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POWER QUALITY INDICES OF SIX–PHASE ASYNCHRONOUS MOTOR DRIVE PROTOTYPE

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Abstract: The multiphase electric drives are of interest in fields where reliability and higher torque are guiding criteria, especially important in electric traction. In this paper a six–phased asynchronous machine electric drive for traction systems is analyzed for power quality indices. The driving factors for analysis of viability of such systems are dynamic properties and efficiency. Efficiency is a complex measure for electric systems, such as the asynchronous motor is designed to work with perfectly sinusoidal waveforms of voltages and currents, an impossible fact for variable speed and torque mechanical loads, where power converters are necessary to drive the motor. The part of drive efficiency that will be the center of this study is the power quality indices of the designed prototype multiphase electric drive. Specifically, how much distortion is to be expected in a variable speed drive comprised of six–phased asynchronous motor with scalar control, and how will it affect the active power that drives the load. The tools to determining the harmonic distortion and impact on the power quality, and subsequently on energy transfer efficiency, are also calculated numerically. The current standards that reflect this analysis are the IEEE Standards 1459–2010 and 519–2014, and the European equivalent IEC 61000–3–6, which all rely on the Fast Fourier Transform to decompose the waveform. The main limitation of this method is the applicability to steady signals. The real active power will then be deduced from the current and voltage harmonic distortions to determine the efficiency of power transfer to the electric drive.
Keywords: power quality, power factor, six–phase induction motor, fast Fourier transform, modeling

1. INTRODUCTION

Novel traction methods and diagrams are still researched to reach a better efficiency, reliability, and sustainability [1, 2]. Most common solution for electric traction is currently the induction motor, and the multi–phase induction motor drives are a common topic to improve the traction[3, 4].

A topic that was less discussed is the six–phsae induction motor drive efficiency of power transfer(6PIMD) [5] – a topic of power quality (PQ) and electromagnetic compatibility (EMC). Some research has been done to analyze the PQ of 6PIMD, such as the functioning of the six–phase induction motor in fault conditioning[6].

The criterion of PQ that determines the efficiency of power transfer is the power factor. The concepts that facilitate the understanding of powers in three–phase systems are generally related to the classic active, reactive, and apparent power [7]. Because power electronics generate many harmonics, both in the supply network and in the motor itself, a more thorough research part in electric drives is necessary to include the distorting power [8]. A distorting powers analysis is necessary to determine the power transmitted through high order harmonics that affects the efficiency of power transfer from supply to mechanical load, and the coexistence of the electric drive with the supply network.

The goal of this research is to analyze the current and voltage waveforms, and subsequent power calculations in the sparce research area of multi–phase drive EMC analysis in transient mechanical states. The modeled drive was previously determined by the research team [4], and calculations were already presented in the distortions of the electric drive [5]. This paper develops on the power PQ analysis of the 6PIMD into the powers and power factors for each phase of the motor, since a unified and accepted theory does not exist for multi–phase systems. The instrument for decomposing the voltage and current signal is the Fast Fourier Transform, and subsequent power calculations are done according to the universally accepted IEEE 1459–2010 standard [9].

2. MODELING

The electric drive is driven by a test motor, designed for 2.2 kW output power, to connect to a six–phase voltage source of 220V. This is the motor design that will first be prototyped before prototyping the higher necessary power for urban traction. The designed 6–phase induction motor drive was modeled in Figure1. The modeled system supplies DC voltage to the six–phase inverter, built on half–bridge topology, creating a voltage source inverter. The motor data are presented in table1. The system specifics that are simulated are presented in table2.

The modeling output are electrical (Figure 2) and mechanical (Figure 3) parameters. The electrical parameters voltage and current are isolated for a single–phase, later the calculations were done on all six phases. The dynamic proprieties of the 6PIMD show that the model is viable (Figure 3), with an acceptable response of torque, while a slight decrease in rotor angular velocity is present when the torque reference reaches the step variation.

Table 1. Main data of induction motor

Rated power, kW	2.2
Rated phase voltage, V	220
Rated supply frequency, Hz	50
Rated phase current, A	6.1
Phases	6
Pairs of poles	2

