1. Ivan TEMELKOVSKI, 2. Goran RAFAJLOVSKI, 3. Goga CVETKOVSKI, 4. Mihail DIGALOVSKI

Faculty of Electrical Engineering and Information Technologies, Ss. Cyril and MethodiusUniversity in Skopje

doi:10.15199/48.2025.03.29

Impact of high order harmonics on the motor copper losses and operating characteristics

***Abstract**. In this paper, a three-phase low-voltage squirrel cage induction motor is considered. From the short-circuit test, the operating characteristics are obtained in two different ways: once when the induction motor is connected directly to the network and another when the motor is inverter fed. Furthermore, an analysis of the high order harmonics is given and the copper losses that occur during the no-load test of the induction motor are determined. A qualitative analysis of the results is given and the significant impact of the inverter on the copper losses is highlighted.*

***Streszczenie.** W artykule rozpatrzono trójfazowy silnik elektryczny klatkowy niskiego napięcia. Charakterystyki pracy uzyskuje się z próby zwarciowej na dwa różne sposoby: raz, gdy silnik elektryczny jest bezpośrednio podłączony do sieci, i drugi, gdy silnik jest zasilany z falownika. Dodatkowo przeanalizowano harmoniczne wyższego rzędu i określono straty w miedzi powstałe podczas testu silnika indukcyjnego bez obciążenia. Przedstawiono jakościową analizę wyników i podkreślono istotny wpływ falownika na straty w miedzi. (**Wpływ wyższych harmonicznych na straty miedzi w silniku i jego charakterystykę pracy**)*

Keywords: high order harmonics, motor copper losses, operating characteristics, impact
Słowa kluczowe: wyższe harmoniczne, straty miedzi w silniku, charakterystyki pracy, wpływ

Introduction

Nowadays the effects that power electronics cause on the power quality, and also on the operation of the induction motors can no longer be ignored. This is due to the increased use of power electronics, but also due to the feedback effects of the power grid. For that reason, the analysis of the high order harmonics that occur in induction motors is of great importance for the electric power industry [2]. Induction motors are electrical machines that are usually designed to operate at a nominal sinusoidal voltage. Because of this, any distortion of the voltage waveform and the presence of high order harmonics impact on their operation and efficiency. Thus, voltage harmonics increase the power losses in the magnetic circuit of the induction motors, while current harmonics increase the power losses in their windings. These increased power losses contribute to additional heating of the electric machine, thereby reducing its life. Therefore, there is no doubt that the presence of higher harmonics should be subject to a more detailed analysis.

Theoretical basis

It is well-known from the theory that any non-sinusoidal waveform can be equivalent as a sum of multiple sine waveforms with different frequency, according to Fourier analysis. In that direction, non-sinusoidal voltages and currents can be expressed as:

(1)

$$v(t) = \sqrt{2}[V_1 \sin \omega_0 t + \sum_{k=2}^{\infty} V_k \sin(k\omega_0 t + \varphi_k)]$$

(2)

$$i(t) = \sqrt{2}[I_1 \sin \omega_0 t + \sum_{k=2}^{\infty} I_k \sin(k\omega_0 t + \theta_k)]$$

where

V_1, I_1 are the fundamental voltage and current,

V_k, I_k are the k^{th} order harmonic voltage and current,

φ_k, θ_k are the phase angles of the k^{th} order harmonic voltage and current, and

ω_0, is the radian frequency of the fundamental wave.

According to the IEEE-519, the total voltage harmonics distortion factor (THD-*U*) is defined as:

(3)

$$THD_U(\%) = \sqrt{\frac{\sum_{k=2}^{\infty} V_k^2}{V_1^2}} \times 100\,\%$$

and the amount of voltage distortion due to the k^{th} order harmonic is measured by the voltage distortion factor (*VDF*) as:

(4)

$$VDF(\%) = \frac{V_k}{V_1} \times 100\%$$

Copper losses

The copper losses are given in relation of the first harmonic current component according to this relation [1]:

(5)

$$\Delta P_{js(1)} = 3R_{s(1)} \cdot I_{s(1)}^2$$

Assuming that the winding is normally composed from wiring conductors, it is clear that the skin-effect influence on stator resistance $R_s(h)$ will be insignificant [1]:

(6)

$$R_{s(h)} = R_{s(1)} + \sum_{h=2}^{N} R_{s(h)} \approx R_{s(1)}$$

The relationship based on the relative performance unit considering the harmonics influence is given as [1]:

