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Research Article

DIAGNOSIS OF ROTOR FAULT USING NEURO-FUZZY INFERENCE SYSTEM

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ABSTRACT

The three-phase induction machine (IM) has a large importance and it is widely used as electromechanical system device, and because of their; robustness, reliability, and simple design with the well developed technologies. In spite of all cited advantages, the induction machines are suscptible to various types of electrical and mechanical faults that can lead easly to excessive downtimes, which can lead to tuge losses in terms of maintenance and production. This work presents a reliable approach for diagnosis and detection of broken bar faults in induction machine. The detection of faults is based on monitoring of the stator current signal. Also the calculation of relative energy value for each level of signal decomposition is determinated by using package wavelet, and this method will be useful as data input of Adaptive Neuro-Fuzzy Inference System (ANFIS). In the ANFIS approach the adaptive Neuro-Fuzzy inference system is able to identify the rotor of induction machine state with high precision.This method is applied by using the *MATLAB®/Simulink* software.

Keywords: Induction machine; diagnosis; detection; Neuro-Fuzzy inference system.

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NOMONCLATURE

L_b	Leakage inductance of a rotor bar
L_e	Leakage inductance of a portion of a short-circuit ring
L_{rp}	Principal inductance of a rotor mesh
L_{sp}	Principal inductance of a stator phase
L_{sr}	Mutual inductance between the stator phase and rotor mesh
M_s	Mutual inductance between two stator phases
M_{rr}	Mutual inductance between the stator phase and rotor mesh
N_r	Number of rotor bars
N_s	Number of stator turns
p	Number of poles
R_d	Resistance of a broken rotor bar
R_b	Resistance of healthy rotor bar
R_e	Resistance of a portion of a ring
R_s	Resistance of a stator phase
a	Distance between two rotor bars
θ	Rotor position

1. INTRODUCTION

The induction machines (IM) are widly used in various fields, such as electrical drives system and main component of any industrial areas that involve production processes [1, 2]. In spite of their low cost, reliability and robustness, breakdown in electrical machines lead to failure of the entire production system which cause considerable financial losses. Consequently, early detection faults are very useful for avoiding failure and allow minimizing the downtime [3, 4]. Rotor faults are one of the most important faults of these machine types [5, 6].

The presence of broken rotor bar in the squirrel cage generates an asymmetry of geometric and electromagnetic of rotor circuit. As a result, this fault reduces the average value of the electromagnetic torque and increases the amplitude of oscillations in the rotor speed. Hence, these consequences generate mechanical vibrations and lead to abnormal function and maybe a total deterioration of the induction machine [7].

According to the literature, there are several techniques of the diagnosis and detection of electrical and/or mechanical faults in stator and/or rotor faults of electrical machines drives, especially, the methods that based on time domain or frequency domain techniques, which have been suggested to detect stator failures. Many research efforts focused on frequency signature analysis for stator and rotor faults. These works were intersted to use different signals of machine such as; machine currents. The motor current signature analysis (MCSA), discrete wavelet transform (DWT), current envelope (CE), extended Park's vector approach (EPVA), instantaneous power signature analysis (IPSA) and Short-Time Fourier Transform (STFT), etc, for extracting useful information from different signals [8, 9]. The artificial intelligences (IA) such as Expert Systems, Algorithm (GA), support victor machine (SVM), fuzzy logic system inference, artificial neural network (ANN) or combined structure techniques of artificial neural fuzzy interference system (ANFIS), combined Genetic and ANFISs, are mostly used in the modern monitoring approaches of IM [10, 11]. Adaptive Neuro-Fuzzy Inference System (ANFIS) is the adaptive networks that are functionally equivalent to fuzzy inference system (FIS). The Sugeno type ANFIS uses a hybrid learning algorithm (FIS and ANN) to identify parameters of Sugeno-type fuzzy inference system. It combines the least squares method and the back propagation gradient descent method for training (FIS) membership function parameters to emulate a given training data set. An ANFIS works by applying neural learning rules to identify and tune the parameters and structure of a Fuzzy Inference System (FIS). There are several features of the ANFIS which enable it to achieve great success for a large range of applications [12, 13]. Therefore, in order to increase the effectiveness and the reliability of the monitoring in the field of the induction machine supervision, our proposed approach is based on Neuro-Fuzzy inference system (ANFIS). In the aim to analyzing the stator currents for diagnosis and monotoring the faults, the global mathematical model of induction machine is developed and simulated via software *MATLAB® /Simulink.*