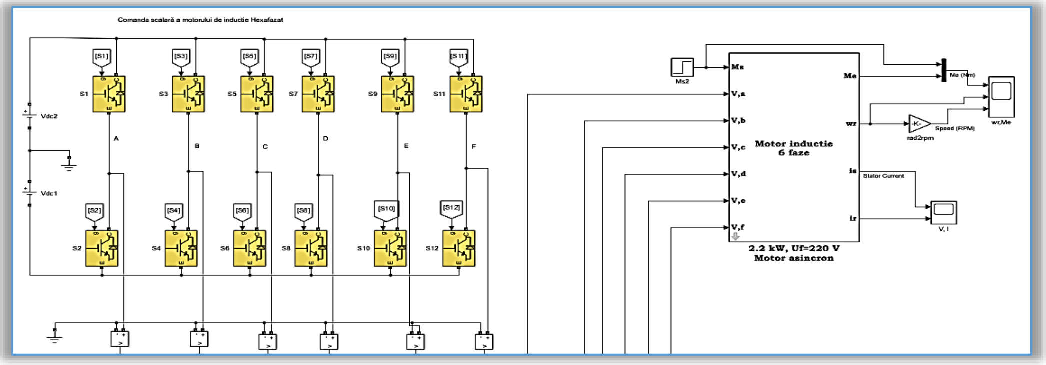

Figure 1. Sis–Phase Electric Drive Model

Table 2. System description

Control	U/f scalar control
PWM	Lead–edge
Switching frequency	20 kHz
Load	Step load
Signal decomposition method	FFT
Power calculation method	IEEE 1459–2010 + Budeanu theory

Table 3. Identified periods in the starting of the 6PIMD

Stage	Time period
Tranz 1	1 – 1.02 s
Tranz 2	1.02 – 1.04 s
Tranz 3	1.04 – 1.06 s
Steady	1.06 – 1.08 s

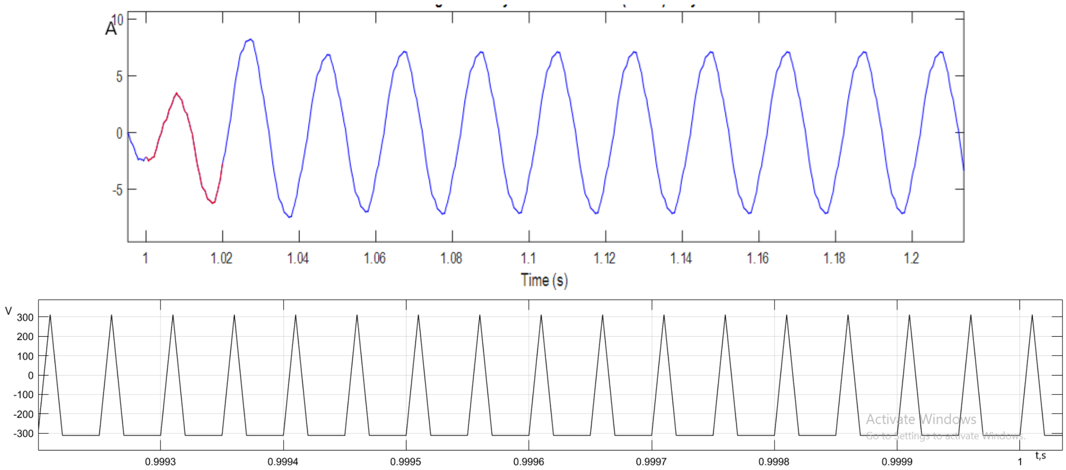

Figure 2. Top – Singhe phase current of the 6 PIMD, Bottom – Singhe phase voltage of the 6 PIMD

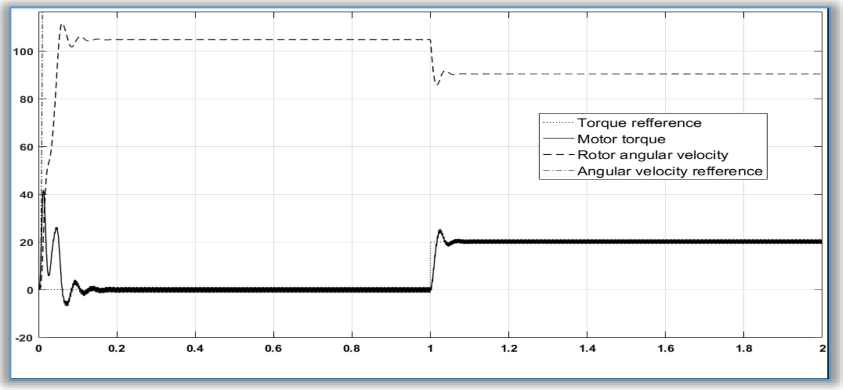

Figure 2. Mechanical characteristics of the 6PIMD

From Figure2, 4 characteristic stages in the evolution of the current were identified for subsequent calculations. Due to the limitations of the FFT calculation method, the stages were divided in periods (table 3).

From the identified evolution stages the powers and distortion calculations will be done on the most distorted stage, Tranz 1. In the following chapter the methodology of calculation is presented, alongside the results.

