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THE INDUCTION MACHINE. MODELLING AND SIMULATION.

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Abstract:*simulation analysis is made for various operating regimes of an asynchronous machine functioning at variable speed. In the first phase, machine parameters are introduced which the author concluded and the experimental information is combined with information from specialty books , through his own methods ,revealed at a previous chapter. We must keep in sight that when simulating an asynchronous machine in no-load mode we have three ways: without pelicular effect, with pelicular effect theoretically estimated and with pelicular effect experimentally estimated. Simulations can be done for a motor system or for a generator system, working with load, keeping track of time variation of the current, torque and speed. With the results gained we can obtain validity for the models(patterns) built Analyzing these simulations , we can highlight the influence of temperature over the evolution of current and pulses ,and also these aspects can be observed when considering the pelicular effect.*
Keywords: *induction machine. modelling and simulation*

1.INTRODUCTION

We must analyze by simulation the behavior of the machine for different voltages and different supply frequencies as well as for situations that consider adding or removing motor load. A special attention must be given when studying the asynchronous machine working in a saturated regime. This kind of regime presents superior harmonics through the current. We must calculate the valuables of these harmonics so we can be able to adapt a filtering strategy, because powerful electronic machineries pollutes the electromagnetic systems. We are given the determination methods for harmonic amplitudes for different plugging tension and constant torque, the elevator case, or for variable torque and constant tension , the electrical traction systems(tram, trolley, electrical trains)

2. INDEPENDENT PARAMETERS WITH SATURATION DEGREE

2.1. Simulation structure

The first step is to connect the different blocks of the simulation structure, fig.1, so we can obtain the final model [12] and the opportunity to succeed the simulation for as many situations and functioning regimes for the asynchronous machine as possible[8] [11], followed by the description of the component blocks that find themselves in the simulation structure.

2.2. Introducing parameters

The essential catalog parameters used for describing the function of an asynchronous machine [3],[6], are:

- R_1 stator winding resistance
- R_2 rotor resistance reported to the stator
- R_{Fe} equivalent resistance for leakage (Fe)
- X_h main reactance
- $\left(X_1 + X_2^{'}\right)$ dispersion(leakage) reactance
- P_{frec} friction loses
- J moment of inertia
- P number of pole pairs

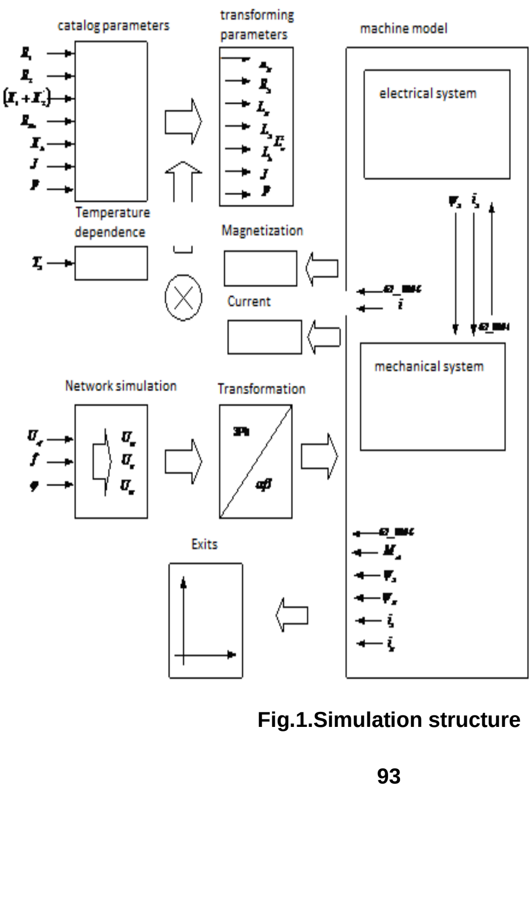

Fig.1.Simulation structure

2.3. Calculation of simulation parameters

For a further simulation study [14],the catalog parameters are to be transformed in simulation parameters. Mainly the machine and the pattern must be studied completely separated.[14] ,[15]

The identified machine parameters are for the "delta" connection. The parameters for the Y connection are smaller.

The asynchronous machine analyzed has 5.5 kW; Δ / Y 400V / 690, 11A / 6.9A
torque 1440 1/min.The parameters values for the machine used for simulation are presented in table 1.

