A NOVEL APPROACH FOR INDUCTION MACHINE PARAMETER ESTIMATION

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The magnitude and the phase of the complex driving-point impedance are also measured by supplying the stator winding with a variable frequency sinusoidal voltage, such that the ratio V1max/f is preserved constant. Using these sampled driving-point impedance as reference, model parameters are obtained, starting from the symbolic impedance computed before, by an iterative identification algorithm based on Output Error method or by solving a number of the independent equations having as unknowns the parameters of interest. Finally, the proposed estimation techniques were tested and validated on simulation data on a three phase squirrel cage induction motor with deep rotor bars.

REZUMAT. Lucrarea prezintă o nouă metodă de estimare a unor parametri ai motoarelor cu inducție, bazată pe rezultatele unor măsurări realizate asupra sistemul real. Se estimează parametrii care sunt dificil sau imposibil să fie măsurați în mod direct. Pornind de la schema echivalentă a unei faze a motorului funcționând în regim sinusoidal şi neglijând saturația circuitului magnetic, se generează, folosind metoda nodală modificată, expresia simbolică a impedanței de intrare în domeniul operațional. Parametrii doriți se calculează printr-un algoritm iterativ bazat pe metoda minimizării erorii de ieşire, unde parametrii de interes sunt variabilele unui sistem de ecuații independente.

Cuvinte cheie: maşină de inducție, estimarea aparametrilor, metoda minimizării erorii de ieşire, funcție de transfer

ABSTRACT. Our paper present a new method to estimate the induction motor parameters based on some measurements performed on the real system, the parameters of interest being those which are difficult or impossible to be measured directly. Starting from the equivalent scheme on a phase of the induction motor in sinusoidal behavior and neglecting the saturation phenomena, we generate the driving-point impedance (the input impedance) in full symbolic form, obtaining an appropriate frequency space representation based on the complex or Laplace modified nodal equations (MNE).

Keywords: induction machine, parameter estimation, output error method, transfer function

1. INTRODUCTION

Classical method for parameter determination uses the no-load and locked rotor tests results. This classical parameter determination method is sometimes impractical for initializing a motor drive. To simplify the initialization process, motor parameters can be estimated from manufacturer data by the drive processor. In one of these methods, motor parameters are estimated from manufacturer data with a numerical method [1]. This off-line parameter estimation method requires a computer and necessary software to make these calculations. In this method, initial values of motor parameters are calculated with some assumptions. After that, each parameter is changed from initial value to zero with small steps. This step size defines the accuracy. For each possible combination of parameters, exact equivalent circuit of induction machine is used and mechanical power, reactive power at full load and breakdown torque are calculated. Results of these calculations are compared with manufacturer supplied data and errors of these calculations are found. Then each error is weighted in accordance to the importance of these calculations by the user of this method. Total weight of the errors is calculated for each possible combination. This method is finalized by selecting the motor parameters by looking into minimum error weight.

Numerous approaches have been exposed for induction model identification based on data that can become easily available [1-6]. Most of these approaches formulate the estimation problem as a nonlinear least squares minimization problem that estimates all the unknown parameters simultaneously. This difficult problem is being solved either by traditional mathematical numerical techniques (Newton type methods) [5-8] or by computational intelligence-based techniques (genetic algorithms) [1-3]. Numerical techniques are very efficient; however, they are not to be very robust and they can provide suboptimal solutions or no solution at all, depending on the stiffness of the problem and on the initialization of the iterative solution algorithm [1-3]. Furthermore, they require good knowledge of the analytical models used [1-3]. Due to these drawbacks, computational intelligence techniques have been also applied that require less information on the underlying mathematical model and are more robust, at the expense of large amount of computational time [1-3] and lack of insight in the problem solution.

During last two decades, there has been a new interest in Output Error techniques [9-12]. An overview of approaches is given in [11-12]. Output Error (OE) methods are based on iterative minimization of an output error quadratic criterion by a Non Linear Programming (NLP) algorithm. This technique requires much more computation and do not converge to unique optimum. But, OE methods present very attractive features, because the simulation of the output model is based only on the knowledge of the input, so the parameter estimates are unbiased. Moreover, OE methods can be used to identify linear and/or nonlinear systems.