3. DISTORTIONS AND POWER CALCULATIONS

Reactive power is considered as the main component of power theory to distort the PF from optimal values. Though the mathematical principles are simple to understand, as stated below, reactive power alone cannot determine distorted systems. A comprehensive study on the power theory, problems, and their improvement was done in [7].

The standard IEEE 1459–2010 conforms to a simplified calculation for sinusoidal waveforms. It starts that with the instantaneous power is the product of instantaneous values of current and voltage, reaching the value of PF (1–8). The definitions issued by the Romanian Academician Constantin Budeanu in 1927 for reactive and fictitious (distorting) powers were used when obtaining the generalization of the formulas used for powers calculation in the single–phase case [100]. Within this theory the powers are considered as bi–linear forms and the active and reactive powers for the case of three–phase systems with four wires are expressed as follows (for three phase systems with non–symmetrical and non–linear load)

Within this theory the distorting and apparent powers (both for the fundamental harmonic and at global level – for all harmonics) are defined, and applied to each phase separately.

$$p = vi \quad (1)$$

$$p = p_a + p_q \quad (2)$$

$$p_a = VI\cos\theta[1 - \cos(2\omega t)] = P[1 - \cos(2\omega t)] \quad (3)$$

$$p_q = -VI\sin\theta\sin(2\omega t) = -Q\sin(2\omega t) \quad (4)$$

$$P = VI\cos\theta \quad (5)$$

$$Q = VI\sin\theta \quad (6)$$

$$S = \sqrt{P^2 + Q^2 + D^2} \quad (7)$$

$$D = (V_{e1}^2 \cdot I_{eH}^2) + (V_{eH}^2 \cdot I_{e1}^2) + (V_{eH}^2 \cdot I_{eH}^2) \quad (8)$$

$$PF = P/S \quad (9)$$

where:

≡ p – instantaneous power
≡ p_a – instantaneous active power
≡ p_q – instantaneous reactive power
≡ v, i – instantaneous voltage and current
≡ V, I – RMS values of voltage and current
≡ V_a, V_b, V_c – phase voltage
≡ I_a, I_b, I_c – phase currents
≡ V_{eH}, V_{e1} – effective harmonic voltage, effective fundamental voltage
≡ I_{eH}, I_{e1} – effective harmonic current, effective fundamental current
≡ Θ – phase angle between voltage and current
≡ S,P,Q, D – apparent, active, reactive and distorting powers
≡ PF – power factor

Table 4. Current FFT decomposition results

Phase	Fundamental RMS, A	Distorting RMS, A	Total RMS, A	THD, %
i1_1	12.07	1.6	12.18	13.25
i2_1	9.83	2.37	10.11	24.16
i3_1	10.58	0.81	10.61	10
i4_1	12.07	1.6	12.18	13.25
i5_1	9.83	2.37	10.11	24.16
i6_1	10.58	0.81	10.61	10

Table 5. Voltage FFT decomposition results

Phase	Fundamental RMS, V	Distorting RMS, V	Total RMS, V	THD, %
u1_1	10.69	1.51	10.80	14.11
u2_1	8.79	2.37	9.10	26.99
u3_1	9.41	0.91	9.46	9.64
u4_1	10.69	1.51	10.80	14.11
u5_1	8.79	2.37	9.10	26.99
u6_1	9.41	0.91	9.46	9.64

Table 6. Power calculations

Phase	Active power		Reactive power		Distorting power	Apparent power		Total Power Factor
	Total	Funda.	Funda.	Total		Total	Funda.	
	kW		VAr		VArD	kVA		–
1	1.33	1.28	12.72	13.32	3.94	13.386	12.784	0.096
2	0.97	0.86	8.92	13.17	9.69	13.206	8.961	0.065
3	1.01	0.99	7.68	7.98	1.36	8.044	7.744	0.123
4	1.33	1.28	12.72	13.32	3.94	13.386	12.784	0.096
5	0.97	0.86	8.92	13.17	9.69	13.206	8.961	0.065
6	1.01	0.99	7.68	7.98	1.36	8.044	7.744	0.123

4. CONCLUSIONS

The data shows that the model symmetrized the 2 pairs of phases, thus having all data equal.

In table 5 are presented the calculated powers and power indices of the 1st transient of the 6PIMD. The fundamental active power is lower than the total, meaning there are distortions that actively heat the system.

Another factor at starting the motor is clearly defining the phenomenon of magnetization of the motor. As is normal, the reactive power necessary to create the EMF driving the motor is highly over the active power of the motor. This can also be attested in the total power factor.

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