ENERGETIC PERFOMANCES SIMULATION OF A TECHNOLOGICAL LINE COMPOSED BY ASYNCRONOUS MOTORS, POWERED UP IN HARMONIC REGIME

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Abstract - This paper presents an improved mathematical model, to calculate power and energy losses within asynchronous machine(ASM) which operates in harmonic regime(HR) and respectively the simulations done on presented model basis on technological lines(TL) composed by asynchronous motors with known characteristics, made in Romania. After a brief review of some aspects regarding operation of ASM in HR, in the second part of the paper is presented the algorithm and mathematical model applied on energetic performances simulation of ASM which operates in HR. The third part presents the result of simulations done based on mathematical model to a known structure power consumer, respectively S.C. „CONGIPS" S.A. from city of Oradea. The last part of the paper expresses the resulted conclusions of the analysis.

Keywords: asynchronous machine, technological line, harmonic regime, simulation, power losses.

1. INTRODUCTION

It is well known the fact the HR have a number of negative effects, both on electrical equipments and on power distribution networks. The main negative effects of the existence of HR are:

- increases of power losses(into conductive materials, magnetic materials and dielectric materials);
- the appearance of over-voltages(resonance on some voltage harmonics, the increase of neutral point voltage potential at Y connection of transformers or other types of power consumer);
- the appearance of over-currents (current resonance, overload of null circuit of three-phase power network).

Asynchronous machine (ASM) is a power consumer with important share within power consumer's category so the matter of electrical energy (EE) quality in power networks where they are present, represents a important concern with high impact. The main negative effects of HR on rotary machines and implicitly on ASM are:

- the increase of winding and magnetic core temperatures, caused by additional power losses in conductive and magnetic materials;
- changes of electromagnetic torque of ASM, leading to efficiency reduction of it;
- the appearances of torque oscillations at ASM shaft, leading to materials ageing and additional vibrations;
- changes of magnetic induction in ASM air gap, due to higher order harmonics;
- interaction between magnetic flux determined by fundamental harmonic and magnetic flux of high order harmonics.

Effects regarding additional power losses are considered slightly more important because it influences directly the power energy consumption, at consumer's level.

In field literature there are a number of HR and additional power losses in HR calculation analysis methods [1, 2] and respectively a number of concerns regarding the operation of ASM in HR analysis [3, 4, 5, 7, 8].

The model presented below is based on harmonic effects superposition principle [6] respectively harmonic components method [6], as it described on [8, 9], to which has been applied power losses correctional coefficients established through experiments [8, 10]. Basically for each power losses component a correctional factor has been established. These correctional factors have been determined either by calculations [8] or measurements [10]. This approach allows us to imprint a practical character to the considered model.

2. MATHEMATICAL MODEL

To evaluate energetic performances of ASM operating in HR, it's required to establish power losses separated by types (active, reactive) and by ASM components (in magnetic core, in windings, mechanical). The analysis of HR influence on energetic performances of ASM implies comparative evaluation of power losses in reference regime (RR) and in the considered HR.

For operative determination, industrial, of power losses in ASM operating in HR, it must be known the following initial elements:

- Rated parameters of ASM: rated power and current, rated voltage and frequency, efficiency, rated speed, rated power losses in windings and in magnetic core, mechanical losses;
- Characteristics of HR: maximum order of harmonics taken into consideration, voltage and current harmonic amplitudes, up until the maximum order chosen;
- Characteristics of ASM operation service: values of relative torque and time of operation at these values of torque;

To evaluate the energetic effects of ASM working in

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RR and HR and in order to be able to make the simulation the following mathematical model will be used, which will be presented as follows. Within this model the following are assumed to be known:

❒ rated parameters of ASM;

❒ rated active power losses in sinusoidal and symmetrical regime, at rated values of effective voltage and frequency, separated by categories: in windings (ΔP_{Wn}), in magnetic circuit(ΔP_{Fn}), mechanical(ΔP_{Mn}) and additional(ΔP_{Sn}).

