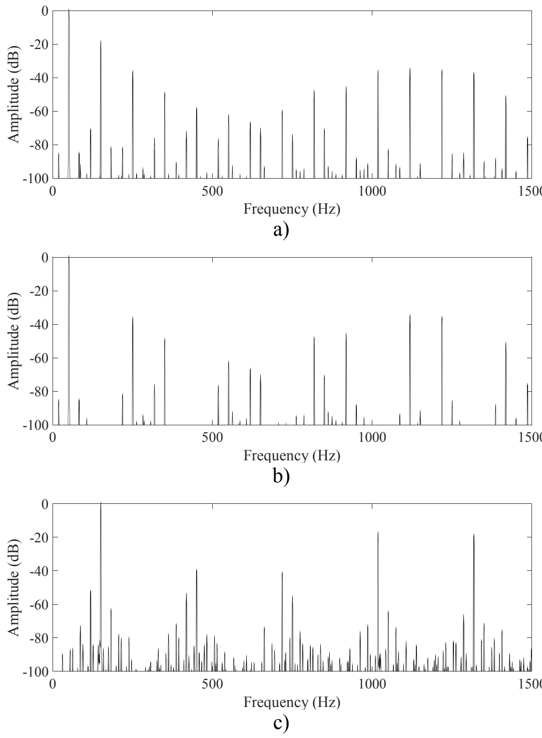


Fig. 6. a) Phase, b) line and c) zero-sequence current frequency spectra of the motor with 48 rotor slots.

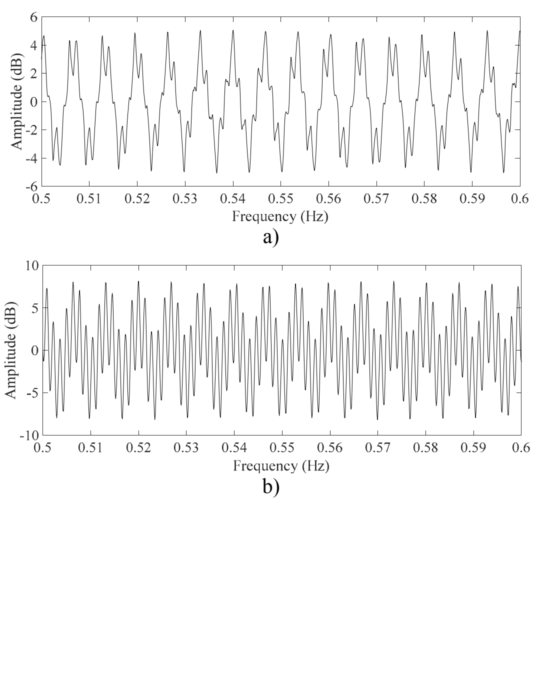
G. Zero-Sequence Current Waveforms

The zero-sequence current waveforms are presented for all studied cases in Fig. 7.

The impact of strong rotor slot harmonics is evident in the cases of 28 and 40 rotor slots (Fig. 7-b and Fig. 7-d). The distorion of the third harmonic is stronger in Fig, 7-d due to the fact that the influencing rotor slot related harmonic is located at higher frequency (Fig. 4-c) than the one for the motor with 28 rotor slots (Fig. 2-c).

The distortion due to rotor slot harmonics is negligible in motors with 30 and 41 rotor slots. So, the zero-sequence waveform is more sinusoidal-like.

An average distortion state is observed in the cases of the motors with 24 and 48 rotor slots.



