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Influence of Electrical Circuit Parameter Changes on the Local Stability of a Three-Phase Cage Induction Motor Fed with Variable Frequency

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Abstract – **The paper presents the mathematical support and the results of some simulations related to a new method of analyzing the stability of induction motors powered at variable frequency. After a brief introduction to the proposed issue, the mathematical model of the motor, written with relative values, is detailed. Taking this model as a starting point, a Matlab stability analysis program was created. By running this program, a series of graphs were obtained, detailed in the paper (two graphs are represented each, obtained for different conditions, which facilitate their comparison and obtaining conclusions). They refer to four specific cases regarding the modification of static inductance, rotor inductance, stator resistance and rotor resistance. Analyzing these graphs, the necessary conclusions were drawn. The conclusions are important, mainly in the design phase of the machine, to finalize the structure corresponding to the most stable operation of the drive system with asynchronous motor and static voltage and frequency converter. They highlight the influences of the most important parameters of the motor on the stability of the functioning of systems with such a structure. The paper ends with a representative bibliography for the proposed study.**

Cuvinte cheie: *motor asincron, frecventa variabila, stabilitate, model matematic, Matlab, simulari.*

Keywords: *induction motor, variable frequency, stability, mathematical model, Matlab, simulations.*

I. INTRODUCTION

The problem of asynchronous motors powered at variable frequency is very topical due to the multiple practical applications that use this type of actuation [1]-[5], etc.

This all the more recently when there is a massive shift to the use of electric cars [6], [7], [8] etc.

The use of an unconventional power supply can lead to stability problems of the actuation system.

To avoid this problem, the stability analysis is required, the analysis quite popular in the current literature [9], [10], [11].

The present paper is part of this trend. The influences of the motor parameters on the stability are analyzed with the help of some modeling in the Matlab environment.

II. THE MATHEMATICAL MODEL IN RELATIVE VALUES

To achieve the proposed circuit, the mathematical model of the induction machine written in relative values was used [12].

The notations are those used in specialized literature:

$$\begin{aligned}
\omega_s^* &= s_{ks}(\underline{\Psi}_s^* - k\underline{\Psi}_r^{/*}) + \frac{d\underline{\Psi}_s^*}{dt^*} + j\omega_s^*\underline{\Psi}_s^* \\
0 &= s_{kr}(\underline{\Psi}_r^{/*} - k\underline{\Psi}_s^*) + \frac{d\underline{\Psi}_r^{/*}}{dt^*} + j(\omega_s^* - \omega^*)\underline{\Psi}_r^{/*} \\
h \cdot \frac{d\omega^*}{dt^*} &= -\frac{k}{x_{rt}^{/*}}\mathrm{Im}\left[(\underline{\Psi}_s^*)^*\underline{\Psi}_r^{/*}\right] - m_r^*
\end{aligned} \tag{1}$$

The condition is imposed that the pulsation changes in jumps with a small value.

In this case it is obtained:

$$\begin{aligned}
&\omega_s^* + \Delta\omega_s^* = s_{ks}\left\lfloor \underline{\Psi}_s^* + \Delta\underline{\Psi}_s^* - k(\underline{\Psi}_r^{/*} + \Delta\underline{\Psi}_r^{/*})\right\rfloor + \\
&+ \frac{d(\underline{\Psi}_s^* + \Delta\underline{\Psi}_s^*)}{dt^*} + j(\omega_s^* + \Delta\omega_s^*)(\underline{\Psi}_s^* + \Delta\underline{\Psi}_s^*) \\
&0 = s_{kr}\left\lfloor \underline{\Psi}_r^{/*} + \Delta\underline{\Psi}_r^{/*} - k(\underline{\Psi}_s^* + \Delta\underline{\Psi}_s^*)\right\rfloor + \\
&+ \frac{d(\underline{\Psi}_r^{/*} + \Delta\underline{\Psi}_r^{/*})}{dt^*} + \\
&+ j(\omega_s^* + \Delta\omega_s^* - \omega^* - \Delta\omega^*)(\underline{\Psi}_r^{/*} + \Delta\underline{\Psi}_r^{/*} + \Delta\underline{\Psi}_r^{/*})
\end{aligned} \tag{2}$$

$$\begin{aligned}
&h \cdot \frac{d(\omega^* + \Delta\omega^*)}{dt^*} = -\frac{k}{x_{rt}^{/*}}. \\
&.\mathrm{Im}\left\{\left[(\underline{\Psi}_s^*)^* + \Delta(\underline{\Psi}_s^*)\right] \cdot (\underline{\Psi}_r^{/*} + \Delta\underline{\Psi}_r^{/*})\right\} - m_r^*
\end{aligned}$$

The equations from (1) and (2) are processed accordingly.