In this paper, we present a new method to estimate the induction motor parameters based on some measurements performed on the real system. Starting from the equivalent scheme on a phase of the induction motor in sinusoidal behavior and neglecting the saturation phenomena, we can generate the driving-point impedance (the input impedance) in full symbolic form. The magnitude and the phase of the complex driving-point impedance can be measured by supplying the stator phase with a variable frequency sinusoidal voltage, such that the ratio V_{1max}/f is preserved constant. We can also determine the numeric values of the magnitude and the phase of the complex driving-point impedance using the catalogue data of the analyzed induction motor. The approach is based on an appropriate frequency space representation of the induction motor, using the complex or Laplace modified nodal equations (MNE).

2. INDUCTION MOTOR PARAMETER ESTIMATION USING THE TRANSFER FUNCTIONS

We consider a linear circuit (a linear system) which works in in the frequency domain. In this way we can generate any transfer function which describes the circuit behavior. Selected circuit model contains only the lumped circuit elements and possible the independent sources (the input signals). This circuit type is described, in the time domain, by a set of the ordinary differential linear equations which using the Laplace or Fourier transform can be change in the algebraic linear equations in the frequency domain.

Any two-port linear circuit, which works in steady-state behavior (in the frequency domain) , can transform a signal set $\underline{\mathbf{X}} = [\underline{X}_1 \quad \underline{X}_2]^t$ in the other signal set $\underline{\mathbf{Y}} = [\underline{Y}_1 \quad \underline{Y}_2]^t$ using a transfer function matrix as:

$$\begin{bmatrix} \underline{X}_1 \\ \underline{X}_2 \end{bmatrix} = \begin{bmatrix} \underline{F}_{11} & \underline{F}_{12} \\ \underline{F}_{21} & \underline{F}_{22} \end{bmatrix} \cdot \begin{bmatrix} \underline{Y}_1 \\ \underline{Y}_2 \end{bmatrix} \quad (1)$$

The matrix coefficients from the relation (1) are transfer (circuit) functions which take values in the complex number set and depend on the circuit parameters and on the complex frequency s or $j\omega$.

In the function of the nature of the input and ouput quantities we can define the different parameters in respect of the two ports as: $\underline{Z}$, $\underline{Y}$, $\underline{H}$, the fundamental parameters $\underline{A}$, $\underline{B}$, $\underline{C}$, and $\underline{D}$, $\underline{S}$ etc.

Starting from the equivalent scheme on a phase of the induction motor in sinusoidal behavior and neglecting the saturation phenomena (Figure 1), we can generate the diving-point impedance (the input impedance) in full symbolic form. The magnitude and the phase of the complex driving-point impedance can be measured by supplying the stator phase with a variable frequency sinusoidal voltage, such that the ratio V_{1max}/f is preserved constant.

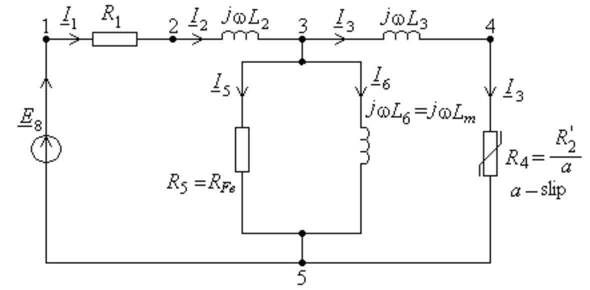

Fig. 1. Equivalent scheme (on a phase) of the induction motor.

We can also determine the numeric values of the magnitude and the phase of the complex driving-point impedance using the catalogue data of the analyzed induction motor. The approach is based on an appropriate frequency space representation of the induction motor, using the complex or Laplace modified nodal equations (MNE). To generate the driving-point impedance in full symbolic form it is used the SYMNAP – SYmbolic Modified Nodal Analysis Program [19] and SYTFGP – SYmbolic Transfer Function Generation Program [20]. These programs are based on the modified nodal analysis (MNA) and it generates, starting from the circuit net list, the *Y, Z, H*, and fundamental parameters, for any the linear and/or nonlinear time-invariant two-port analog circuits, in symbolic form. These are new software environments which allow the analysis and design of linear or nonlinear analog circuits, even when they have excess elements. These are two interactive tools that combine symbolic and numeric computational techniques, and which uses the facilities of symbolic simulator Maple to manipulate the symbolic expressions.