Table 1.

Catalog sizes	Simulation parameters calculation	Δ simulation values	Y simulation values
R_1 = 2.78Ω	$R_S = R_1$	2.78 Ω	0.927 Ω
R_2'= 4.25Ω	$R_R' = R_2'$	4.25Ω	1.416 Ω
R_{Fe} = 3777Ω	$R_{Fe} = 0$	0 Ω	0 Ω
X_h = 207Ω	$L_h = \frac{X_h}{2\pi f}$	0.6589 H	0.2196 H
$\left(X_1 + X_2^{'}\right)$ = 13.35Ω	$L_S = L_R = \frac{1}{2}\frac{X_1 + X_2^{'}}{2\pi f} + L_h$	0.6801 H	0.2267 H
	$L_\sigma^2 = L_S \cdot L_R - L_h^{\ 2}$	28.45 mH	3.16 H
P_{frec}	$P_{frec} = P_{frec}$	167.1 W	167.1 W
J	J = J	0.02738kgm²	0.02738kgm²
p	P=p	2	2

$$L_h = \frac{X_h}{2\pi f} \tag{1}$$

$$L_S = L_R = \frac{1}{2}\frac{X_1 + X_2^{'}}{2\pi f} + L_h \tag{2}$$

$$L_\sigma^2 = L_S \cdot L_R - L_h^{\ 2} \tag{3}$$

Leakage will be neglected ($R_{Fe} = \infty$ Ω).The transformation ratio is unknown so we will consider $X_1 = X_2'$.

2.4 Network simulation

We will consider the fact that the engine is plugged in a symmetrical network. The network is initial simulated for the next parameters ,table 2:

Table 2.

U_{ef}	Effective voltage value	400V
F	Frequency	50Hz
φ	Initial cosφ phase angle oscillation	0^0

Once validating a correct functioning for the implemented model, the supply parameter values will be modified when necessary

2.5. Load simulation

The load is introduced as a load moment depending on time[8]. With some help from the *Look-up-table* block, a block that realizes value interpolation , can be simulated, for example, the next loads:

- Adding or removing motor load
- Ramp load

2.6. Coordinate transformation

The influence and the behavior of the windings, symmetrical distributed within the machine, a re described in a rectangular system formed by two axis , ***3Ph >> αβ***

$$x = x_\alpha + jx_\beta \qquad x_\alpha = \frac{1}{3}\left(2x_U - x_V - x_W\right) \qquad x_\beta = \frac{1}{\sqrt{3}}\left(x_V - x_W\right) \quad 4)$$

αβ >> 3Ph

$$x_U = x_\alpha \qquad x_V = \frac{1}{2}\left(\sqrt{3}x_\beta - x_\alpha\right) \qquad x_W = \frac{1}{2}\left(-\sqrt{3}x_\beta - x_\alpha\right) \tag{5}$$

2.7. Machine model (pattern)

The complete description of a stator and rotor for an asynchronous machine is formed by five complex equation and a real equation. Deducting equations in stator coordinates was presented in the second chapter.

For simulation the equation must ,as much as possible, be complete. The machine is described by an electrical and a mechanical pattern.[1] , [2] , [15].

Electrical model.

Stator flow chaining

$$\psi_{S\alpha} = \int \left(u_{S\alpha} - R_S i_{S\alpha}\right) dt$$

$$\psi_{S\beta} = \int \left(u_{S\beta} - R_S i_{S\beta}\right) dt \tag{6}$$

Rotor flow chaining

$$\psi_{R\alpha} = \int \left(- R_R i_{R\alpha} - p\omega_{mec} \cdot \psi_{R\beta}\right) dt$$

$$\psi_{R\beta} = \int \left(- R_R i_{R\beta} + p\omega_{mec} \cdot \psi_{R\alpha}\right) dt \tag{7}$$

Stator current

$$i_{S\alpha} = \psi_{S\alpha} \frac{L_R}{L_\sigma^2} - \psi_{R\alpha} \frac{L_h}{L_\sigma^2} \qquad i_{S\beta} = \psi_{S\beta} \frac{L_R}{L_\sigma^2} - \psi_{R\beta} \frac{L_h}{L_\sigma^2} \tag{8}$$