It is obtained:

$$\begin{aligned}
&\Delta\omega_s^* = (s_{ks} + j\omega_s^* + s) \cdot \Delta\underline{\Psi}_s^* - s_{ks} \cdot k \cdot \Delta\underline{\Psi}_r^{/*} + \\
&+ j \cdot \underline{\Psi}_s^* \cdot \Delta\omega_s^*
\end{aligned} \tag{3}$$

$$0 = -s_{kr} \cdot k \cdot \Delta\underline{\Psi}_s^* + (s_{kr} + s)\Delta\underline{\Psi}_r^{/*} + j(\Delta\omega_s^* - \Delta\omega)\underline{\Psi}_r^{/*}$$

$$h\frac{d(\Delta\omega^*)}{dt} = -\frac{k}{x_{st}^*}\mathrm{Im}\left[\left(\underline{\Psi}_s^*\right) \cdot \Delta\underline{\Psi}_r^{/*} + \underline{\Psi}_r^{/*} \cdot \Delta\left(\underline{\Psi}_s^*\right)^*\right]$$

(the operational variable was denoted with s).

In the following, a series of simplifications of the writing were made.

The following approximations can also be made:

$$j\underline{\Psi}_s^* = 1 \quad \text{and} \quad j\underline{\Psi}_r^{/*} = k\,. \tag{4}$$

Under these conditions, the (3) relationships become:

$$0 = (s_{ks} + j\omega_s^* + s)\Delta\underline{\Psi}_s^* - s_{ks}\cdot k\cdot\Delta\underline{\Psi}_r^{/*} \tag{5}$$

$$k(\bigl(\Delta\omega^* - \Delta\omega_s^*\bigr) = -s_{kr}\cdot k\cdot\Delta\underline{\Psi}_s^* + (s_{kr} + s)\Delta\underline{\Psi}_r^{/*}$$

Next, it is considered that the motor was running without load before changing the frequency.

In this case, due to the low frequency of the rotor current, its active component can be neglected.

So it can be written:

$$\Delta\underline{i}_r^{/*} = \Delta i_{dr}^{/*} + j\Delta i_{qr}^{/*} \cong \Delta i_{dr}^{/*} = \frac{\Delta\underline{\Psi}_r^{/*} - k\Delta\underline{\Psi}_s^*}{dx_s^*} \tag{6}$$

By solving the system (5) relatively to $\Delta\Psi_s^*$ and $\Delta\Psi_r^{/*}$ by replacing these relations in (6), after computations, it is obtained:

$$\Delta i_{dr}^{/*} = \frac{s + j\omega_s^* + \varepsilon}{s^2 + (s_{ks} + s_{kr} + j\omega_s^*)s + s_{kr}(\varepsilon + j\omega_s^*)}\cdot \tag{7}$$
$$\cdot k(\Delta\omega^* - \Delta\omega_s^*)$$

In the previous relation, the notation was used:

$$\varepsilon = (1 - k^2)s_{ks} = \frac{r_s^*}{x_s^*} = \frac{r_s^*}{x_r^{/*}}\,. \tag{8}$$

When $\omega_s^* \geq 0{,}1$ it results that it can be considered (with approximation):

$$\left(\underline{\Psi}_s^*\right)^* = 1 \quad \text{and} \quad \underline{\Psi}_r^{/*} = -jk \tag{9}$$

The Laplace transform is applied to relation (9).

It is obtained:

$$hs\cdot\Delta\omega^* = -\frac{k}{x_{st}^*}\mathrm{Re}(\Delta\underline{\Psi}_r^{/*} - k\Delta\underline{\Psi}_s^*)\,, \tag{10}$$

The equivalent relation has the form:

$$hs\cdot\Delta\omega^* = -\frac{k}{x_{st}^*}\mathrm{Re}(\Delta\underline{\Psi}_{dr}^{/*} - k\Delta\underline{\Psi}_{ds}^*)\,, \tag{11}$$

or:

$$hs\cdot\Delta\omega^* = -k\Delta i_{dr}^{/*} \tag{12}$$

In what follows, using the previous relations, the stability of systems with such a structure will be analyzed.