In the case when we take into account the saturation phenomena we use the time analysis based on the state equations in respect of (d,q,0) coordinates [13 - 15, 21, 22].

The aim of our paper is the induction motor simulation in order to estimate the electrical parameters of one device phase (R_1 – resistance of the stator phase, $L_{\sigma 1} = L_2$ - inductance of the stator phase, $L_m = L_6$ – mutual inductance between a stator phase and a rotor phase, $R_{Fe} = R_5$ – the resistance corresponding to the iron losses, $L_{\sigma 2} = L_3$ - inductance of one rotor phase, $R_2^{'} = R_2$ - resistance of one rotor phase, and the slip a). In general, the parameters which are not measured direct as: $L_m = L_6$, $R_{Fe} = R_5$, $L_{\sigma 2} = L_3$, $R_2^{'} = R_2$, and the slip a. Some of these parameters (L_m, R_{Fe}, $L_{\sigma 2}$, $R_2^{'}$, and a) can not be measured directly.

The estimation procedure starts with the full symbolic generation of the driving-point impedance as a function of frequency, $Z_{ii}(f)$. Keeping as variables the induction motor parameters which have to be estimated $x_1, x_2, ..., x_p$ while the other parameters are substituted by their nominal values, for n_f frequency samples the following objective function is built:

$$f = \sum_{k=1}^{n_f} \left(\left| Z_{ii}(f_k) \right| - \left| Z_{ii}(f_k, x_1, x_2, ..., x_p) \right| \right)^2 \quad (2)$$

The objective function (2) is minimized using one of the *fminimax* functions from the Matlab toolbox [17]. Usually, the n_f is greater than p.

Fminimax finds the minimum of a problem specified by:

$$\min_{\boldsymbol{x}} \max_{[\boldsymbol{F}_i]} \{\boldsymbol{F}_i(\boldsymbol{x})\} \text{ such that } \begin{cases} \boldsymbol{c}(\boldsymbol{x}) \le \boldsymbol{0} \\ \boldsymbol{c}_{eq}(\boldsymbol{x}) = \boldsymbol{0} \\ \boldsymbol{A} \cdot \boldsymbol{x} \le \boldsymbol{b} \\ \boldsymbol{A}_{eq} \cdot \boldsymbol{x} \le \boldsymbol{b}_{eq} \\ \boldsymbol{lb} \le \boldsymbol{x} \le \boldsymbol{ub} \end{cases} \quad (3)$$

where: $\boldsymbol{x}$, $\boldsymbol{b}$, $\boldsymbol{beq}$, $\boldsymbol{lb}$, and $\boldsymbol{ub}$ are vectors, $\boldsymbol{A}$ and $\boldsymbol{A}_{eq}$ are matrices, and $\boldsymbol{c}(\boldsymbol{x})$, $\boldsymbol{c}_{eq}(\boldsymbol{x})$, and $\boldsymbol{F}(\boldsymbol{x})$ are functions that return vectors. $\boldsymbol{F}(\boldsymbol{x})$, $\boldsymbol{c}(\boldsymbol{x})$, and $\boldsymbol{c}_{eq}(\boldsymbol{x})$ can be nonlinear functions.

The syntax of the *fminimax* routine is:

1. The complex driving-point impedance $\underline{Z}_{ii}$

$$[\boldsymbol{x}, \boldsymbol{f}_{\mathbf{val}}] = \text{fminimax}(@\text{myfun}, \boldsymbol{x}_0), \quad (4)$$

where $\boldsymbol{x}_0$ is the guess initial values of the unknown parameter vector, ***fval*** is the vector values of the function f at the n_f frequency samples. The solution is searched within the domain bounded by the lower bound (***lb***) and the upper bound (***ub***) specified by the user.

Fminimax minimizes the worst-case value of a set of multivariable functions, starting at an initial estimate. This is generally referred to as the *minimax* problem. Starts at $\boldsymbol{x}_0$ and finds a minimax solution $\boldsymbol{x}$ to the functions described in *fun*. Details about routine *minimax* can be found in [17, 23-24].

Usually $Z_{ii}(f)$ is a rational function of frequency. The polynomial coefficients of the nominator and of the denominator are complex products of the system parameters in which each parameter of the induction motor appears once at the unity power for a linear system and at bigger than the unity power for the nonlinear case.