The following assumptions are admitted:

❒ magnetic circuits saturation is neglected;

❒ variation of magnetic circuits resistance due to skin effect is neglected;

❒ ASM air gap is considered to be uniform;

❒ mutual inductivities between stator and rotor circuits varies sinusoidal with rotor position;

❒ at working voltage of ASM power losses in dielectric are neglected

2.1. Active power losses (APL)[8, 9]

➢ **APL in ASM windings** are expressed with the expression:

$$\Delta P_W = m^2 \cdot \Delta P_{Wn} \cdot \left(1 + k_{Di}^2\right) \cdot k_{\Delta P_W} \tag{1}$$

where $m = M_R/M_n$ – relative torque of ASM;

M_n - ASM rated torque;

$k_{DI} = \dfrac{\sqrt{\sum\limits_{\nu \geq 2} I_\nu^2}}{I_1}$ - distortion coefficient of current or current total harmonic distortion THD_I;

$k_{\Delta P_W}$ - is correctional coefficient of APL in windings;

ν is harmonic order.

➢ **ALP in ASM magnetic core** are determined with expression:

$$\Delta P_F = \Delta P_{Fn} \cdot \left(1 + k_{DF}\right) \cdot k_{\Delta P_F} \tag{2}$$

where:

$k_{DF} = \sum\limits_{\nu \geq 2} \left(\dfrac{U_\nu}{U_1}\right)\left(\dfrac{1}{\nu}\right)$ - addition factor of APL in magnetic core of ASM operating in HR;

$k_{\Delta P_F}$ is correctional coefficient of APL in magnetic circuit.

When expression (2) has been written we considered that $U_1 = U_n$ and $f_1 = f_n$.

➢ **Mechanical and additional power losses**

These two types of losses are dependent on slip.

For a quick evaluation of slip (s), at a given value of relative load (m) and under HR conditions, we will admit the specific assumptions of Kloss formula [11], valid for medium and high power ASM to which this analysis is justified. In order to estimate HR effect on slip and therefore the two power losses categories, we propose the application of a iterative calculation, as follows:

❒ First it is considered:

$$\frac{s_1}{s_n} = \frac{M_R}{M_n} = m \Rightarrow s_1 = s_n \times m \tag{3}$$

❒ It is calculated [12]:

$$s\nu = \begin{cases} 1 - \dfrac{1 - s1}{\nu}, \text{ for } \nu = 3p + 1 \\ 1 + \dfrac{1 - s1}{\nu}, \text{ for } \nu = 3p - 1 \end{cases} \tag{4}$$

❒ Electromagnetic torque correspondent to ”ν” harmonic order can be expressed in the same way like electromagnetic torque correspondent to fundamental harmonic:

$$M_{e\nu} = m_1 \cdot \frac{R_2^{'}\left(I_{2\nu}^{'}\right)^2}{S_\nu \cdot \Omega_\nu} = M_{e1} \cdot \frac{\left(\dfrac{I_\nu}{I_1}\right)^2}{\nu \cdot \dfrac{s_\nu}{s_1}} \tag{5}$$

where: m_1 – phase number of stator;

$I_{2\nu}$ – rank ν component of rotor current reduced to stator;

I_{21}- fundamental harmonic of rotor current reduced to stator;

R_2 – one-phase rotor winding resistance, reduced to stator;

Ω_1 –synchronism angular speed of stator magnetic field.

❒ Electromagnetic torque of high order harmonics:

$$\Delta M_e = \sum_{\substack{\nu \geq 2 \\ \nu \neq 3p}} M_{e\nu} = Me1 \cdot \sum_{\substack{\nu \geq 2 \\ \nu \neq 3p}} \frac{\left(\dfrac{I_\nu}{I_1}\right)^2}{\nu \cdot \dfrac{s_\nu}{s_1}} \tag{6}$$

❒ Electromagnetic torque of ASM in HR:

$$M_e = M_{e1} - \Delta M_e = M_{e1} \cdot \left(1 - k_{IMD}\right) \tag{7}$$

where: k_{IMD} – unavailability(decrease) coefficient of ASM electromagnetic torque, in HR against RR.

$$\Delta M_e = \sum_{\substack{\nu \geq 2 \\ \nu \neq 3p}} M_{e\nu} = Me1 \cdot \sum_{\substack{\nu \geq 2 \\ \nu \neq 3p}} \frac{\left(\dfrac{I_\nu}{I_1}\right)^2}{\nu \cdot \dfrac{s_\nu}{s_1}} \tag{8}$$

❒ The slip is recalculated (s) considering the reduction of electromagnetic torque in HR (M_e), against RR (M_{e1}):

$$s = \frac{s_1}{1 - k_{IMD}} = \frac{s_n \cdot m}{1 - k_{IMD}} \tag{9}$$

❒ With obtained value of slip (s) obtained on expression (9) basis, we recalculate: s_ν, k_{IMD}, and s, applying expressions (4), (8) and (9).