III. STABILITY ANALYSIS

To analyze the stability of induction motors powered at variable frequency, a complex program was created [13].

The program, made in the Matlab environment, contains three modules that realize:

- the necessary calculations for the representations corresponding to the motor with real parameters;

- the necessary calculations for the representations corresponding to the motor with modified parameters;

-representation of comparative characteristics.

This program was used to study the influences of inductances (stator and rotor) and resistances (stator and rotor).

To carry out the simulations, a 1.1 kW induction motor with a short-circuited rotor was considered, with the following parameters:

R_s=7,5 Ω; $R_r^{/}$=5,5 Ω; Ls=0,529H;

$L_r^{/}$=0,528 H; L_{sh}=0,498 H; J=0,004 kgm^2.

The following numerical cases were considered:

A. Cases Ls=0,529 H, Ls=0,54 H ;

B. Cases Lr=0,528 H , Lr=0,54 H;

C. Cases Rs=7,5 Ω , Rs=9 Ω;

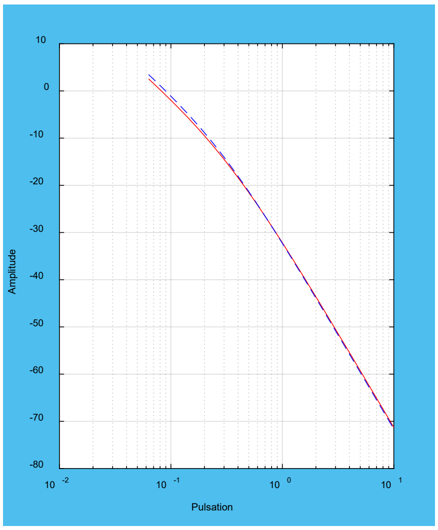
D. Cases Rr=5,5 Ω, Rr=7 Ω.

The graphs corresponding to the four cases are represented in figures 1-4.

The following features are detailed:

- amplitude - pulsation;
- phase - pulsation;
- amplitude – phase;
- the hodograph.

A. Figures obtained for the case of changing the static inductance



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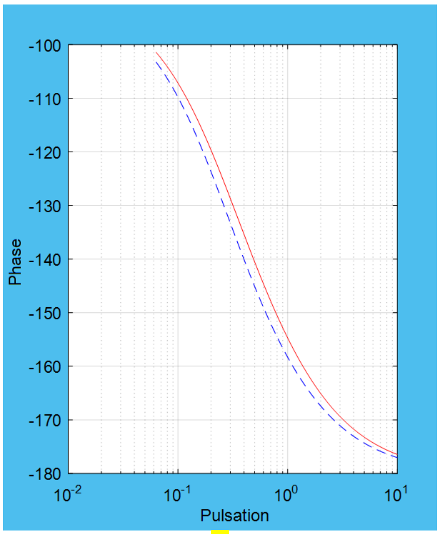

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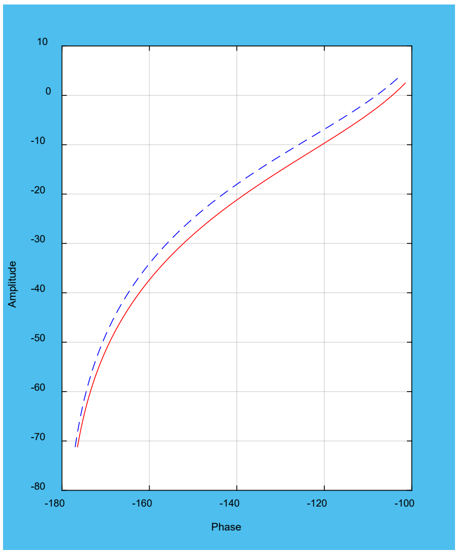