The parameter estimation can be done also by solving a system of p nonlinear algebraic equations with real or complex coefficients as follows:

$$\left| Z_{ii}(f_k) \right| - \left| Z_{ii}(f_k, x_1, x_2, ..., x_p) \right| = 0, \; k = 1,2,..,p \quad (5)$$

for real coefficients and

$$Z_{ii}(f_k) - Z_{ii}(f_k, x_1, x_2, ..., x_p) = 0, \; k = 1,2,..., p \quad (6)$$

for the complex ones.

Obviously, the equation systems (5) and (6) need the knowledge of the input impedance values in p frequency samples.

The number of the parameters which can be estimated with the equations (5) and (6) depends on the efficiency of the routine used for solving. In general, the maximum number of the estimated parameter is less or equal than three.

Because, in general, the nonlinear algebraic equation systems have multiple solutions, the designer has to choose the solution corresponding to the real system.

3. EXAMPLES

Example 3.1: We consider as the first example an asynchronous three phase squirrel cage motor with long rotor bars which has the following nominal parameters:

f_n = 60 Hz ; p = 3; $R_s = R_1$ = 0.053 Ω ;
$R_2^{'} = R_2$ = 0.0657 Ω ; $L_{1\sigma} = L_2$ =1.035 mH;
$L_{s\sigma}^{'} = L_3$ = 0.955 mH ; $L_\mu = L_m = L_6$ = 28.1 mH;
$R_{Fe} = R_5$ = 200.0 Ω, and a_n = 0.026.

$$Zii := (-247.673152\ I\, f^3\ L2\ L3\ L6\ a - 39.4384\ (L6\ a\ L3\ R5 + L2\ L6\ a\ R5 + L6\ a\ L3\ R1 + L2\ a\ L3\ R5 + L2\ L6\ R2)\, f^2 + 6.28\ I\,(L6\ R5\ R2 + L2\ R5\ R2 + L6\ a\ R1\ R5 + L6\ R1\ R2 + a\ L3\ R1\ R5)\, f + R1\ R5\ R2) \Big/ (-39.4384\ f^2\ L6\ a\ L3 + 6.28\ I\,(L6\ a\ R5 + L6\ R2 + a\ L3\ R5)\, f + R5\ R2)$$

2. Estimation of R_1 and L_2 using the expression (5):

$$SolutionL2R1\_sim := [L2 = 0.00103499,\ R1 = 0.053]$$
$$SolutionL2R1\_exp := [L2 = 0.0010343,\ R1 = 0.053105]$$
$$eps\_L2 := -0.066667 \quad eps\_R1 := 0.1981$$

3. Estimation of R_1 and L_2 using the expression (6):

$$SolutionL2R1\_sim := [L2 = 0.001035 - 0.27176\ 10^{-25}\ I,\ R1 = 0.05299999 + 0.116188\ 10^{-24}\ I]$$
$$SolutionL2R1\_exp := [L2 = 0.00103499 + 0.28846\ 10^{-8}\ I,\ R1 = 0.052995 + 0.5558\ 10^{-6}\ I]$$
$$eps\_L2 := -0.0009662 \quad eps\_R1 := -0.0094151$$

4. Estimation of the parameters $L_2 = L_{\sigma 1}$, $R_2 = R'_2$, and a using the expression (2)

Running the routine *myfunL3R2a* and considering the initial guess vector:

x_0= [0.000955*0.001;0.065434*1.015;0.026*1.015],
we get the following solution:

x =
0.00094145
0.06641536
0.02639043

The nominal values of the parameters L_3, R_2, and a are:

$L'_{\sigma 2} = L_3$ = 0.000955 H; $R'_2 = R_2$ = 0.065434 Ω; $a = 0.026$.

The relative errors have the expressions:
eps_L3=-1.41895 [%]; eps_R2=1.49977 [%];
eps_a=1.50167 [%].

