ENERGETICAL PERFORMANCES OF SINUSOIDAL PWM STRATEGY FOR THE INDUCTION MOTOR AND VOLTAGE INVERTER SYSTEM: SIMULATION AND EXPERIMENTAL APPROACH

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Abstract **– The electric drive is a main component of industrial equipment designed for small or large complexity, because the achievement of finished goods implies the adjustable mechanical energy available at the output of the system. Because the static converters are needfull in such a system, the evolution of the converter's command sub-systems was also needful, to improve their performance. The aim of this paper is the energetical analysis of the drive system and it had been performed on an experimental stand and on it's equivalent SIMULINK model for different static operation points. It was considered feeding the asynchronous motor from an indirect voltage source static converter using the sinusoidal modulation as command strategy. Two cases had been taken into consideration: feeding the motor with the same RMS voltages and achieving the same mechanical shaft power. The global model of the drive system, created in MATLAB/SIMULINK environment, provides all the needed information in order to calculate the parameter values for comparing the energetic performances, and highlights the fact that the load torque and frequency have their influence on power quality indicators. The frequencies considered for the energetic analysis are 10Hz, 20H and 50Hz, and the load was adjusted up to the nominal value.**

The induction motor model implements the equations which considers the magnetic resistance and main field saturation with the variation of the static magnetizing inductance, depending on the magnetizing current. The following power quality indicators had been taken in to consideration: efficiency, power factor, electrical losses.

Keywords**:** *electric drive, static converter, induction motor, quality indicators, sinusoidal PWM modulation*

1. INTRODUCTION

Starting from the square-wave modulation the sinusoidal modulation appeard and improved to minimize copper losses, torque ripple, etc. Pulse width modulation (PWM) techniques used today to control the modern static converters as part of high–power machine drives, strongly depend on switching frequency of the power semiconductors.

Electromechanical drive is an essential component of technical equipments for industrial activities of high or low complexity, because obtaining the product necessitate mechanical energy available the output drive system.

2. THEORETICAL ASPECTS

2.1 The operated equipment

To obtain experimental data needed to determine the energetical performances of each modulation sinusoidal method, was used a stand type Leybold [9]. This contains (Fig. 1, Fig. 2):

- mono phase full controlled bridge rectifier;
- DC link circuit of the voltage inverter;
- three phase voltage inverter with IGBT transistors and its control modulus;
- asynchronous driving motor;
- the load (asynchronous motor of special construction and its torque control modulus);
- measurement and recording equipment (Fluke 41b analyzer and Metrix OX 7042 – M oscilloscope).

Power system components have the nominal operated data indicated below:

- Motor: P_N=250W; U_N = 230V; I_N = 1.32A;
- $\cos\varphi$ = 0.79; n_N = 1350 rot/min.
- Inverter: U_N = 230V; I_N = 10A.
- Load: P_N=250W; U_N =230V; M_N=2Nm.

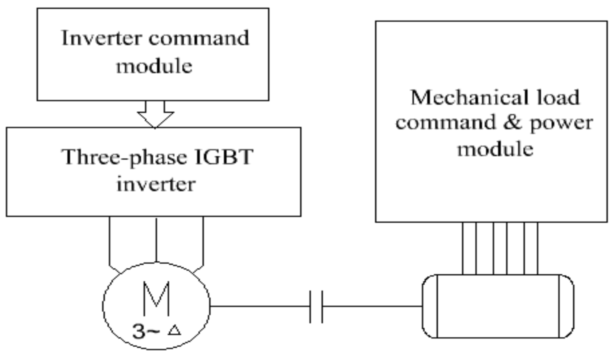

Figure. 1: The drive system block diagram

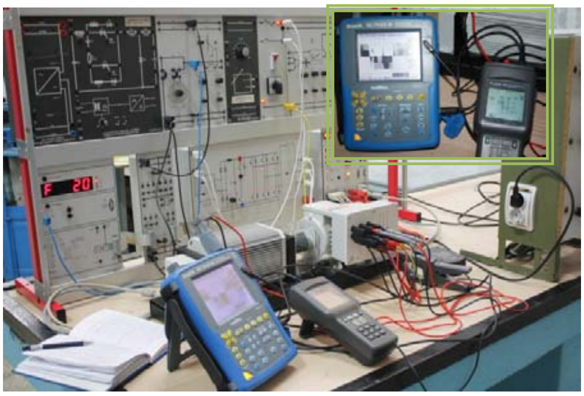

Figure. 2: The experimental workbench

To obtain experimental data required to determine the energetical performances of induction motor feeding with sinusoidal voltage and frequency in the 10Hz-50Hz interval, it was supplied by a synchronous generator (6.2kVA), in a platforme whose structure contains (Figure 3):

- one voltage and frequency static converter used to adjust the drive speed of the asynchronous auxiliary motor, respectively to adjust the given voltage frequency;
- one induction motor for driving the synchronous generator;
- asynchronous generator adjusted by excitation current to determine the actual value of the desired value;
- the load and the measuring and recording equipment used in the previous stand.