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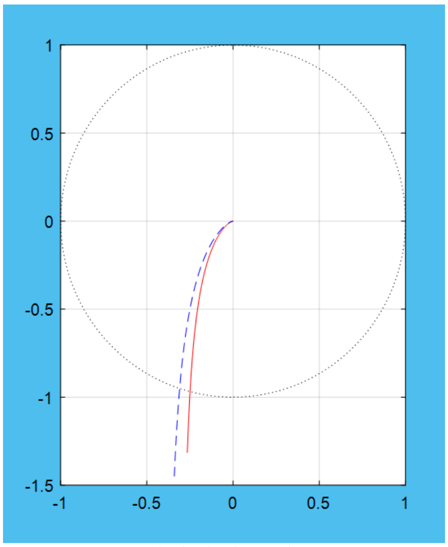
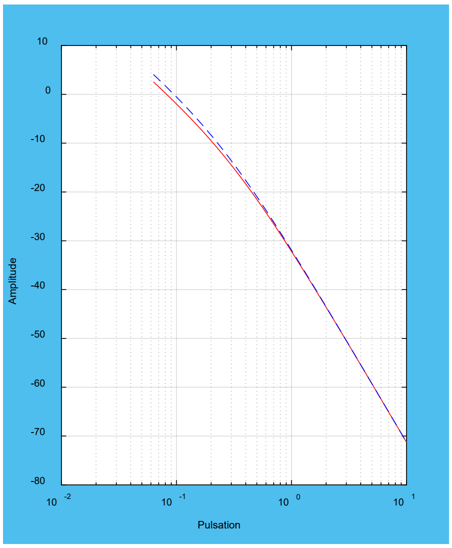


d) the hodograph

Fig. 1. Characteristics corresponding to the cases Ls=0.529 H (red), Ls=0.54 H (blue).

B. Figures obtained for the case of changing the rotor inductance



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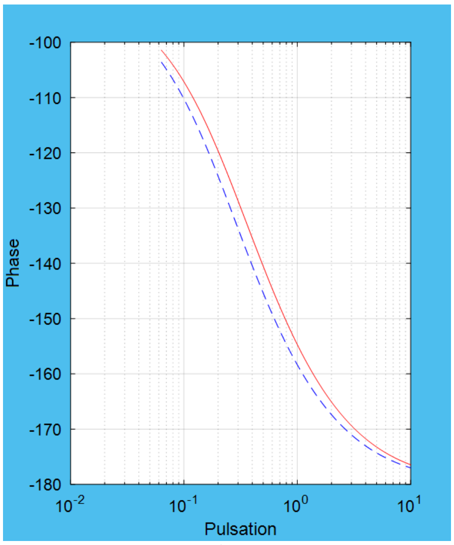

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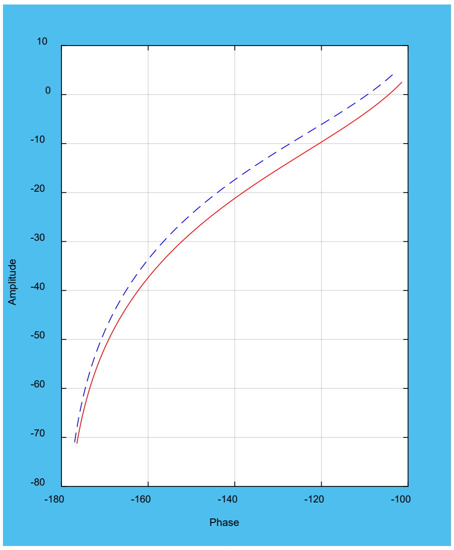

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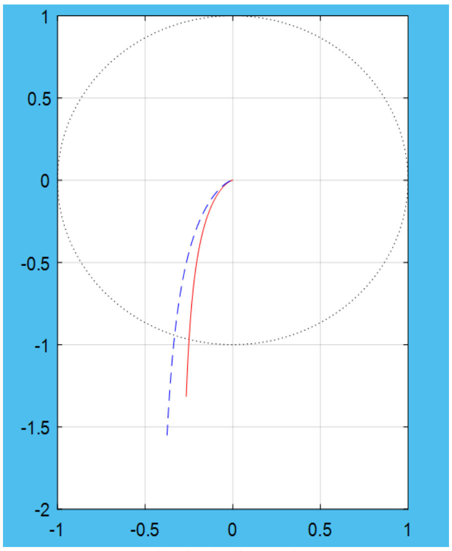
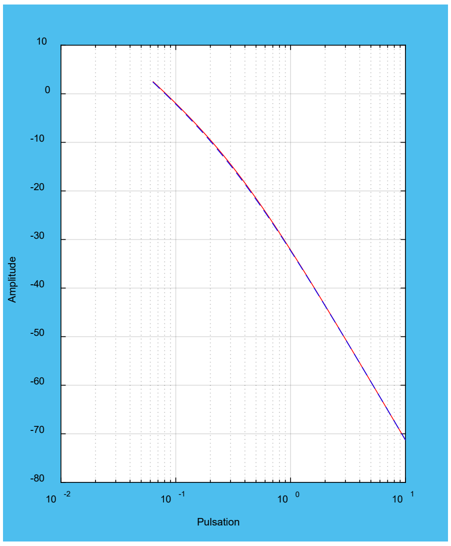