5. Estimation of the parameters $L_2 = L_{\sigma 1}$, R_1, $L_3 = L'_{\sigma 2}$, and $R_2 = R'_2$ using the expression (2)

Running the routine myfun*L2R*1L3R2 and considering the initial guess vector:

x_0 = [0.001035*0.0001;0.000955*0.00001;0.053*0.01;
0.065434*0.01],
we get the following solution:

x =
0.0010392
0.0009495
0.0527124
0.0654223

The nominal values of the parameters L_2, R_1, L_3, and R_1 are:

$L'_{\sigma 1} = L_2 = 0.001035\,\mathrm{H}$; $R_1 = 0.053\,\Omega$;
$L'_{\sigma 2} = L_3 = 0.000955\,\mathrm{H}$; $R'_2 = R_2 = 0.065434\,\Omega$.

The relative errors have the expressions:
eps_L2=.407826 [%]; eps_R1=-.542588 [%];
eps_L3=-.57504 [%]; eps_R2=-.17925e-1 %].

6. Estimation of the parameters $L_3 = L'_{\sigma 2}$, $R_2 = R'_2$, $L_6 = L_m$, and $R_5 = R_{Fe}$ using the expression (2)

Running the routine *myfunL3R2L6R5* and considering the initial guess vector:

x_0 = [0.000955*0.0001;0.065434*0.01;
0.0281*0.01;190.0],
we get the following solution:

x =
1.0e+002 *
0.00000956
0.00065482
0.00028064
1.89999999

The nominal values of the parameters L_3, R_2, L_6, and R_5 are:

$L'_{\sigma 2} = L_3$ = 0.000955 H; $R'_2 = R_2$ = 0.065434 Ω;
$L_6 = L_m = 0.0281\,\mathrm{H}$; $R_5 = R_{Fe}$ = 200.0 Ω.

The relative errors have the expressions:
eps_L3=.723487e-1 [%]; eps_R2=.728367e-1 [%];
eps_L6=-.12889 [%]; eps_R5 := -5.0 [%].

Example 3.2: As the second example is considered an asynchronous three phase which has the following nominal parameters:

f_n = 50 Hz ; p = 4; $R_s = R_1$ =1.07131 Ω;
$R'_2 = R_2$ = 1.2951 Ω ; $L_{1\sigma} = L_2$ =0.00835 H;

$L'_{s\sigma} = L_3 = 0.04543$ H ; $L_\mu = L_m = L_6 = 0.1070572$ H;
$R_{Fe} = R_5 = 250.0\ \Omega$, and $a_n = 0.096$.

The simulation results are:

1. The complex driving-point impedance $\underline{Z}_{ii}$

$$Zii := (-247.6731521 I f^3\, L2\, L3\, L6\, a - 39.4384\,(L6\, a\, L3\, R5 + L2\, L6\, a\, R5 + L6\, a\, L3\, R1 + L2\, a\, L3\, R5 + L2\, L6\, R2)\, f^2 + 6.28\, I\,(L6\, R5\, R2 + L2\, R5\, R2 + L6\, a\, R1\, R5 + L6\, R1\, R2 + a\, L3\, R1\, R5)\, f + R1\, R5\, R2) \,/\, (-39.4384 f^2\, L6\, a\, L3 + 6.28\, I\,(L6\, a\, R5 + L6\, R2 + a\, L3\, R5)\, f + R5\, R2)$$

2. Estimation of R_1 and L_2 using the expression (5):

$SolutionL2R1\_sim$:= [$L2$ = 0.00835399, $R1$ = 1.07131]
$SolutionL2R1\_exp$:= [$L2$ = 0.0083538 , $R1$ = 1.07133]
eps_L2 := -0.0022744 eps_R1 := 0.0018669

3. Estimation of R_1 and L_2 using the expression (6):

$SolutionL2R1\_sim$:= [$L2 = 0.008354 - 0.9951\ 10^{-25}\ I$, $R1 = 1.07131 - 0.11176\ 10^{-22}\ I$]
$SolutionL2R1\_exp$:= [$L2 = 0.008354 - 0.9512\ 10^{-7}\ I$, $R1 = 1.0713 - 0.5788\ 10^{-6}\ I$]
eps_L2 := $0.6482\ 10^{-8}$ eps_R1 := -0.00093344

4. Estimation of the parameters $L_2 = L_{\sigma 1}$, $R_2 = R'_2$, and a using the expression (2)

Running the routine *myfunL3R2a* and considering the initial guess vector:
x_0 = [0.000955*0.001;0.065434*1.015; 0.026*1.015],
we get the following solution:

x =
0.00094145
0.06641536
0.02639043

The nominal values of the parameters L_3, R_2, and a are:
$L'_{\sigma 2} = L_3 = 0.000955$ H; $R'_2 = R_2 = 0.065434\ \Omega$;
$a = 0.026$;

The relative errors have the expressions:
eps_L3=-1.41895 [%]; eps_R2=1.49977 [%];
eps_a=1.50167 [%].