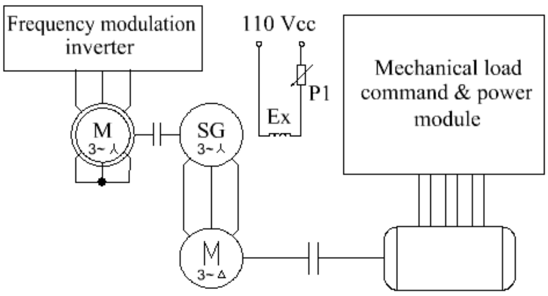

Figure 3: The stand structure for the energetical performances of induction motor supplied by sinusoidal voltage.

2.2 Sinusoidal modulation

According to the principle of pure sinusoidal modulation, the easiest type of PWM , the elements T_+ and T_- are found on the same phase of the inverter are ordered on the intervals on the one hand $u_c > u_r$ and on the other hand $u_c < u_r$.

Considering the synchronous control, odd index modulation and multiples of 3 and the optimal correlate between reference signal and command signal (u_r must have a maximum or a minimum in the middle of each u_c alternance) you can use a single reference signal for the three-phase. So, the harmonic spectral of output voltage contains only even harmonics. The voltage frequency on load is equal with command voltage frequency and RMS voltage value is proportional with the command voltage amplitude - [4],[8]

Load voltage approximation with a sinusoid is even better, as the reference voltage period is smaller in relation with command voltage period, respective as the frequency modulation factor is bigger. Through the PWM command, beside solid wave command, THD factor becomes better by reducing the low order harmonic amplitudes and increasing harmonics order of significant amplitude in relation with the fundamental.

2.3 Power quality indicators

In the completed studies, for computing the active and the reactive power, the complex aparent power theory [1] (pq theory) has been used. In the pq theory, the instantaneous complex aparent power is defined as the product of the voltage phasor ($\underline{u}$) and the complex conjugate of the current phasor ($\underline{i}^*$) - [2]:

$$\underline{s} = p + jq = \frac{3}{2}\underline{u}\cdot\underline{i}^* = \frac{3}{2}\left[u_d i_d + u_q i_q + j\left(-u_d i_q + u_q i_d\right)\right] \quad (1)$$

The real and the imaginary components of complex aparent power are:

$$p = \frac{3}{2}\left(u_d i_d + u_q i_q\right) \quad (2)$$

$$q = \frac{3}{2}\left(-u_d i_q + u_q i_d\right) \quad (3)$$

Is widely accepted that the average value of the real part p, over one period of the voltages and currents (T) gives exactly the active power P:

$$P = \frac{1}{T}\int_{t-T}^{t} p dt \quad (4)$$

It's also widely accepted that that the average value of the imaginary part q, over one period of the voltages and currents (T) gives the reactive power Q:

$$Q = \frac{1}{T}\int_{t-T}^{t} q dt \quad (5)$$

Starting from the instantaneous complex aparent power, the aparent power can be defined [5], [7], keeping true Bucholtz's formula [3]. Thus:

$$S_f = \sqrt{\frac{1}{T}\int_{t-T}^{t}\frac{U^2}{|\underline{u}|^2}|\underline{s}|^2 dt} \tag{6}$$

Where $\underline{\boldsymbol{U}}^2$ is the square RMS value of the voltage phasor modulus,

$$U^2 = \frac{1}{T}\int_{t-T}^{t}|\underline{u}|^2 dt \tag{7}$$

So, the aparent power is given by:

$$S_f = \sqrt{\frac{1}{T}\int_{t-T}^{t}\frac{U^2}{|\underline{u}|^2}\frac{9}{4}|\underline{u}|^2|\underline{i}|^2 dt} = \frac{3}{2}UI \tag{8}$$

Considering the quadrature relationship between powers, the distorsion power is defined as

$$D_f^2 = S_f^2 - P^2 - Q^2 \tag{9}$$

The power quality analisys is based on the power quality indicators [6] specified below: the power factor, the drive motor efficiency and the electrical losses.

3. EXPERIMENT PROTOCOL

Before the real-time experiments, a Matlab / Simulink model was performed and several simulation scenarios were considered. For the simulation protocol it was considered feeding the asynchronous motor from an indirect voltage source static converter for the sinusoidal modulation, and also from a three-phase sinusoidal voltage source, so the performances could be compared.