2. INDUCTION MOTOR MODEL

2.1. Multi meshes model of rotor broken bars fault

By the consideration that the studied induction machine has three phases concentric winding in stator circuit and N_r bars, the rotor is which can be described as N_r idantical and equally spaced rotor loops, each loop comprises tow rotor bars plus the connection parts of the end-rings between them as shown in figure 1 [14].

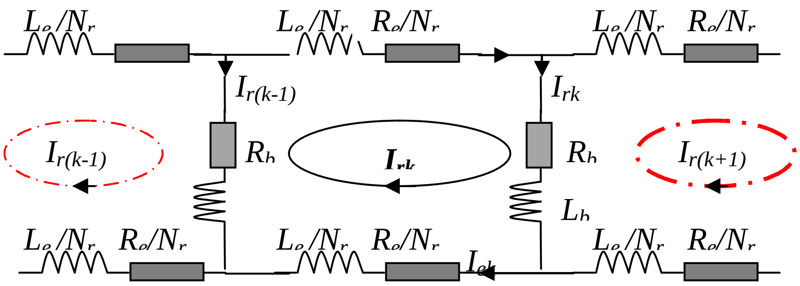

Fig.1. Rotor meshs circuit topology

The global mathematical model of the squirrel cage induction machine is expressed by the following matrix [15]:

$$[V] = [R][I] + \frac{d}{dt}([L][I]) \tag{1}$$

Where,the matrix of voltage and current are respectively given Eq. (2) and Eq. (3):

$$[V]=\begin{bmatrix}[V_s]\\ \\ [V_r]\end{bmatrix} \tag{2}$$

$$[I]=\begin{bmatrix}[I_s]\\ \\ [I_r]\end{bmatrix} \tag{3}$$

With, the system of different stator and rotor vectors matrix of voltage and currents is presented as follows:

$$\begin{cases}[V_s] = [\,V_{s1} \quad V_{s2} \quad V_{s3}]^t\\ [I_s] = [\,I_{s1} \quad I_{s2} \quad I_{s3}]^t\\ [V_r] = [0 \quad 0 \quad 0 \ldots \quad 0]^t_{1\times N_{r+1}}\\ [I_r] = [I_{r1} \quad I_{r2} \quad I_{r3} \ldots \quad I_{rk} \cdots \quad I_{rN_r} \; I_e]^t_{1\times N_{r+1}}\end{cases} \tag{4}$$

The global resistance is expressed by the following matrix:

$$[R]=\begin{bmatrix}[R_s]_{3\times3} & \vdots & [0]_{3\times N_r} & \vdots & [0]_{3\times1}\\ \cdots & \cdots & \cdots & \cdots & \cdots\\ [0]_{N_r\times3} & \vdots & [R_r]_{N_r\times N_r} & \vdots & -\frac{R_e}{N_r}[1]_{N_r\times1}\\ \cdots & \cdots & \cdots & \cdots & \cdots\\ [0]_{1\times3} & \vdots & -\frac{R_e}{N_r}[1]_{1\times N_r} & \vdots & R_e\end{bmatrix} \tag{5}$$