Knowing the final value of the slip, in given conditions (m, k_{IMD}), the two categories of power losses, dependant on slip, can be calculated.

ASM mechanical losses are expressed with the following expression:

$$\Delta P_M = \Delta P_{Mn} \cdot \left(\frac{1-s}{1-s_n} \right)^2 = \Delta P_{Mn} \cdot \left(\frac{1 - \frac{s_n \cdot m}{1-k_{IMD}}}{1-s_n} \right)^2 \quad (10)$$

Considering the calculation method of additional power losses in reference regime (RR), additional power losses in HR can be expressed as follows:

$$\Delta P_s = \sum_{\nu \geq 1} \Delta P_{s\nu} = \sum_{\nu \geq 1} \Delta P_{sn} f_\nu m_\nu \frac{1-s}{1-s_n} \quad (11)$$

or

$$\Delta P_s = \Delta P_{sn} \frac{f_1}{f_n} m \frac{1-s}{1-s_n} \left[1 + \sum_{\nu \geq 2} \nu (\frac{I_\nu}{I_1})^2 \right] \quad (12)$$

Considering that fundamental harmonic has the rated frequency ($f_1=f_n$), we can write:

$$\Delta P_s = P_{s1} \left(1 + k_{DS} \right) \quad (13)$$

where: $\Delta P_{s1} = \Delta P_{sn} m \frac{1-s}{1-s_n}$ (14)

- additional power losses correspondent to fundamental harmonic:

$$k_{DS} = \sum_{\nu \geq 2} \nu \left(\frac{I_\nu}{I_1} \right)^2 \quad (15)$$

- increase factor of additional power losses in HR against RR:

ASM mechanical power losses is calculated depending on ASM shaft height (H), which is given in ASM catalogs, through the following expression [13]:

$$\Delta P_{Mn} = \frac{0,65}{1000} \cdot \left(\frac{n_n}{1000} \right)^2 \cdot (0.0156 \cdot H)^4 \text{ [kW]} \quad (16)$$

where H – in ASM shaft height given in mm
n_n – rated speed given in [rot/min]

ASM additional power losses are estimated [10] by the following expression:

$$\Delta P_{sn} = 0,005 \cdot P_n \text{ [kW]} \quad (17)$$

If we consider that stator windings rated power losses are equal to those in rotor windings meaning $P_{Wn1} = P_{Wn2}$ it is obtained:

$$P_{W2n} = \frac{(P_n + \Delta P_{mecn}) \cdot s_n}{1-s_n} \quad (18)$$

Then total power losses, in windings, will be:

$$\Delta P_{Wn} = 2 \cdot P_{W2n} = 2 \cdot \frac{(P_n + \Delta P_{Mn}) \cdot s_n}{1-s_n} \quad (19)$$

where P_n – ASM rated power, in kW
$s_n = \frac{n_s - n_n}{n_s}$ – specific slip(n_n, n_s are rated speed and synchronism speed).

Powers balance equation on ASM is:

$$\Delta P_n = \Delta P_{Fn} + \Delta P_{Wn} + \Delta P_{Mn} + \Delta P_{sn} \quad (20)$$

Therefore rated power losses in iron will be:

$$\Delta P_{Fn} = \frac{P_n \cdot (1-\eta_n)}{\eta_n} - \Delta P_{wn} - \Delta P_{Mn} - \Delta P_{sn} \quad (21)$$

In expression it has been replaced total power losses

$$\Delta P_n = \frac{P_n \cdot (1-\eta_n)}{\eta_n} \quad (22)$$

2.2. Reactive power losses (RPL)[8, 9]

Inside ASM occur the following reactive powers: magnetizing reactive power of magnetic circuits (rotor, stator and air gap) and reactive power correspondent to dispersion magnetic field.