The global model of the drive system was obtained by interconnecting the models corresponding to each component of the drive system-[8].

Through the experimental protocol, the needed values to be measured in order to determine the energetic performances of the asynchronous motor has been established: phase voltage, line current (the motor is in the delta connection); active power at motor side and total power factor (all provided by the Fluke 41b analyzer), for feeding the motor at constant frequency (10, 20, and 50 Hz) and different values of the load torque (0; 0.2 ;0.4; 0.6; 0.8; 1) T_N.

The voltage RMS values corresponding to each working point has been established as follows:

In case of feeding with sinusoidal voltage, for each working point, feeding the motor with a RMS voltage value that can ensure the same mechanical power at the motor shaft as when feeding the motor with PWM voltage.

Taking into account the experimental protocol and starting from measured data for a static operating point, the other quantities needed to determine the energetic performances was calculated and the comparative analysis could be achieved.

For each operating point the waveforms of voltage and current had been recorded, and also, the following quantities: the RMS values of voltage and current, active power, rotor speed, and torque, respectively. Recorded data processing was done in Matlab (Simulink). It should be noted that power quality computing was made based on the recorded waveforms, torque and rotor speed, using Matlab Simulink models developed by the authors -[8].

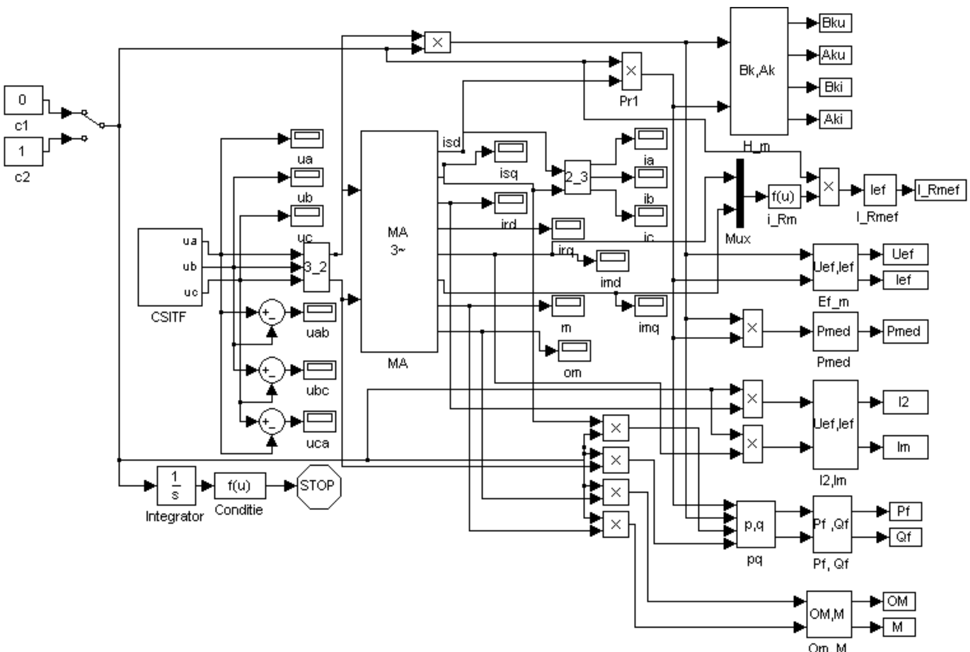

Figure 4 SIMULINK model of the drive system with asynchronous motor and voltage source inverter

4. EXPERIMENTAL RESULTS

4.1. Results based on the Matlab Simulink model of the driving system

Energetic performances were analyzed based on the model in figure 4, at the same frequency (10, 20 and 50 Hz) based on the graphical representations for the most significant power quality indices.