(7)

$$p_{js,\Sigma h}(\%) = \frac{\sum_{h=2}^{N} R_{s(h)} \cdot I_{s(h)}^2}{R_{s(1)} \cdot I_{s(1)}^2} \cong \frac{\sum_{h=2}^{N} I_{s(h)}^2}{I_{s(1)}^2}$$

The total stator coper losses in respect of the harmonics are given as [1]:

(8)

$$\Delta P_{js(1)} = \Delta P_{js(1)}(1 + p_{js,\Sigma h})$$

Experimental setup

In order to confirm the great influence of higher harmonics on the operating characteristics, several experiments are conducted to a three phase squirrel cage induction motor in the Laboratory for Electrical Machines, Transformers and Apparatuses (LEMTA) at the Faculty of Electrical Engineering and Information Technologies (FEEIT). The characteristics of the equipment are given as follows:

- Three phase squirrel cage induction motor (Fig.1): Type RZK08/8, P_n=0.75 kW, U_n=380 V, I_n=2.3 A, n_n=680 rpm, f_n=50 Hz, $cos\varphi_n$=0.68
- Omni-quant instrument for power quality measurement (Fig. 2): for measuring parameters relevant to power quality. The instrument measures phase and line voltages and currents, active, reactive and apparent power, total voltage and current harmonic distortion, power factor, harmonic spectrum up to 50th harmonic etc. The computer connection is enabled through RS485 interface and Damon software. Other characteristics are given in Table 1.
- SINAMICS G120 C inverter, input 3AC 400-480 V±10%, 5.5 A, output 0-480 V, I_n =4.1 A, motor 2 hp

Table 1. Omni-quant instrument characteristics

Current measurement	Voltage measurement (max 500 V~phase voltage)
Power ~0.2 VA	Power ~0.1 VA
Rated current at X/5 A (X/1 A) 5 A (1 A)	Phase voltage range 50-500 V~
Current limit 6 A	Line voltage range 90-870 V~
Overloading (1s) 60 A	Rated frequency 15-180 Hz
	Input impedance 2 MΩ/phase

The experiments conducted in this study (Figure 3) consist of three different cases:

- No load test in order to evaluate iron losses when the induction motor is fed by invertor according to the IEC standards
- No load test in order to evaluate iron losses when the induction motor is connected to the grid by the help of three phase autotransformer according to the IEC standards
- Measuring parameters relevant to power quality when the induction motor is directly connected to the grid at the rated voltage

Fig.1. Three phase squirrel cage induction motor

Fig.2. Omni-quant instrument for power quality measurements

Fig.3. Experimental setup in LEMTA

Results of the measurements from the short-circuit test

The stator winding resistance was measured by the help of a Wheatstone bridge and found to be 0.7 Ω. Based on the measured current harmonics, the stator copper losses of the motor are determined. From the short-circuit test in laboratory conditions at reduced voltage, the total power losses were obtained. All parameters relevant to power quality such as phase and line voltages and currents, active, reactive and apparent power, total voltage and current harmonic distortion, power factor, harmonic spectrum up to 50th harmonic were obtained during the measurements by the Omni-quant instrument.

- Impact on the copper losses

For the same supply voltage that is applied to the motor, knowing the value of the resistance of the stator winding, the following results were calculated for the copper losses:

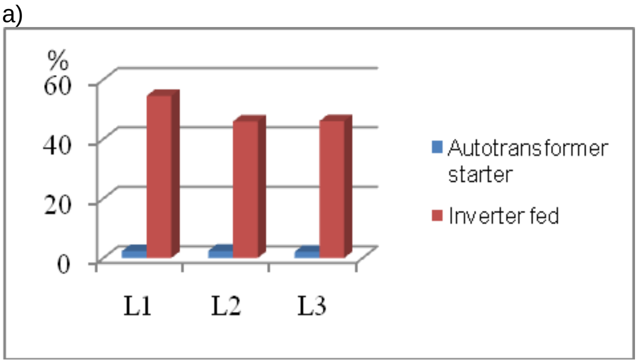
- P_{sc}=33,3 (W) - when induction motor is supplied from the grid by the help of an autotransformer
- P_{sc}=172 (W) - when induction motor is inverter fed

Taking into account the results, it can be seen that the total power losses in the case when the induction motor is inverter fed during the short-circuit test approximately 5.17 times higher than the power losses obtained when the motor is connected directly to the network.