d) the hodograph

Fig. 2. Characteristics corresponding to the cases Lr=0.528 H (red), Lr=0.54 H (blue).

C. *Figures obtained for the case of changing the stator resistance*



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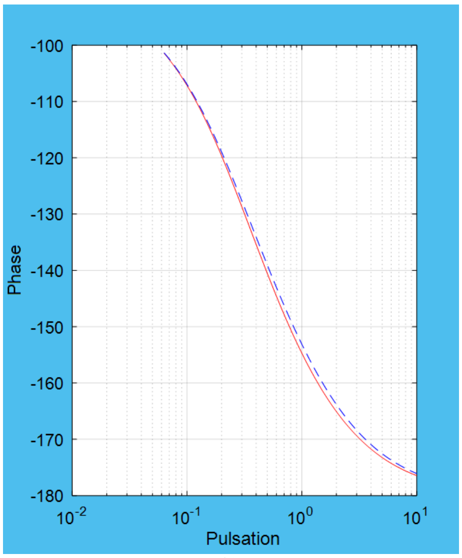

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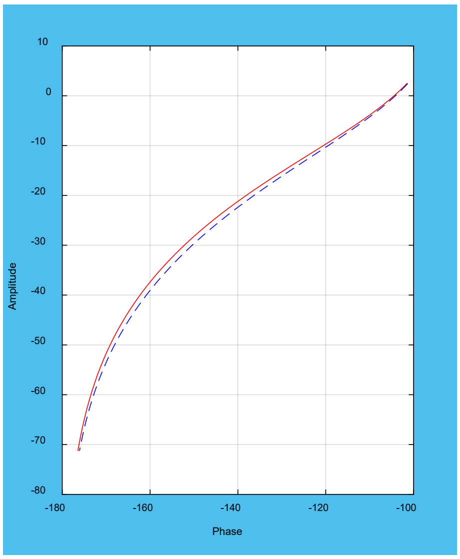

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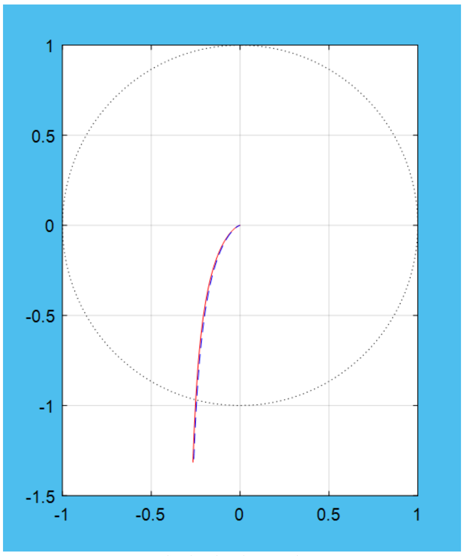
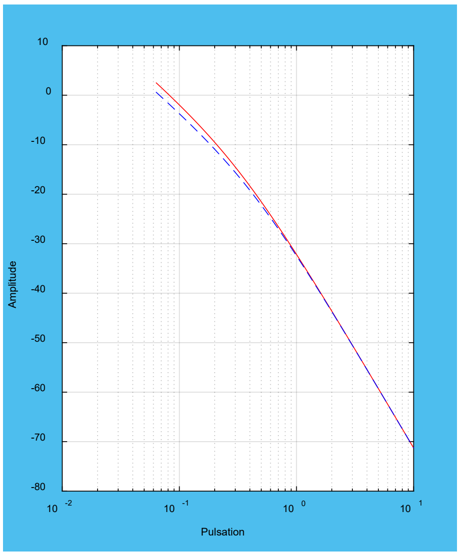


d) the hodograph

Fig. 3. Characteristics corresponding to the cases Rs=7,5 Ω (red), Rs=9 Ω (blue).