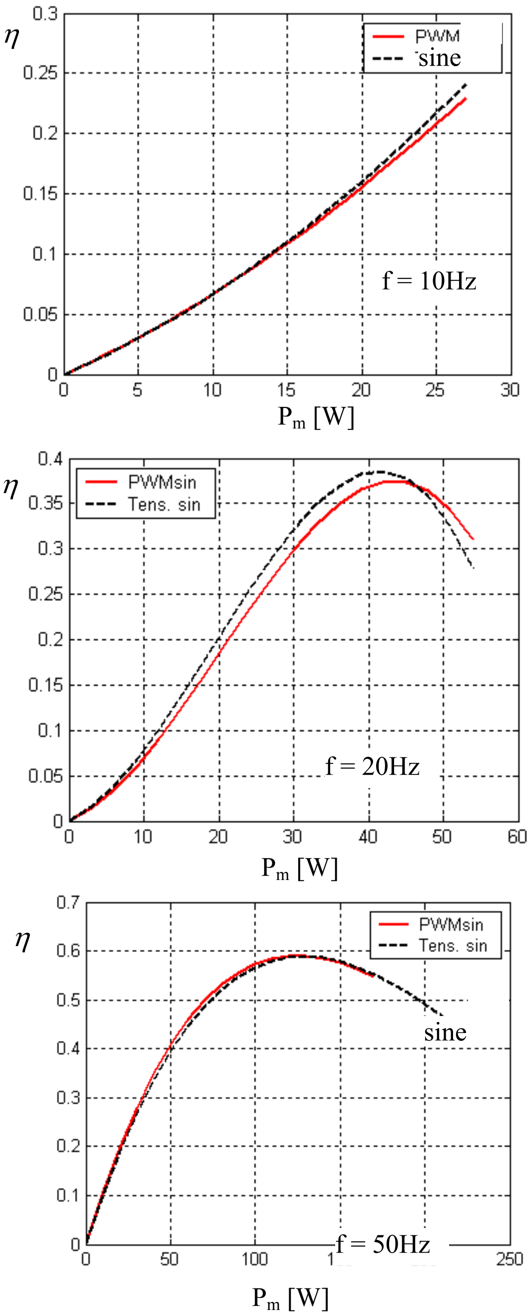

Figure 5: Effeciency depending on the mechanical power for an inverter with sinusoidal modulation and sinusoidal feeding for three command frequencies

At 50 Hz frequency (fig. 5) the efficiency corresponding to sinusoidal modulation, for all values of the mechanical power, equals the efficiency of sinusoidal voltage feeding.

The power factor depends on the inverter command frequency and as well on the mechanical power value. If for 20 and 50Hz frequency, the evolution is normal, for 10Hz it exists a local minimum and maximum close the 0.9 value.

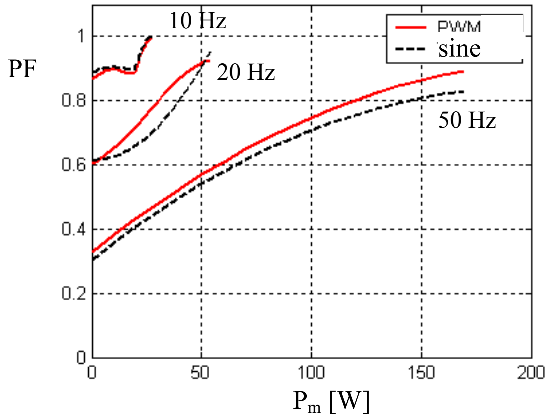

Figure 6: Power factor depending on the mechanical power for an inverter with sinusoidal modulation and sinusoidal feeding

4.2. Results based on the on-line experimental data

Energetic performances were analyzed at the same frequency (10, 20 and 50 Hz) based on the graphical representations for the most significant power quality indices.

The energetic performances obtained for the same mechanical shaft power, for the frequency of 10 Hz, when feeding the motor from the PWM voltage inverter and from the corresponding sinusoidal voltage are presented by fig. 7, fig. 8, fig. 9.

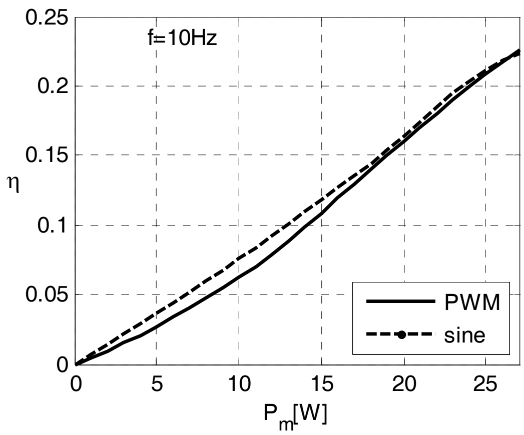

Figure 7: Efficiencies versus mechanical power

The efficiency is increased for sinusoidal voltage feeding (fig. 7), but the difference to the big loads is very small.

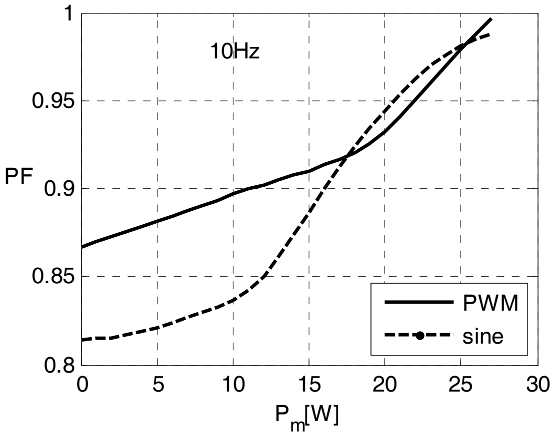

Figure 8: The power factor versus mechanical power

The power factor (fig. 8) is significantly bigger for PWM control up to approx. ½ of full load. Still, the power factor corresponding sinusoidal feeding becomes bigger, the difference decreases at high loads.