- Impact on the total harmonic distortion

A huge impact of the electronic components can also be seen by the obtained results for the total harmonic distortion. As can be seen from the picture (Fig.4), the total voltage harmonic distortion increases by about 50%, while the total current harmonic distortion by about 100% in the cases when the induction motor is inverter fed. These figures clearly show that the impact of harmonics occurred in the motors for each of the phases (L1,L2 and L3) should not be neglected.

a)



b)

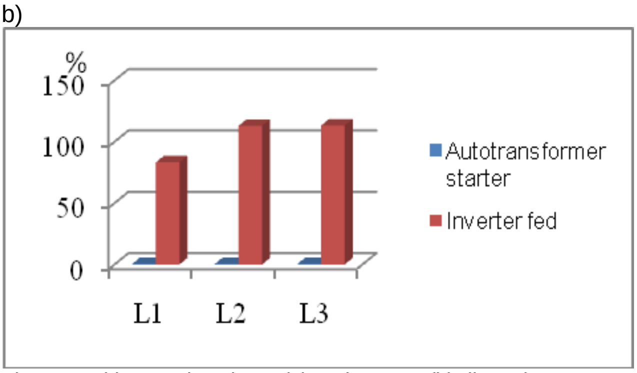


Fig. 4 Total harmonic voltage (a) and current (b) distorsion

Figure 5 shows the operating characteristics *P*=f(*U*) obtained from short-circuit test for each of the two regarded cases: once when the induction motor is fed using an autotransformer, and another when the motor is fed using an inverter. A huge difference can easily be seen in terms of the values of the power in both cases, which should not be overlooked for sure.

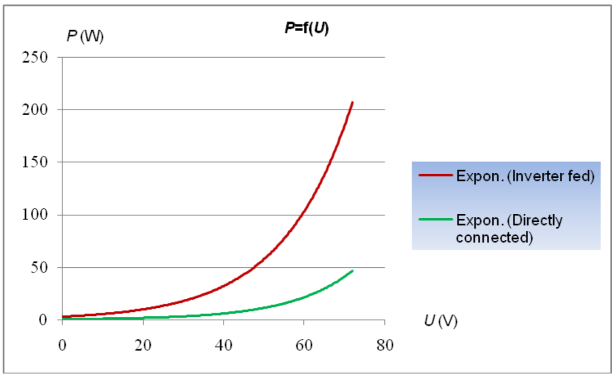


Fig. 5 . *P-U* characteristic curve

Results obtained from the no-load test

It is experimentally confirmed that voltage harmonics have a different impact depending on the different cases: when induction motor is connected directly to the grid, by the help of an autotransformer, or by the help of an inverter. In order to compare their influence for each of the three different cases, the induction motor is connected to the rated voltage of the network (U_n=400 V) for each of the three cases. The results obtained from the measurements are shown in Table 2 for each harmonic order (O). The spectrum of voltage harmonics for each phase is shown in Figures 6, 7 and 8, respectively. It can be noted that the third voltage harmonic when the induction motor is inverter fed has a dramatically higher value compared to the harmonics of the same order in the other two cases.

Table 2. Voltage harmonics

O	%of Fundamental								
	Directly connected			*Autotransformer*			*Inverter fed*		
Ph	L1	L2	L3	L1	L2	L3	L1	L2	L3
2	0	0	0	0.02	0.01	0.02	0	0	0
3	3.75	3.55	3.9	0.07	0.6	0.36	22	19.8	22
4	0	0	0	0.01	0.01	0.01	0	2.4	0
5	1.25	1.33	1.25	1.22	1.58	1.23	0	0.09	0
6	0	0	0	0.01	0	0.01	0	0	0
7	1.3	1.33	1.16	1.29	1.36	1.26	0	0.02	0
8	0	0	0	0.01	0.01	0.01	0	0	0
9	0.02	0	0	0.19	0.37	0.3	0.14	1.9	1
10	0	0	0	0	0	0	0	0.04	0
11	0.5	0.3	0.41	0.58	0.59	0.59	0	0	0
12	2.18	2.25	2.33	0.01	0	0	0	0	0
15	0	0	0.05	0.04	0.14	0.17	0	0.2	0
17	0.15	0.12	0.17	0.24	0.2	0.27	0	0.06	0