The two loss components (ΔQ_0, ΔQ_K) are expressed for ($U_1 = U_n$ and $f_1 = f_n$), as follows:

- **Magnetizing reactive power:**

$$\Delta Q_0 = \Delta Q_{0n} \cdot (1 + k_{DQ0}) \cdot k_{\Delta Q_0} \quad (23)$$

where ΔQ_{on} – ASM magnetizing reactive power in RR (rated)

$$k_{DQ0} = \sum_{\nu \geq 2} \frac{1}{\nu} \frac{U_\nu}{U_1} \quad (24)$$

is increase factor of RPL in ASM magnetic circuits at HR operation.

$k_{\Delta Q_0}$ - correctional coefficient of RPL in magnetic circuit

- **Reactive power losses due to dispersion:**

$$\Delta Q_k = m^2 \cdot \Delta Q_{kn} \cdot (1 + k_{DQk}) \cdot k_{\Delta Q_k} \quad (25)$$

where ΔQ_{kn} - RPL due to dispersion, rated;

$$k_{DQK} = \sum_{\nu \geq 2} \nu (\frac{I_\nu}{I_1})^2 \quad (26)$$

is increase factor of RPL due to dispersion, ASM operating in HR.

$k_{\Delta Q_k}$ - correctional coefficient of RPL due to dispersion.

➢ **Total and additional power losses** are assessed on the following components basis (ΔP_W, ΔP_F, ΔP_M, ΔQ_0, ΔQ_k).

Knowing the reactive power (Q_n) absorbed by ASM in reference regime (RR) rated (U_n, f_n P_n), the two components (ΔQ_{on}, ΔQ_{Kn}) will be determined by solving the equations system:

$$\begin{cases}\Delta Q_{0n} + \Delta Q_{Kn} = Q_n \\ \dfrac{\Delta Q_{0n}}{\Delta Q_{Kn}} = \dfrac{X_m}{X_K}\end{cases} \qquad (27)$$

where, X_m, X_K – magnetizing reactance (X_m) and short-circuit reactance (X_K) of ASM in (RR).

2.3. Total and additional power losses

❒ **Overall active power loses (APL), in HR**

$$\Delta P_D = \left(1 + k_{DI}^2\right) \cdot m^2 \cdot \Delta P_{Wn} + \left(1 + k_{DF}\right) \cdot \Delta P_{Fn} + \\ + \left(\frac{1 - \dfrac{s_n \cdot m}{1 - k_{IMD}}}{1 - s_n}\right)^2 \Delta P_{Mn} + \\ + \left(\frac{1 - \dfrac{s_n \cdot m}{1 - k_{IMD}}}{1 - s_n}\right) \cdot \left(1 + k_{DS}\right) m \cdot \Delta P_{Sn} \qquad (28)$$

❒ **Additional active power losses(deviation) in HR against RR:**

$$\Delta P_D = k_{DI}^2 m^2 \Delta P_{Wn} + k_{DF} \Delta P_{Fn} + \\ + \left[\frac{k_{IMD}\left(2 s_n m + k_{IMD} - 2\right)}{\left(1 - s_n\right)^2 \left(1 - k_{IMD}\right)^2}\right] \Delta P_{Mn} + \\ + \left[\frac{k_{Ds}\left(1 - k_{IMD} - s_n m\right) - k_{IMD}}{\left(1 - k_{IMD}\right)\left(1 - s_n\right)}\right] m \Delta P_{sn} \qquad (29)$$

❒ **Total reactive power losses in HR**

$$\Delta Q_D = \left(1 + k_{DQ0}\right) \cdot \Delta Q_{0n} + \left(1 + k_{DQK}\right) m^2 \Delta Q_{Kn} \qquad (30)$$

❒ **Additional reactive power losses(deviation) in HR against RR**

$$\delta\left(\Delta Q_D\right) = k_{DQ0} \Delta Q_{0n} + k_{DQK} m^2 \Delta Q_{Kn} \qquad (31)$$

Total and additional power losses depend, for a given ASM, by following variables: (m, U_v. I_v. f_v) in RD. These variables are having random nature, which assumes application of a statistical- probabilistically approach on a given analysis time.