The explanation can be as the load small by feeding with PWM voltage which leads to the same mechanical performance, the equivalent circuit has a stronger resistive character.

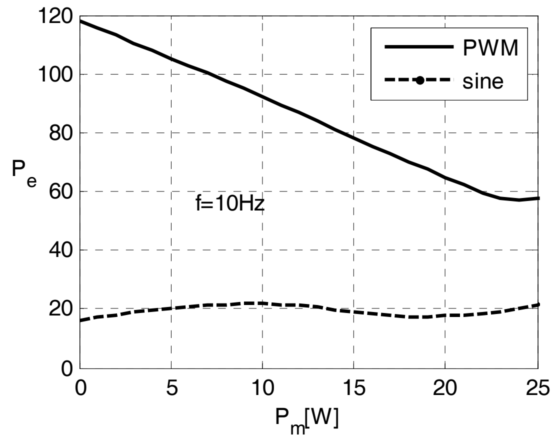

Figure 9: The electrical losses versus mechanical shaft power

The main electrical losses are much higher for the PWM control; they decrease with load increasing suggesting the motor operation in supersaturating regime.

The energetic performances obtained for the same mechanical shaft power, for the frequency of 20 Hz, when feeding the motor from the PWM voltage inverter and from the corresponding sinusoidal voltage are presented by fig. 10, fig. 11, fig. 12.

The efficiency is bigger for sinusoidal voltage feeding, but the difference to the big loads becomes smaller.

The power factor is significantly bigger for PWM control up to approx. ½ of full load after this once with the load increasing it obtain the same power factor. The explanation can be as the load small by feeding with PWM voltage which lead to the same mechanical performance, the equivalent circuit has a stronger resistive character.

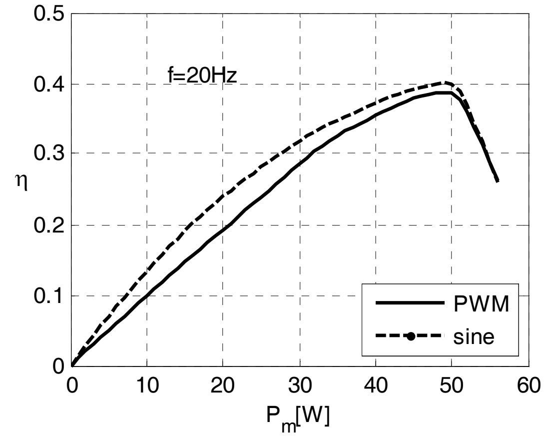

Figure 10: Efficiencies versus mechanical power

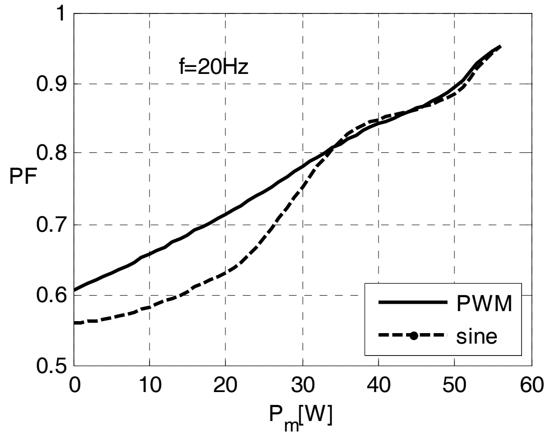

Figure 11: The power factor versus mechanical power

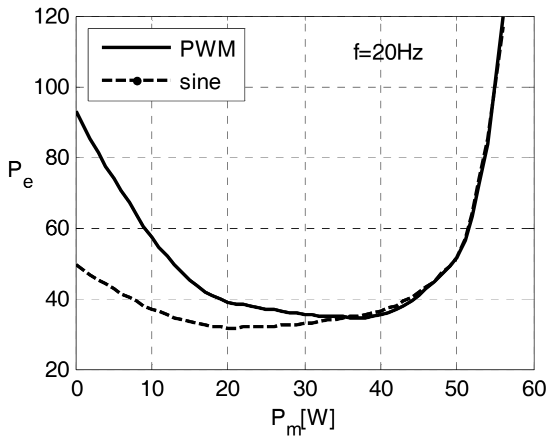

Figure 12: The electrical losses versus mechanical power

The main electrical losses, at operation at zero load are double in control PWM case and the difference decreases once with the load increase, suggesting the motor operation in supersaturating regime until approx.½ of full load at the motor loading bigger of ½ of full load they becomes equal.