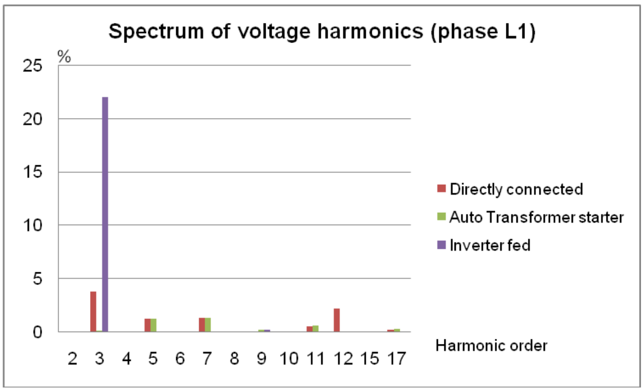


Fig. 6 Spectrum of voltage harmonics (phase L1)

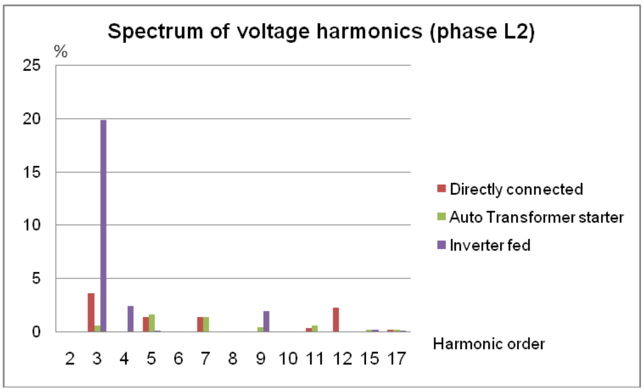


Fig. 7 Spectrum of voltage harmonics (phase L2)

The impact of the inverter can also be seen from the total harmonic voltage and current distortion, as shown in Figure 9 and 10, respectively. Table 3 gives the values of the total harmonic voltage distortion for each of the cases. It can be noticed that the inverter fed induction motor is accompanied by the value of the total voltage harmonic distortion that is about five times higher than the other cases. Since the iron losses in the motor depend on the square of the voltage, it is clear that the inverter contributes significantly to their increase.

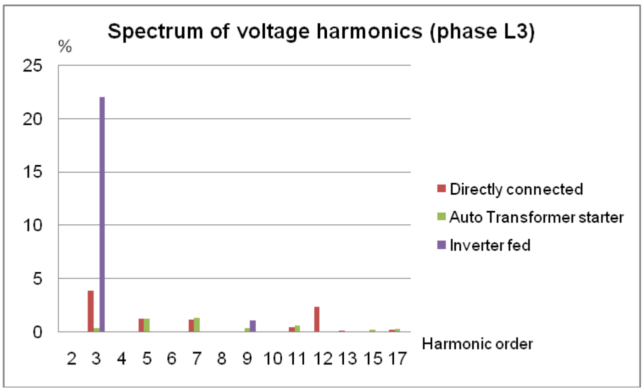


Fig. 8 Spectrum of voltage harmonics (phase L3)

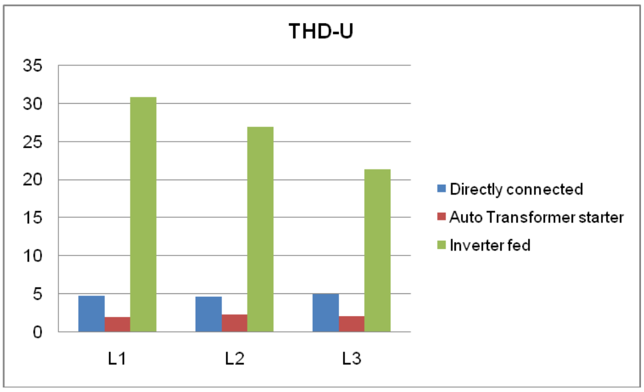


Fig. 9 Total harmonic voltage distortion (THD-U)

Unlike the voltage total harmonic distortion, the current harmonic distortion is observed not to vary over a large range (Figure 10). This is due to the origin of current harmonics. It can be noticed that the total current harmonic distortion is higher when the induction motor is fed directly to the network, and lower when an inverter is used.