D. Figures obtained for the case of changing the rotor resistance



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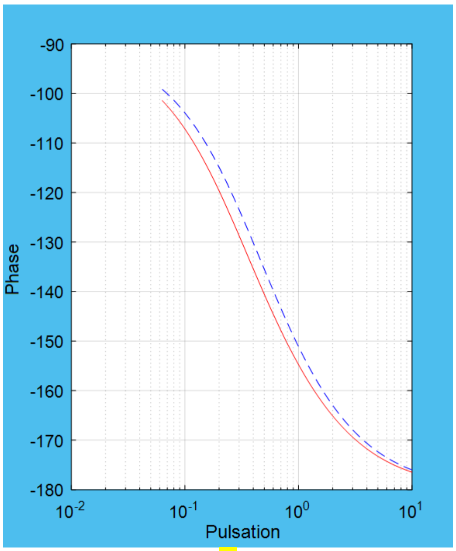

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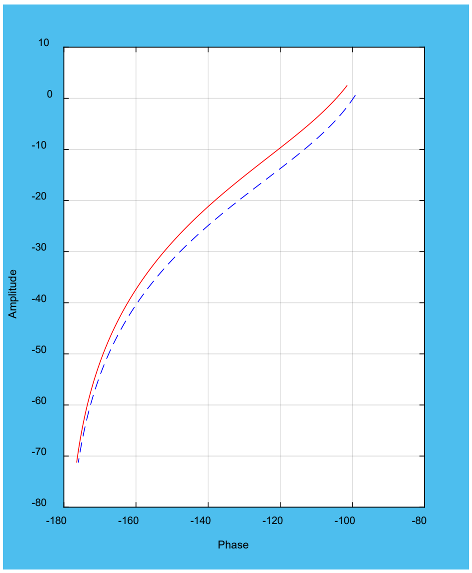

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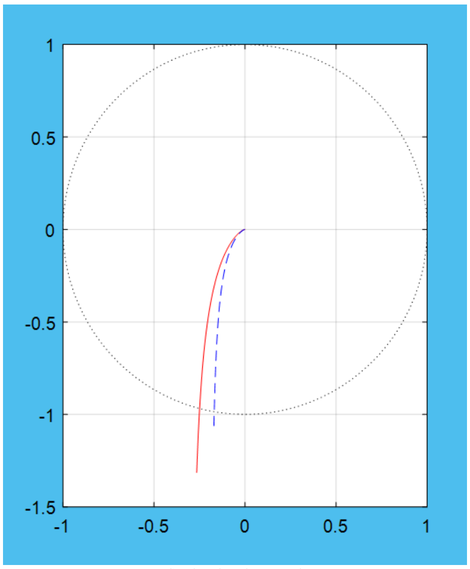

d) the hodograph

Fig. 4. Characteristics corresponding to the cases Rr=5,5 Ω (red), Rr=7 Ω (blue).

IV. CONCLUSIONS

The characteristics in figures 1-4 provide a series of mathematical results, centralized in tables I and II.

TABLE I.
THE VALUES OF THE CHANGED PARAMETERS

Parameters	Abs. value	Phase margin
L_s	0,529	75,54
	0,54	71,94
$L_r^{/}$	0,528	75,54
	0,54	70,62
R_s	7,5	75,54
	9	75,86
$R_r^{/}$	5,5	75,54
	7	80,25

TABLE II.
THE PERCENTAGE VARIATIONS OF THE PARAMETERS

Parameters	Percent variation of the parameter	Percent variation of the phase margin
L_s	2,08	4,7
$L_r^{/}$	2,27	6,5
R_s	20	1,3
$R_r^{/}$	27,2	6,2

From the analysis of the previous results, the following conclusions were obtained:

- when the static inductance increases, the stability of the system decreases;

- when the rotor inductance increases, the stability also decreases;

- the increase in the value of the stator resistance determines the increase in stability;

- increasing the value of the rotor resistance also leads to increasing the stability of the system;

- the inductances influence the stability of the motor the most (with a plus for the rotor inductance);

- the smallest influence is the resistance of the stator winding.

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