The energetic performances obtained for the same mechanical shaft power, for the frequency of 50 Hz, when feeding the motor from the PWM voltage inverter and from the corresponding sinusoidal voltage are presented by fig. 13, fig. 14, fig. 15

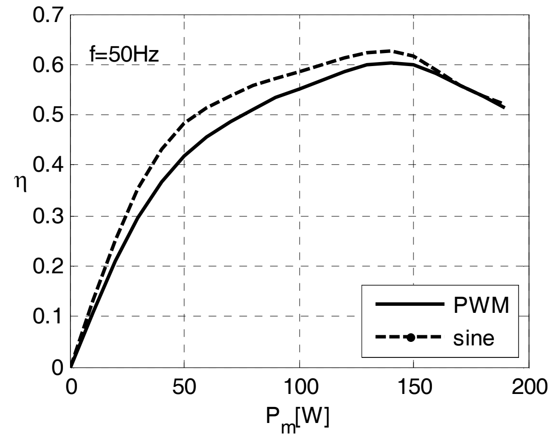

Figure 13: Efficiencies versus mechanical power

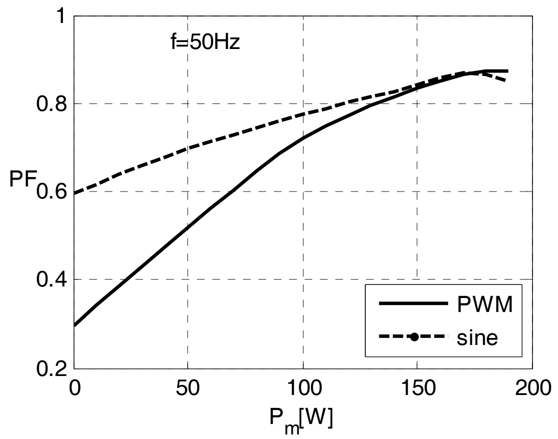

Figure 14: The power factor versus mechanical power

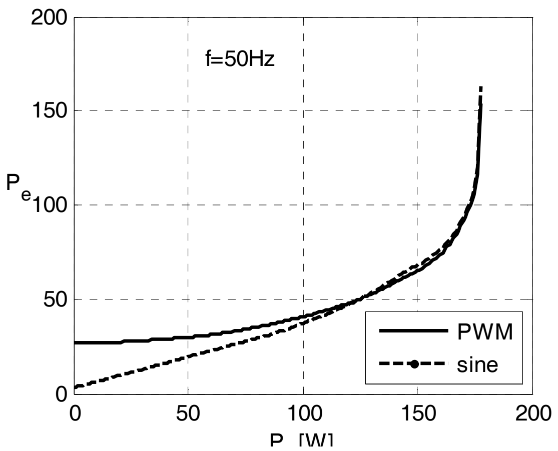

Figure 15: The electrical losses versus mechanical shaft power

The efficiency obtained is better than the sinusoidal feeding (fig. 13) decrease reducing by interval ends.

The power factor (fig. 14) is significantly increased for the sinusoidal feeding than at the control PWM, until to approx 3/4 of full load then once with the load increasing obtain the same power factor.

The main electrical losses (fig. 15) are sensitive higher for feeding with PWM voltage at load until 1/2 of rated load, after which they are comparable.

The energetic performances obtained for the same RMS voltage value, for the frequency of 10 Hz, when feeding the motor from the PWM voltage inverter and from the corresponding sinusoidal voltage are presented by fig. 16, fig. 17, fig. 18.

When feeding the motor with the same RMS voltage, the dependences between the efficiency and the mechanical shaft power are overlapped, suggesting the fact that the two regimes are equivalent.

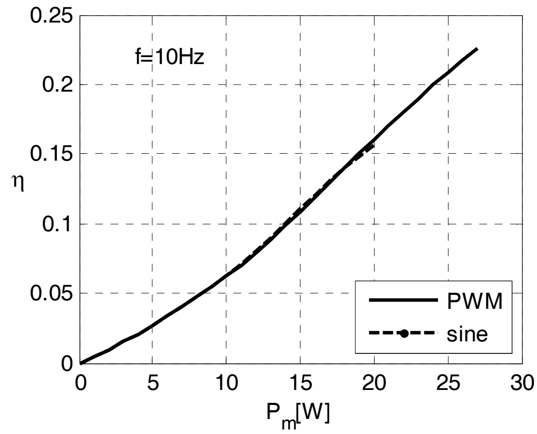

Figure 16: Efficiency versus mechanical shaft power

It can be seen that the power factor is higher when feeding the motor with sinusoidal voltage, and this difference increases even more at high loads.