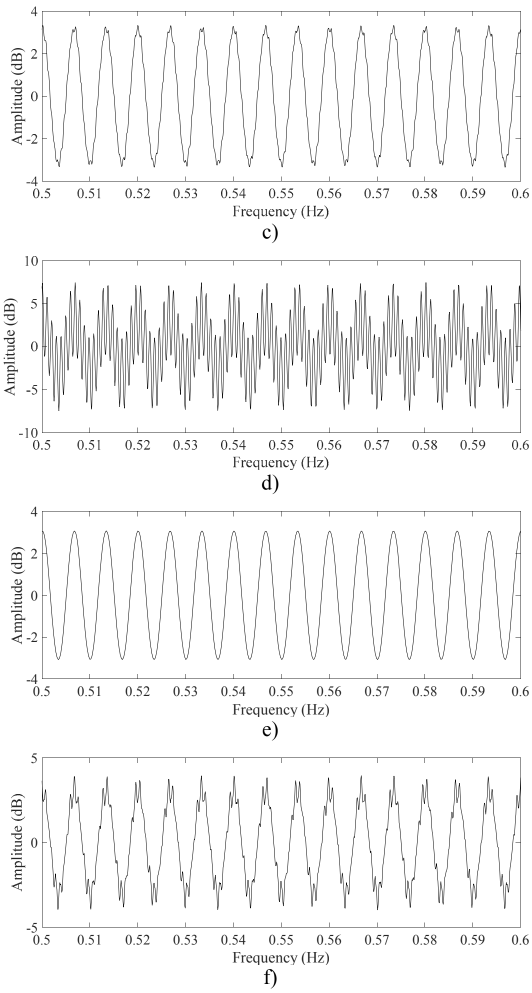


Fig. 7. The zero-sequence current waveforms of the motors with: a) 24, b) 28, c) 30, d) 40, e) 41 and f) 48 rotor slots.

III. Experimental Testing

Experimental testing has been performed on a 3-phase, 1.1kW, 230V, 4-pole induction motor with 36 stator and 28 rotor slots. A DC generator supplying a variable resistance was coupled to its shaft and played the role of the load. The experimental test bed is shown in Fig. 8.


Fig. 8. Illustration of the experimental setup.

The analysis results are shown in the following Fig. 9.

One can see that the experimental results verify the simulations with accuracy. The rotor slot related harmonics at 419.8Hz and 719.8Hz decrease significantly of the phase current is compared to the line current. And those harmonics are very strong in the zero-sequence current spectrum. Those observations fully agree with the results of Fig. 2.

Some differences between simulation and experiment can be also observed. Firstly, the third harmonic has decreased amplitude but still exists in the line current as well as the above mentioned rotor slot related harmonics at 419.8Hz and 719.8Hz. The reason for this is easily explained through the zero-sequence current spectrum of Fig. 9-c. There is an unexpected strong harmonic at 50Hz. This is clearly due to some asymmetry between the phase currents caused by a combination of inherent machine asymmetries due to manufacturing, asymmetrical wiring and imballance voltage supply [10]. It has to be noted that the tested motor is small and as a consequence easilly affected by asymmetries. Finally, the PSH at 719.8Hz proves to be slightly weaker than the one at 150Hz in the zero-sequence current. This is due to the fact that the real induction motor's rotor has skewed bars to decrease the impact of the rotor slot harmonics. On the other hand the FEM models were simulated unskewed.

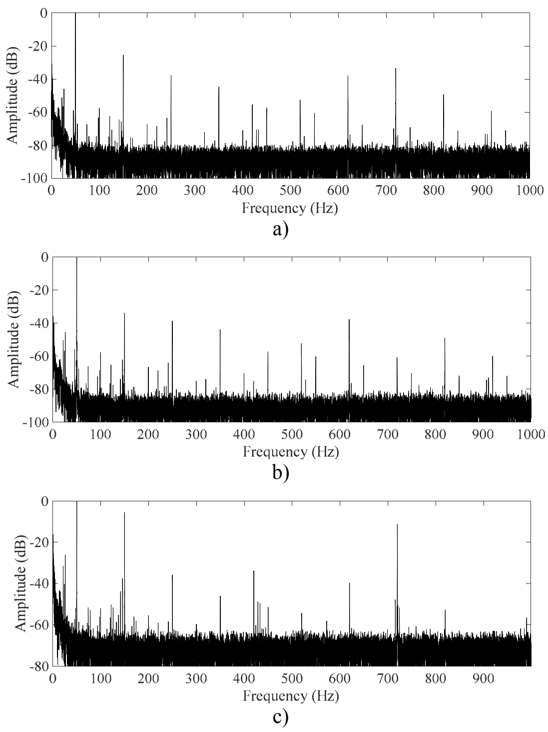


Fig. 9. a) Phase, b) line and c) zero-sequence current frequency spectra of the real induction motor operating under rated load (experimental results).

IV. Conclusions

In this work, the authors illustrate that the rotor slot number plays an important role on the zero-sequence harmonic index of induction motors. Depending on the combination between magnetic poles and rotor bars, several rotor slot related harmonics are expressed in the zero-sequence current spectra or not. The experimental results verify the theroetical and simulation ones with accuracy. The findings of this work are valluable for direct application in the condition monitoring as well as design of 3-phase cage induction motors.

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