Rotor current

$$i_{R\alpha} = -\psi_{S\alpha} \frac{L_h}{L_\sigma^2} + \psi_{R\alpha} \frac{L_S}{L_\sigma^2}$$

$$i_{R\beta} = -\psi_{S\beta} \frac{L_h}{L_\sigma^2} + \psi_{R\beta} \frac{L_h}{L_\sigma^2} \tag{9}$$

Mechanical model

Machine momentum

$$M_{el} = \frac{3p}{2}\left(\psi_{S\alpha} i_{S\beta} - \psi_{S\beta} i_{S\alpha}\right) \tag{10}$$

Torque

$$\omega_{mec} = \frac{1}{J} \int \left(M_{El} - M_{Sarcina} - M_{Frecare}\right) dt \tag{11}$$

The equation that describe the behavior of the asynchronous machine (6) – (11) can be implemented as a block scheme[16], as it is represented in fig.2.

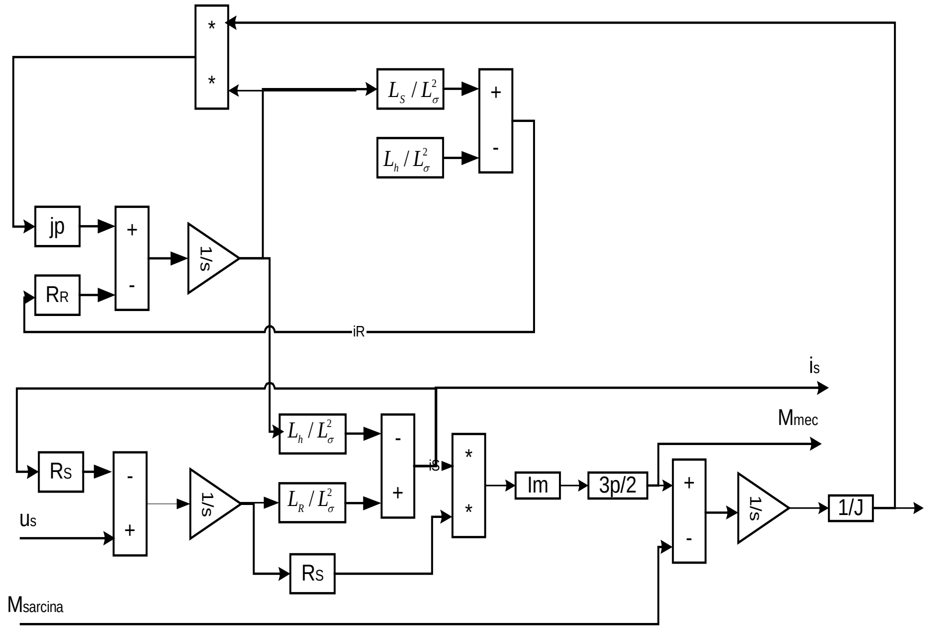

Fig.2 Block scheme for an asynchronous machine with voltage plugging, *$\alpha\beta$ representation*

2.8. Temperature influence over stator and rotor resistance values

For obtaining an asynchronous machine model that takes into consideration the temperature influence [10], some premises must be met:

- The engine has two temperature levels, separated in space, rotor temperature and stator temperature
- The stator and rotor temperatures are coupled ,as in the equation (14)
- The resistances have a linear behavior (12)
- The reactants don’t depend on the temperature
- The temperature analysis is a spontaneous record except the final temperature de $T_{FinalStator}$ = 85^{0}C şi $T_{FinalRotor}$ = 150^{0}C
- $\alpha_{Cu} = 3.9 \cdot 10^{-3}\, 1/K$, $\alpha_{Al} = 4.7 \cdot 10^{-3}\, 1/K$

For simulation within a pre-established temperature the resistance are :
Stator:

$$R_{ST} = R_{S20}\left[1 + \alpha_{Cu}\left(T_{Stator} - 20.3\right)\right] \qquad (12)$$

Rotor:

The rotor resistance [8], [11] is determined for a winding temperature of 84.4^{0}C
This temperature corresponds for a stator temperature of 52.2 ^{0}C.The stator and the rotor have different values for the final temperatures. For a nominal load we can make the following assumptions [7].