For a time interval (Δ_{tk}) in which the mentioned variables are constant, equivalent total active power losses (including APL caused by RPL transport), are expressed as follows:

$$\begin{cases}\Delta P_{tDK} = \Delta P_{DK} + \xi \cdot \Delta Q_{DK} \\ (\Delta P_{DK}, \Delta Q_{DK})\ A(\Delta P_D, \Delta Q_D)\end{cases} \qquad (32)$$

where ξ - energetic equivalent of reactive power [kW/kVAr]

Corresponding energy losses in a time interval (T), in which are registered (M) values of (m, U_v. I_v. f_v) matrix in HR are expressed as follows:

$$\Delta W_{TD} = \sum_{k=1}^{M} \Delta P_{tDK} \cdot \Delta t_k \qquad (33)$$

Considering the additional power losses it can be evaluated the equivalent additional power and energy losses in HR:

$$\begin{cases}\delta(\Delta P_{tDK}) = \delta(\Delta P_{DK}) + \xi \cdot \delta(\Delta Q_{DK}) \\ \delta(\Delta W_{TD}) = \sum_{k=1}^{M} \delta(\Delta P_{tDK}) \Delta t_K\end{cases} \qquad (34)$$

3. ENERGETIC PERFORMANCES SIMULATION OF ASM FROM WHITIN TL OPERATING IN HR

The simulations have been done through dedicated software, made in MATHCAD which is presented in detail in [7]. A practical example has been considered, a power consumer S.C. „CONGIPS” S.A., in order to be able to make the simulations. S.C. „CONGIPS” S.A. is a medium power consumer having as activity the production of molding plaster, high resistance colored concrete tiles, lightweight aggregate concrete blocks, concrete paving, tiles and sandstone adhesive, expanded polystyrene adhesive, high resistance polishing plaster coat.

In order to achieve specific technological processes to make the above mentioned materials, the consumer have two technological lines (TL): paving technological line (PTL) and expanded polystyrene technological line (EPTL). Because of lack of space, in this paper we will present simulation results only for EPTL. The results for the PLT are accessible in [7]. The simulations and evaluations has been conducted for two HR HR1 and HR2, taking into considerations only the harmonics with order up to 9 inclusively. The two HR have the characteristics presented in table 1 and 2.

Table 1 – Characteristics of simulated HR1

ν	1	3	5	7	9
U_v [%]	100	19,8	15,8	9,1	4,3
I_v [%]	100	21,1	14,7	6,9	3,5

Table 2 – Characteristics of simulated HR2

ν	1	3	5	7	9
U_ν [%]	100	43,4	19,2	13,9	11,1
I_ν [%]	100	43,1	18,4	12,9	8,9

Table 3 – ASM categories which exists in EPTL from S.C. „Congips" S.A.[14]

Category	Speed [rot/min]	Rated power [kW]	Pcs.
M-LP0	1500	< 1,1	5
M-LP1	1000, 1500, 3000	1,1 ÷ 4	13
M-LP2	1500	5,5	2
M-LP3	1500, 3000	7,5	4
M-LP4	1500, 1000	11	3
M-LP5	1500	30	4

The most numerous ASM within EPTL are those with rated power around 2,2 kW at 1500 rot/min, used on screw conveyor(mixing spindle). ASM of 7,5 kW have also an important share, by their number and it's total power related to the EPTL installed power. ASM with most power, which have also the biggest share in EPTL, are those at 30 kW at 1000 rot/min used on EPTL mixer.

In order to model and simulate HR impact on energetic effects of ASM from EPTL and considering the above mentioned, it has been taken into consideration the following ASM types manufactured at S.C. Bega Electromotor S.A.:

- (1)AT100L-4A ASM type, at 2,2 kW and 1500 rot./min.
- (1)AT 132S-2B ASM type, at 7,5 kW and 3000 rot./min.
- AT160L-6, at 11 kW and 1000 rot./min.
- AT 225M - 6, at 30 kW and 1000 rot./min.

These types of ASM are three-phased, with siluminiu housing, F insulation class and for general and industrial use.

To establish additional active and reactive power in HR against RR, was taken into account that working regime is 5 days×24 hours/week = 120 hours/week.

To exemplify, we considered a time period of 1 year and so a analysis time of 6240 hours/year and respectively values of relative loading torque m = {0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0).

Below are presented the simulations results done on a single type of motor, due to lack of space.

AT160L-6 ASM type, at 11 kW and 1000 rot/min.

It has been calculated APL and RPL in HR, HR1 and HR2 in tables 4 and 5, respectively in table 6 the deviations of APL and RPL in HR1 and HR2 against RR, for several values of loading factor (m).