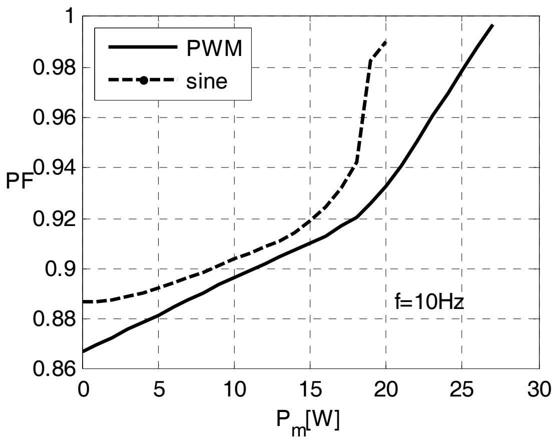

Figure 17: The power factor versus mechanical shaft power

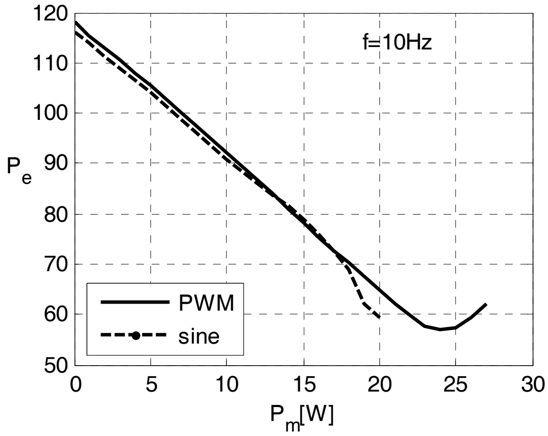

Figure 18: The electrical losses versus mechanical shaft power

The difference between the resulted electrical losses for the two cases is almost zero, making the two cases equivalent.

The energetic performances obtained for the same RMS voltage value, for the frequency of 20 Hz, when feeding the motor from the PWM voltage inverter and from the corresponding sinusoidal voltage are presented by fig. 19, fig. 20, fig. 21.

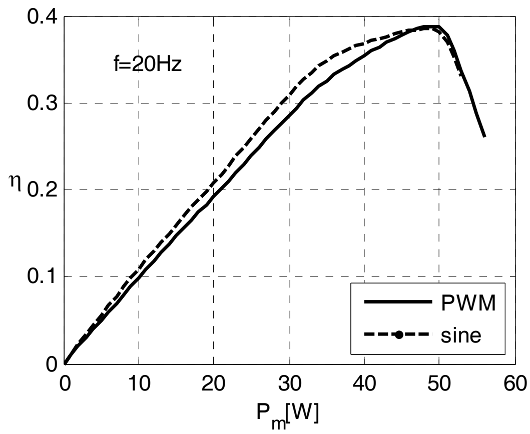

Figure 19: Efficiency versus mechanical shaft power

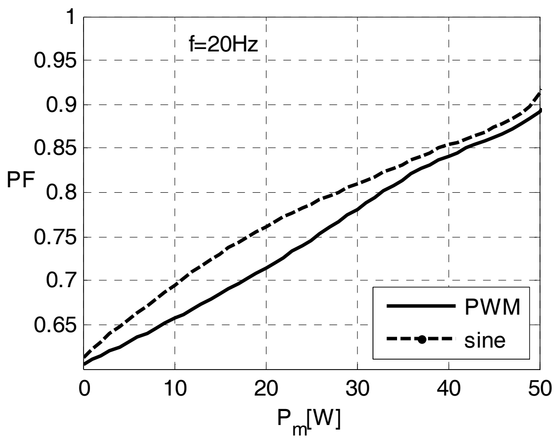

Figure 20: The power factor versus mechanical shaft power

It can be observed a slightly superior efficiency for the sinusoidal voltage feeding than for the PWM voltage.

When feeding with sinusoidal voltage, the power factor is higher compared to the PWM voltage feeding, but, at higher loads the two factors are about the same value.

The total electrical losses are almost equal at low values of the load, and at higher load values, the PWM losses are lower.

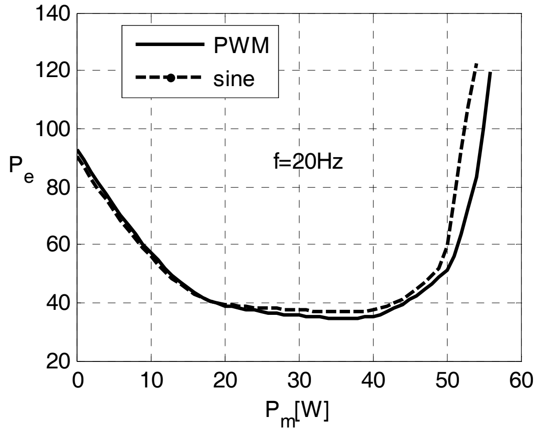

Figure 21: Electrical losses versus mechanical power

The energetic performances obtained for the same RMS voltage value, for the frequency of 50 Hz, when feeding the motor from the PWM voltage inverter and from the corresponding sinusoidal voltage are presented by fig. 22, fig. 23, fig. 24.