$T_{StatorFinal} = 85^0 C$, $T_{StatorFinal} = 150^0 C$, $\tau_{incalzire} = 22.5 \min$, $\tau_{racire} = 45.0 \min$

Rising temperatures within the rotor and the stator

$$T_{Rotor} = 130\left(1 - e^{\frac{t}{\tau_{incalziire}}}\right) + 20 \qquad (13)$$

$$T_{Stator} = 65\left(1 - e^{\frac{t}{\tau_{incalziire}}}\right) + 20$$

The influence of the stator temperature over the rotor ,results from (13)

$$T_{Rotor} = 130\left(\frac{T_{Stator} - 20.3}{65}\right) + 20 \qquad (14)$$

The rotor and the stator resistance can be calculated from the rotor and the stator resistance at an established temperature

Rr = Rr*(1+4.7e-3*(Tr-84.4)) Rs = Rs*(1+3.9e-3*(Ts-20.3)) (15)

2.9 . Inductance dependence on the magnetization current

Simulation with inductances dependent on the magnetization current are implemented with help from the magnetization diagram [4], [5], [6].The feature is calculated at 50Hz which means that the ohm resistance can be neglected, because v $X_L >> R_{Cu}$.

During implementation keep track of the stator inductance dependence on current,fig.3. $L_S = f(I_m)$.

L_s is consisted of two inductances

$$L_S(I_m) = L_{\sigma 1}(I_m) + L_h(I_m) \tag{16}$$

Main inductance and leakage inductance. From (1), (2) results

$$L_h = \frac{X_h}{2\pi f} \quad \rightarrow \quad \frac{L_{\sigma 1}}{L_S} = 0.031 \tag{17}$$

$$L_S = L_R = \frac{1}{2}\frac{X_1 + X_2^{'}}{2\pi f} + L_h \quad \rightarrow \quad \frac{L_h}{L_S} = 0.969 \tag{18}$$

Impedance:

$$Z_S = j\omega L_S \qquad \left|Z_S\right| = \omega L_S \tag{19}$$

The resulted value from the magnetization feature:

$$\left|Z_S\right| = \frac{U}{I_m} \tag{20}$$

Inductance depending on current:

$$L_S(I_m) = \frac{\left(\frac{U}{I_m}\right)}{2\pi \cdot 50Hz} \tag{21}$$

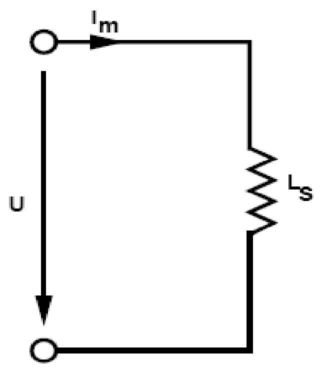

Fig.3 Equivalent winding scheme

From the magnetization scheme,fig.4 we can generate impedance which will be approximate fig.5

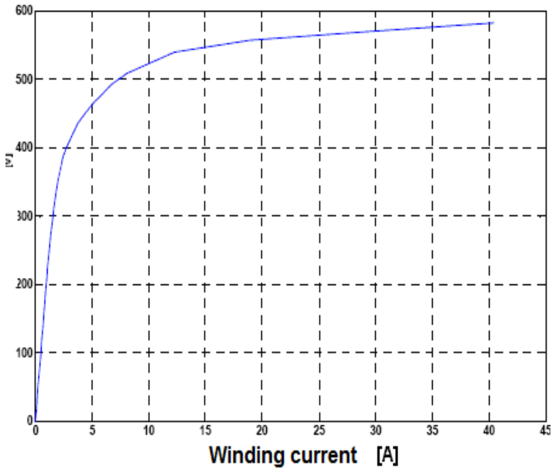

Fig.4 Magnetization diagram

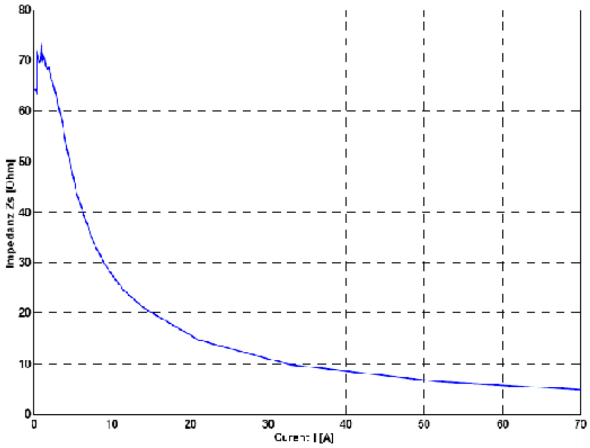

Fig.5 Impedance depending on current

Impedance approximation

The magnetization current – impedance feature will be implemented as a pattern as *Look-up-Table.*