Table 4 – APL in RR, HR1 and HR2 for AT160L-6 ASM type

Motor type	P_n [kW]	**m**	ΔP_W [W]			ΔP_F [W]			ΔP_M [W]			ΔP [W]		
			RR	RD1	RD2	RR	RD1	RD2	RR	RD1	RD2	RR	RD1	RD2
AT160L-6	11	0.1	10.4	11.1	12.9	824.0	919.1	1001.4	24.0	24.0	23.9	864.1	963.0	1046.8
		0.2	41.6	44.6	51.7	824.0	919.1	1001.4	23.9	23.8	23.8	900.8	996.3	1085.4
		0.3	93.5	9.0	116.3	824.0	919.1	1001.4	23.8	23.7	23.7	958.3	960.6	1149.9
		0.4	166.2	178.2	206.8	824.0	919.1	1001.4	23.7	23.6	23.6	1036.5	1129.6	1240.2
		0.5	259.8	278.5	323.2	824.0	919.1	1001.4	23.5	23.5	23.4	1135.4	1229.7	1356.3
		0.6	374.0	401.0	465.4	824.0	919.1	1001.4	23.4	23.3	23.3	1255.1	1352.1	1498.4
		0.7	509.1	545.8	633.4	824.0	919.1	1001.4	23.3	23.2	23.2	1395.5	1496.7	1666.3
		0.8	665.0	712.9	827.3	824.0	919.1	1001.4	23.2	23.1	23.1	1556.6	1663.6	1860.0
		0.9	841.6	902.3	1047.1	824.0	919.1	1001.4	23.1	23.0	23.0	1738.4	1852.9	2079.6
		1.0	1039.0	1113.9	1292.7	824.0	919.1	1001.4	23.0	22.9	22.8	1941.0	2064.4	2325.1

Table 5 – RPL in RR, HR1 and HR2 for AT160L-6 ASM type

Motor type	P_n [kW]	**m**	ΔQ_0 [VAr]			ΔQ_k [VAr]			ΔQ [VAr]		
			RR	RD1	RD2	RR	RD1	RD2	RR	RD1	RD2
AT160L-6	11	0.1	5508.1	6143.6	6693.7	43.7	56.2	83.6	5551.8	6199.8	6777.4
		0.2	5508.1	6143.6	6693.7	174.7	224.7	334.5	5682.8	6368.3	7028.2
		0.3	5508.1	6143.6	6693.7	393.1	505.6	752.6	5901.2	6649.2	7446.4
		0.4	5508.1	6143.6	6693.7	698.9	898.8	1338.0	6207.0	7042.4	8031.7
		0.5	5508.1	6143.6	6693.7	1092.1	1404.4	2090.6	6600.2	7548.0	8784.3
		0.6	5508.1	6143.6	6693.7	1572.6	2022.3	3010.5	7080.7	8165.9	9704.2
		0.7	5508.1	6143.6	6693.7	2140.5	2752.6	4097.6	7648.5	8896.1	10791.3
		0.8	5508.1	6143.6	6693.7	2795.7	3595.2	5351.9	8303.8	9738.8	12045.7
		0.9	5508.1	6143.6	6693.7	3538.3	4550.1	6773.5	9046.4	10693.7	13467.3
		1.0	5508.1	6143.6	6693.7	4368.3	5617.5	8362.4	9876.4	11761.0	15056.1

Table 6 – APL and RPL deviations in HR1 and HR2 against RR, for AT160L-6 ASM type

Motor type	P_n [kW]	m	$\delta(\Delta P_W)$ [W]		$\delta(\Delta P_F)$ [W]		$\delta(\Delta P)$ [W]		$\delta(\Delta Q_0)$ [VAr]		$\delta(\Delta Q_k)$ [VAr]		$\delta(\Delta Q)$ [VAr]	
			RD1	RD2	RD1	RD2	RD1	RD2	RD1	RD2	RD1	RD2	RD1	RD2
(1) AT 160L-6	11	0.1	0.7	2.5	95.1	177.4	98.9	182.7	635.5	1185.6	12.5	39.9	648	1225.6
		0.2	3	10.1	95.1	177.4	95.5	184.6	635.5	1185.6	50	159.8	685.5	1345.4
		0.3	4.7	22.8	95.1	177.4	2.3	191.6	635.5	1185.6	112.5	359.5	748	1545.2
		0.4	12	40.6	95.1	177.4	93.1	203.7	635.5	1185.6	199.9	639.1	835.4	1824.7
		0.5	18.7	63.4	95.1	177.4	94.3	220.9	635.5	1185.6	312.3	998.5	947.8	2184.1
		0.6	27	91.4	95.1	177.4	97	243.3	635.5	1185.6	449.7	1437.9	1085.2	2623.5
		0.7	36.7	124.3	95.1	177.4	101.2	270.8	635.5	1185.6	612.1	1957.1	1247.6	3142.8
		0.8	47.9	162.3	95.1	177.4	107	303.4	635.5	1185.6	799.5	2556.2	1435	3741.9
		0.9	60.7	205.5	95.1	177.4	114.5	341.2	635.5	1185.6	1011.8	3235.2	1647.3	4420.9
		1.0	74.9	253.7	95.1	177.4	123.4	384.1	635.5	1185.6	1249.2	3994.1	1884.6	5179.7