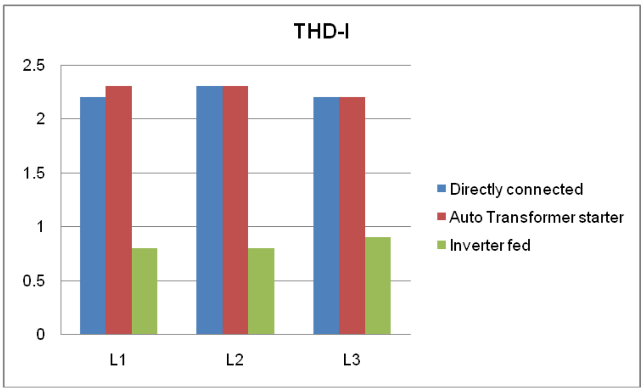


Fig. 10 Total current voltage distortion (THD-I)

Table 3. Total harmonic voltage distortion

Phase	Total Harmonic Voltage Distorsion		
	Directly connected	Autotransformer	Inverter fed
L1	4.7	1.9	30.8
L2	4.6	2.2	26.9
L3	4.9	2	21.29

Table 4. Total harmonic current distortion

Phase	Total Harmonic Current Distorsion		
	Directly connected	Autotransformer	Inverter fed
L1	2.2	2.3	0.8
L2	2.3	2.3	0.8
L3	2.2	2.2	0.9

Conclusion

From the results it can be concluded that the application of the induction motor in different circumstances can greatly affect both its working characteristics and power losses. Of course, if these impacts are not taken into account, the induction motor may be damaged as a result of the unexpected power losses that would occur in some cases. That is one of the main reasons why a qualitative analysis of the different cases has been made, which will enable the proper use of the right induction motor in the right cases. In the end, the main purpose of this paper is to motivate industries and companies to pay attention on the motor that they will decide to use for their purposes, but also on the method that they will choose to start and control the motor. In this way, they will not only save huge financial resources, but also contribute to a better living environment and lower electricity consumption.

Authors: *Research and teaching assistant MSc Ivan Temelkovski, Faculty of Electrical Engineering and Information Technologies, Ss. Cyril and MethodiusUniversity in Skopje, Institut of electrical machines, transformers and apparatuses ul.Rugjer Boshkovich 1000 Skopje E-mail: ivant@feit.ukim.edu.mk; prof.dr inż.Goran Rafajlovski, Faculty of Electrical Engineering and Information Technologies, Ss. Cyril and Methodius University in Skopje, Institut of electrical machines, transformers and apparatuses ul.Rugjer Boshkovich 1000 Skopje E-mail: goran@feit.ukim.edu.mk, prof.dr inż.Goga Cvetkovski Faculty of Electrical Engineering and Information Technologies, Ss. Cyril and Methodius University in Skopje, Institut of electrical machines, transformers and apparatuses ul.Rugjer Boshkovich 1000 Skopje E-mail: gogacvet@feit.ukim.edu.mk, prof.dr inż.Mihail DIgalovski, Faculty of Electrical Engineering and Information Technologies, Ss. Cyril and Methodius University in Skopje, Institut of electrical machines, transformers and apparatuses ul.Rugjer Boshkovich 1000 Skopje E-mail: mihaild@feit.ukim.edu.mk*

REFERENCES

[1] Otýpka J., Pečínka P., Orság P., Stýskala V., "*The Influence of Nonharmonic Voltage Source on Losses in Induction motor*", Conference paper 2017, DOI: 10.1109/EPE.2017.7967246
[2] Y.Birbir and S.Nogay, "*Voltage and Current Harmonic Variations in Three-phase Induction Motors with Different Stator Coil Pitches*", International Journal of Energy, Issue 4, Vol. 1, 2007
[3] Mihail Digalovski, Krste Najdenkoski, Goran Rafajlovski, *"Impact of current high order harmonic to core losses of three-phase distribution transformer"*, Proceedings of EUROCON 2013 (IEEE, Region 8), pp. 1531-1535, Zagreb, Croatia.
[4] L.Tomasz and R.Michal, "*Influence of Higher Harmonics on Losses in Induction Machines*", Technical Transcations Electrical Engineering, DOI:10.4467/2353737XCT.16.262.6061
[5] M.Jiang, J.Tian, H.Hwang Goh, J.Yi, S. Li, D.Zhang , T.Wu, "*Experimental study on the influence of high frequency PWM harmonics on the losses of induction motor", 2022 International Conference on Energy Storage Techno*logy and Power Systems (ESPS 2022), February 25–27, 2022, Guilin, China
[6] Popa G., Deaconu S., Dinis C., Iagăr A., "*Analysis and Simulations of Three-Phase Uniform Charge Power Sources with Current Harmonic Decrease*", International Review of Electrical Engineering (I.R.E.E.)
[7] Ulinuha A., Sari E., "*The influence of harmonic distortion on losses and efficiency of three-phase distribution transformer*", ICETIA 2020, Journal of Physics: Conference Series, 1858 (2021) 012084