Entry values [0 1 2 3 5 6 7 12 18 30 40 70].
Exit values [75 70 60 50 40 33 30 16 11 8 6 4]

Considering this values we can calculate $\boldsymbol{L_S = f(I_m)}$ fig.6

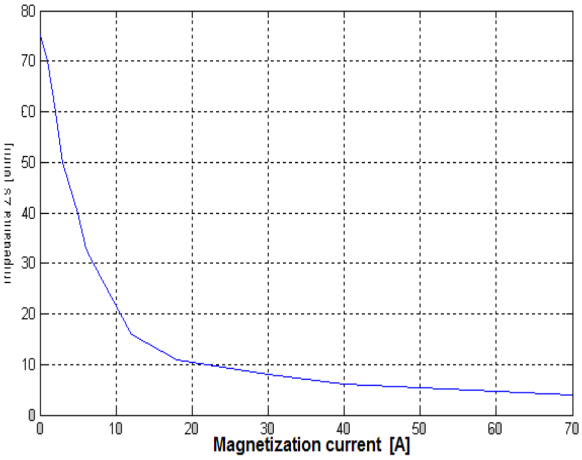

Fig.6 Impedance approximation

From (1) ,(2) ,(3), (17) and (19) results :

$$L_S(I_m)=L_R(I_m)=\frac{|Z_S(I_m)|}{2\pi\cdot 50Hz};\quad L_h(I_m)=0.969L_S(I_m)$$
$$L_\sigma^{\,2}(I_m)=L_S^2(I_m)-L_h^2(I_m)-0.061L_S^2(I_m) \qquad (22)$$

The magnetization current is calculated form the stator current and the rotor current

$$I_m = I_S + I_R' \qquad (23)$$

The equation system which describes the inductances dependence on the magnetization current (22) and (23) is implemented in the Matlab – Simulink pattern [12], as it results from fig.7

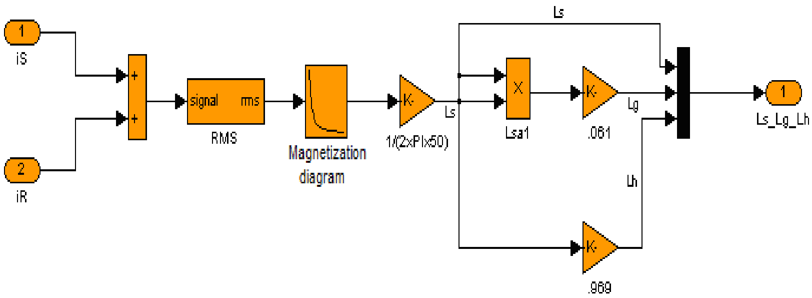

Fig.7 Implementing inductance dependence on magnetization current

2.10. Rotor pelicular effect

Further we will simulate rotor pelicular effect by implementing in Matlab – Simulink, for a concrete example.
Theoretical version

Tab.3 Depth

Functioning regime	f_{RR}[Hz]	D=f(R_{RR}) [mm]
Rest	50	8.27
Nominal	2	41.35

We establish a "classical " form for the transverse section on the rotor notch ,with A=74.6 mm^2, having the following dimensions:

h =19.2 mm B=5.4 mm R =1.6 mm
s = 2 mm h_1 =1.2 mm A =74.6 mm^2

The surfaces , A_A, A_B şi A_C have the same values :

$$A_A = 4mm^2 \qquad A_B = 60mm^2 \qquad A_C = 10mm^2$$

The total surface of the notch is $A_{Crestatura} = 74mm^2$ $\qquad R_{Rd}' = R_R' \dfrac{A_{Crestatura}}{A_{Crestatura\_d}}$ (24)

R_{Rd}' – rotor resistance depending on depth

Calculating notch surface with depth influence [14] , takes place gradually,in four situations :

- If *d > h-h$_1$=18 mm*, the rotor resistance is not limited
- If *16.4 mm = h - h$_1$-R < d < h - h$_1$ = 18mm* then it is valid

$$A_{Crestatura\_d} = R^2\frac{\pi}{4} - \frac{4}{3}(R-h_A)\sqrt{h_A(2R-h_A)} + A_B + A_C \qquad h_A = h - h_1 - d \qquad (25)$$