Additional active and reactive yearly energies consumed by 11 kW ASM due to operating in HR against RR case are given in table 7.

Table 7 – Additional active and reactive yearly energies consumed in HR1 and HR2 against RR, for AT160L-6 ASM type

No.	m	W_{AD} [Wh]		W_{RD} [VArh]	
		RD1	RD2	RD1	RD2
1	0.3	14352	1195584	4667520	9642048
2	0.4	580944	1271088	5212896	11386128
3	0.5	588432	1378416	5914272	13628784
4	0.6	605280	1518192	6771648	16370640
5	0.7	631488	1689792	7785024	19611072
6	0.8	667680	1893216	8954400	23349456
7	0.9	714480	2129088	10279152	27586416
8	1.0	770016	2396784	11759904	32321328

Total yearly active and reactive power losses at the whole TL level, due to operation of ASM in HR, against RR situation, was calculated according to ASM losses with the largest share, by its number and its rated power, whose active and reactive energies losses has been prior calculated.

At EPTL there is the following situation: 6 ASM with 2,2 kW or close rated power, 4 ASM with 7,5 kW or close rated power, 3 ASM with 11 kW or close rated power and 4 ASM with 30 kW.

Total yearly active and reactive power energy losses at the whole EPTL level caused by operation of ASM in HR, against the case of RR, expressed for values of relative loading torque m={0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0) are given in table 8.

Table 8 – Total yearly active and reactive energies consumed at EPTL level, in HR1, HR2 against RR

No.	m	W_{AD} [kWh]		W_{RD} [kVArh]	
		RD1	RD2	RD1	RD2
1	0.3	4082.83	21479.33	63246.14	134913.79
2	0.4	10974.29	22222.51	73126.56	166512.53
3	0.5	10868.21	23369.42	85829.95	207132.43
4	0.6	10886.30	24924.43	101360.06	256786.61
5	0.7	11023.58	26875.68	119710.66	315466.94
6	0.8	11278.18	29221.92	140885.47	383172.82
7	0.9	11669.42	31978.75	164886.38	459911.09
8	1.0	12171.74	35129.33	191706.53	545672.40

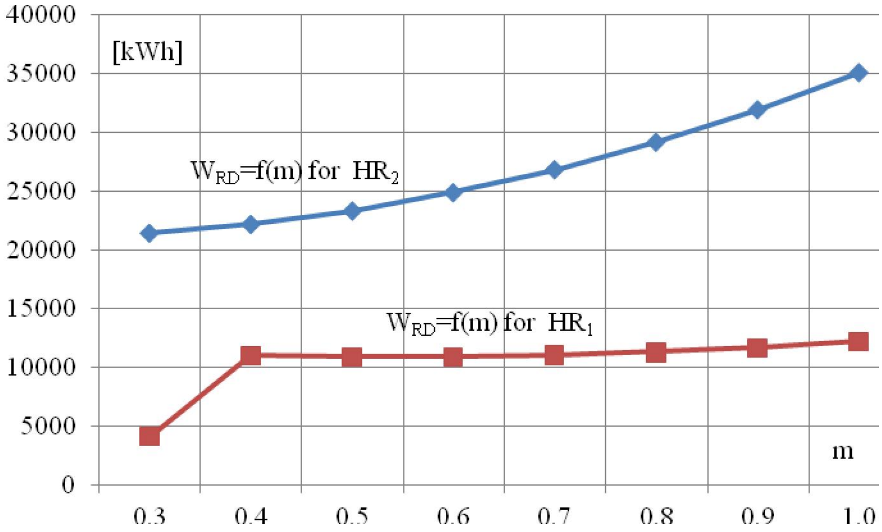

Fig. 1 – Variation of additional yearly active energy losses due to ASM operation in HR, against RR case