In this situation, it can be seen that the two efficiencies are overlapped throughout the load variation interval.

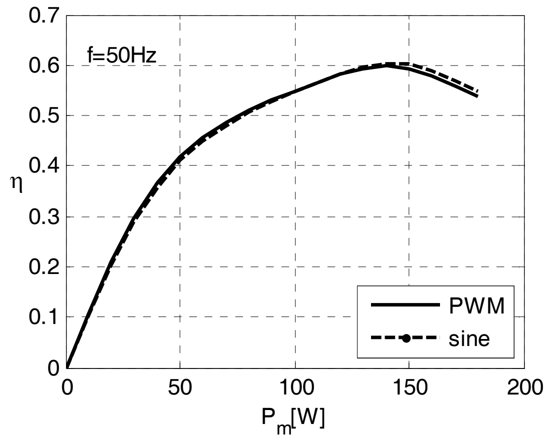

Figure 22: Efficiency versus mechanical shaft power

The difference between the sinusoidal voltage feeding power factor and the PWM voltage feeding power factor (fig. 23) is also negligible over the entire load interval. The total losses for the sinusoidal voltage feeding are approximately equal to the total losses corresponding to the PWM voltage feeding, observing still a slight superiority of the PWM modulation over sinusoidal voltage.

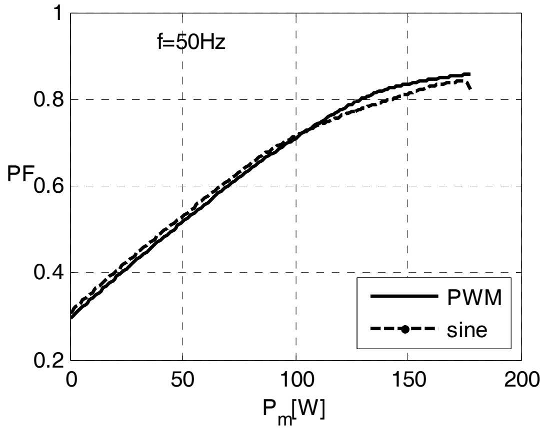

Figure 23: The power factor versus mechanical shaft power

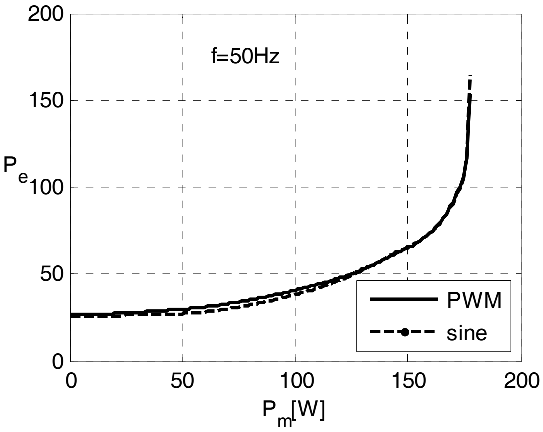

Figure 24: Electrical losses versus mechanical power

5. CONCLUSIONS

For the nominal frequency, it shows that for feeding the motor with the same RMS voltages, the same efficiency is obtained. When the same mechanical shaft power is obtained, the PWM efficiency is smaller until 80% of the rated power. The efficiency dependence keeps the clasic shape, reaching the peak value at 73% of the nominal torque.

When obtaining the same mechanical power, the efficiency difference is maximum (about 15%) at 20% of the rated power, while, when feeding the motor with the same RMS values, the efficiency difference is minor. The power quality indicators revealed their dependence of the load torque at constant frequency, and of frequency at constant torque, respectively.

For all studied frequencies, we remark the fact that the efficiency is higher when feeding with sinusoidal voltage, but at higher loads, the difference becomes very small. At low frequency, a good power factor is achieved for the PWM control until 60% of full load.

At 50 Hz a better power factor results for the sinusoidal voltage feeding for all the load range.

For all the three cases, the electrical losses are higher for the PWM voltage feeding, yet the difference decreases with increasing load suggesting motor operation in suprasaturation regime. The experimental results confirm the simulation results, for the case of the same RMS voltage feeding, regarding the efficiency, but this matching is less true for the power factor.

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