- If *2.7 mm = h - h$_1$-R-B/2 < d < h - h$_1$ - R= 16.4 mm* then it is valid : $A_{Crestatura\_d} = h_B\left(B - \tan\left(\alpha/2\right)h_B\right) + A_C$

$$h_B = d - \frac{B}{2} \qquad (26)$$

- If *0 <d < h - h$_1$-R-B/2 = 2.7 mm* then:

$$A_{Crestatura\_d} = \frac{4}{3}h_C\sqrt{h_C(B-h_C)} \qquad h_C = d \qquad (27)$$

For an efficient processing , the surface of the notch depending on the depth is linear , and fig.8

$$A_{crestatura\_1}(d<10.7)=4.65d-0.05 \quad A_{crestatura\_2}(10.7<d<16.4)=3.7d+10.1$$
$$A_{crestatura\_3}(16.4<d<18)=2.1d+36.25 \quad A_{crestatura\_4}(d>18)=74 \qquad (28)$$

The relations [24], [25] which describe the pelicular effect influence over the value of the rotor resistance , were implemented in Matlab – Simulink pattern as it is shown in fig.9

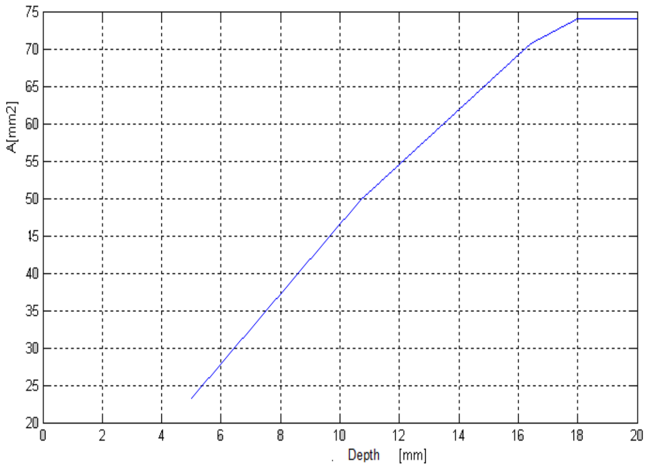

Fig.8 Surface linearization

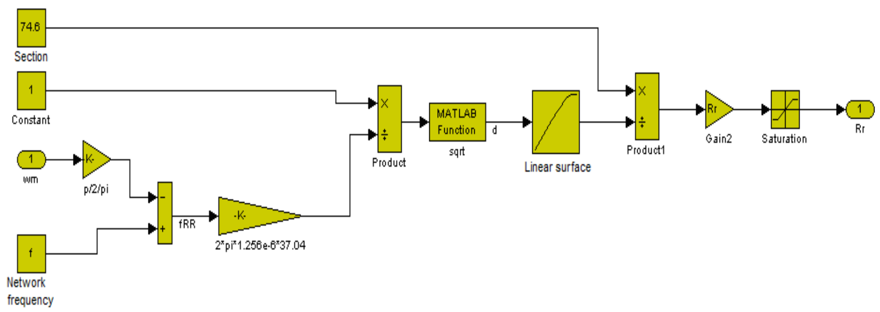

Fig.9 Pelicular effect is supporting the rotor resistance

The experimental version is implemented in Matlab – Simulink and compared with the theoretical method. The nominal torque for the asynchronous machine is 1440 [rpm]. Implementing this dependence in Matlab – Simulink is presented in the next figure :