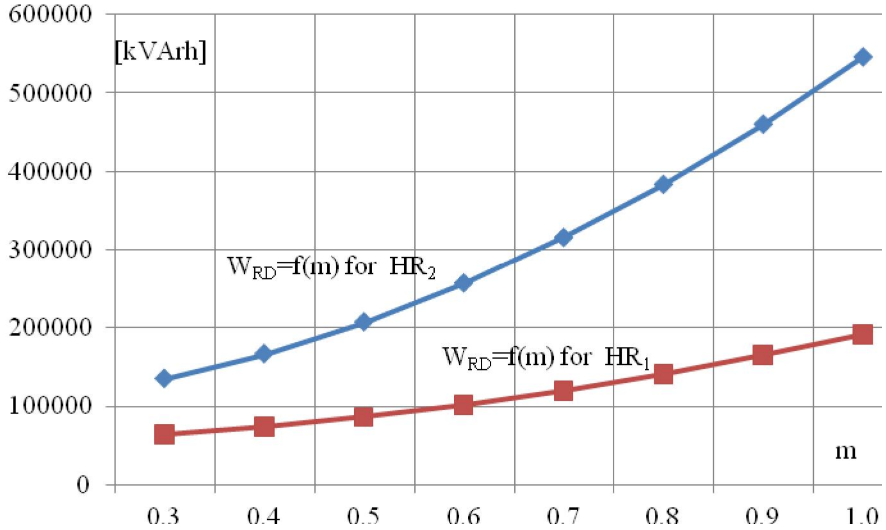

Fig. 2 – Variation of additional yearly reactive energy losses due to ASM operation in HR, against RR case

In figures 1 and 2 are presented the variations of additional yearly active and reactive energy losses, due to operation of ASM in HR against RR case, based on relative loading torque m.

By calculating the active and reactive power and energy losses too from PTL it can be determined the total power and energy losses, at the whole consumers level, S.C. “Congips” S.A., if this would work in HR1 and HR2, against the case when would operate in RR, by summing the losses of the two TL[7].

4. CONCLUSIONS

Mathematical model presented in this paper and simulations results allows us to draw the following conclusions:

➢ To evaluate energetic effects of HR on involved ASM there are two important aspects that must be taken into consideration.

- Evaluation of additional power losses of ASM who operates in HR against the RR case, detailing the power balance according to type (active, reactive) and to ASM components (in magnetic core, in windings, mechanical).
- Determination HR influences on electromagnetic torque produced by ASM.

➢ For a operative determination, correspondent to industrial processes, of ASM power losses, respectively for simulation, the following initial elements are required to be known:

- Rated parameters of ASM: rated power and current, rated voltage and frequency, efficiency, rated speed, rated power losses in windings and in magnetic core, mechanical losses;
- Characteristics of HR: maximum order of harmonics taken into consideration, voltage and current harmonic amplitudes, up until the maximum order chosen;
- Characteristics of ASM operation service: values of relative torque and time of operation at these values of torque;

➢ Mathematical model used to simulate and evaluate HR effects on ASM is based on harmonic effects superposition principle and the experimentally established corrections.

➢ Evaluations done on ASM manufactured in Romania, highlights the fact that additional losses in HR have the same evolution trend as following variables: rated power, ASM loading, current and voltage THD.

➢ These trends are accordingly with the experimental measurements and observations made on ASM service, fact that validates the analytical model used. To refine the analytical model we can act towards to a more accurate establishment of correctional coefficients values of APL and RPL, which implies further more experimental measurements, executed preferable on ASM types and groups, with same characteristics, using input-output method and calorimetric method.

➢ The assessments made with reference to technological lines of consumer S.C. “Congips” S.A., highlights the fact that for a considered HR, the active and reactive energy consumption rises significantly, against RR case.

➢ The results obtained through simulation can be regarded, by power consumers and suppliers, as solutions and exemplifications regarding the approach and treatment of HR energetic impact and identification solutions to increase energetic efficiency of industrial processes.

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