5. Estimation of the parameters $L_2 = L_{\sigma 1}$, R_1, $L_3 = L'_{\sigma 2}$, and $R_2 = R'_2$ using the expression (2).

Running the routine *myfunL2R1L3R2* and considering the initial guess vector:
x_0 = [0.001035*0.0001;0.000955*0.00001; 0.053*0.01; 0.065434*0.01],
we get the following solution:

x =
0.001039
0.000949
0.052712
0.06542

The nominal values of the parameters L_2, R_1, L_3, and R_1 are:
$L_{\sigma 1} = L_2 = 0.001035$ H; $R_1 = 0.053\ \Omega$;
$L'_{\sigma 2} = L_3 = 0.000955$ H; $R'_2 = R_2 = 0.065434\ \Omega$.

The relative errors have the expressions:
eps_L2=.407826 [%]; eps_R1=-.542588 [%];
eps_L3=-.575037 [%]; eps_R2=-.17925e-1 %].

6. Estimation of the parameters $L_3 = L'_{\sigma 2}$, $R_2 = R'_2$, $L_6 = L_m$, and $R_5 = R_{Fe}$ using the expression (2):

Running the routine *myfunL3R2L6R5* and considering the initial guess vector:
x_0 = [0.000955*0.0001;0.065434*0.01; 0.0281*0.01; 190.0],
we get the following solution:

x =
1.0e+002 *
0.000006
0.000655
0.000281
1.899999

The nominal values of the parameters L_3, R_2, L_6, and R_5 are:
$L'_{\sigma 2} = L_3 = 0.000955$ H; $R'_2 = R_2 = 0.065434\ \Omega$;
$L_6 = L_m = 0.0281$ H; $R_5 = R_{Fe} = 200.0\ \Omega$.

The relative errors have the expressions:

eps_L3=.723487e-1 [%]; eps_R2=.7284e-1 [%];
eps_L6=-.12889 [%]; eps_R5 := -5.0 [%].

Remarks

1. We denote that the obtained results by simulation and using the experimental data (when we use the formula (5) and/or the formula (6) to estimate the parameters) are practically identical;
2. The accuracy of the values of the estimated parameters by the *fminimax* routine from Matlab depends deeply on the guess initial values. For the parameters which have the small sensitivities, like resistance R_{Fe} and the slip a, the guess initial values must be very closed with the nominal values;
3. If the number of the parameters which we want to estimate is great than four, we must introduce some restrictions in the *fminimax* routine for that these procedure to be convergent;
4. When the number of the estimated parameters is less equal to two, the formulas (5) and (6) are very efficient. Over three estimated parameters the nonlinear equation system becomes very complicate and the solving of these equations is very difficult;

In the case we take into account the saturation phenomena we can use the estimation procedure based on time domain data and by an iterative identification algorithm based on Output Error method [1-3].

4. CONCLUSIONS

The paper presents a new method to estimate the induction motor parameters based on some measurements performed on the real system. Starting from the equivalent scheme on a phase of the induction motor in sinusoidal behavior and neglecting the saturation phenomena, we can generate the driving-point impedance (the input impedance) in full symbolic form. The magnitude and the phase of the complex driving-point impedance can be measured by supplying the stator phase with a variable frequency sinusoidal voltage, such that the ratio V_{1max}/f is preserved constant. We can also determine the numeric values of the magnitude and the phase of the complex driving-point impedance using the catalogue data of the analyzed induction motor. The approach is based on an appropriate frequency space representation of the induction motor, using the complex or Laplace modified nodal equations (MNE). Three efficient procedures to estimate the parameters of an induction motor are exposed. All procedures are based on the driving-point impedance (the input impedance) computed in full symbolic form. When the number of the estimated parameter is great than two the most efficient procedure is the procedure based on the *fminimax* routine from Matlab. All equations corresponding to the three techniques are the nonlinear ones.

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