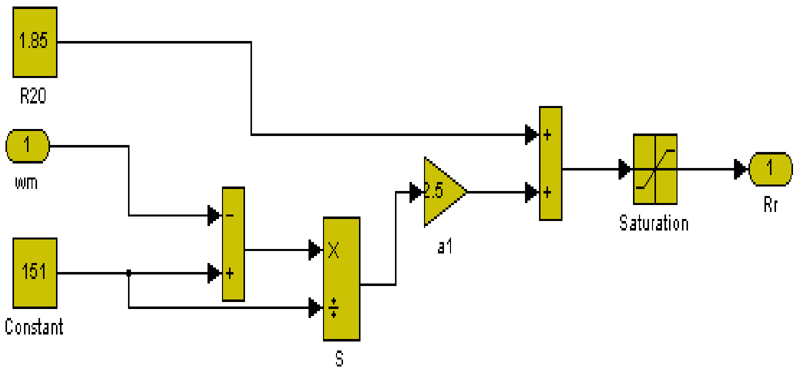

Fig.10 Rotor resistance variation with slide implemented in Matlab – Simulink

We will make a presentation of the current evolution,fig.11a, and torque fig 11b depending on the two implementing methods :
For the following values R_{2N}=1.95[Ω], R_{2P}=4.35[Ω] şi R_{20}=1.85[Ω] we determine the value for the coefficient a_1. It was found after implementing the two methods that the one that depends on the depth needs a bigger calculation volume corresponding to longer time.

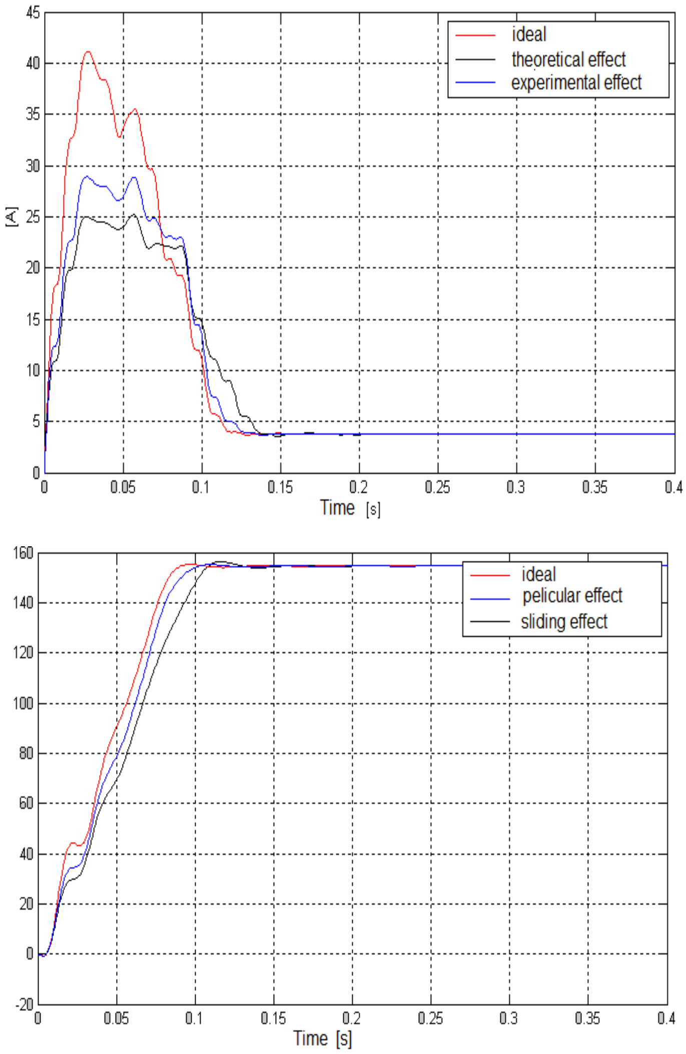

Fig 11.a Time evolution for current in this cases: ideal version , pelicular effect

3. CONCLUSIONS

With simulations at different loads and considering pelicular effect and magnetic saturation we obtain theoretical results that are found in experimental verification mentioned in specialty books. Through simulation we can observe the influence that different component parts have on the model (pattern).[in the case of saturation the influence of tension over the level of harmonics , in the case of pelicular effect the influence of rotor geometrics over the rotor resistance

When simulating an asynchronous machine we must take into consideration:

- Magnetic saturation – when voltage exceeds the value corresponding to unsaturated core
- Pelicular effect within the rotor bars ,especially when rotor high frequencies
- The influence of temperature over the resistance values

It was realized an implementation in the Simulink environement. The dependence of the rotor resistance over sliding.

All the aspects known were taken in consideration when implementing in Matlab – Simulink.

The magnetic saturation is highlighted through stator current harmonics

The harmonic structure of current is a measure for the saturation degree , because at high voltages, the higher harmonics become important.

The mathematic pattern chosen when evaluating magnetic saturation is correct ,because this reflects reality in a certain measure , having as basis the magnetizing feature for the analyzed engine.

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