Where, the matrix of stator and rotor resistances are respectivelly given by Eq.(6) and Eq.(7):

$$[R_s]_{3\times3}=\begin{bmatrix}R_s & 0 & 0\\ 0 & R_s & 0\\ 0 & 0 & R_s\end{bmatrix} \tag{6}$$

$$[R_r]_{N_r\times N_r}=\begin{bmatrix} R_{b0}+R_{b(N_r+1)}+\frac{2R_e}{N_r} & -R_{b0} & 0 & \cdots & \cdots & 0 & -R_{b(N_r+1)} \\ 0 & \cdots & -R_{b(N_r-1)} & R_{bk}+R_{b(N_r-1)}+\frac{2R_e}{N_r} & -R_{bk} & 0 \cdots & 0 \\ -R_{b(N_r-1)} & 0 & \cdots & 0 & -R_{b(N_r-2)} & & R_{b(N_r-1)}+R_{b(N_r-1)}+\frac{2R_e}{N_r} \end{bmatrix} \quad (7)$$

The mutual inductance matrix between stator phases and rotor mesh can be written as following:

$$[M_{sr}]_{Nr\times 1}=\begin{bmatrix} \cdots & -M_{sr}\cos(\theta+ka) & \cdots \\ \cdots & -M_{sr}\cos\left(\theta+ka-\frac{2\pi}{3}\right) & \cdots \\ \cdots & -M_{sr}\cos\left(\theta+ka-\frac{4\pi}{3}\right) & \cdots \end{bmatrix} \quad (8)$$

Where, k is ranging from 0 to N_{r-1}.

The inductances matrix of stator phases expressed by the relationship (9) is of the order (m, m), where m=3:

$$[L_S]_{3\times 3}=\begin{bmatrix} L_{sp} & M_s & M_s \\ M_s & L_{sp} & M_s \\ M_s & M_s & L_{sp} \end{bmatrix} \quad (9)$$

The inductances matrix of rotor N_r bars is expressed by the follows relationship:

$$[L_R]_{N_r\times N_r}=\begin{bmatrix} L_{rp}+2L_b+\frac{2L_e}{N_r} & M_{rr}-L_b & M_{rr} & M_{rr} & \cdots & M_{rr}-L_b \\ M_{rr}-L_b & L_{rp}+2L_b+\frac{2L_e}{N_r} & M_{rr}-L_b & M_{rr} & \cdots & M_{rr} \\ M_{rr} & M_{rr}-L_b & L_{rp}+2L_b+\frac{2L_e}{N_r} & M_{rr}-L_b & M_{rr} & \cdots \\ M_{rr} & \vdots & \vdots & \vdots & \vdots & \vdots \\ \ddots & \ddots & \ddots & \ddots & \ddots & \ddots \\ M_{rr}-L_b & M_{rr} & M_{rr} & \cdots & M_{rr}-L_b & L_{rp}+2L_b+\frac{2L_e}{N_r} \end{bmatrix} \quad (10)$$

The modeling of a broken rotor bar can be modeled by increasing of its resistance value, so that the current transitory through it is devolves to zero, the new structure of rotor meshs circuit in broken rotor bar will be as shown in Figure 2.

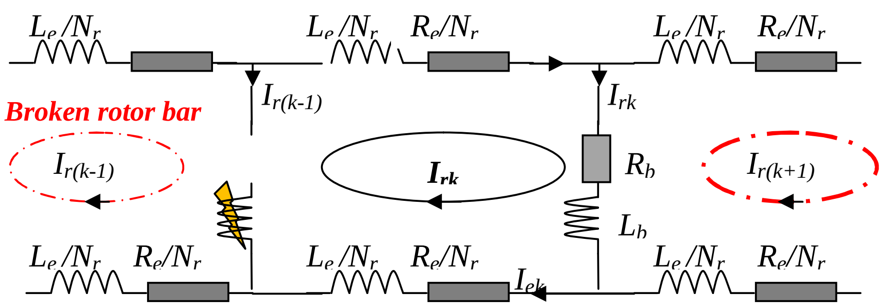

Fig.2. Rotor meshs circuit in one broken rotor bar

This is introduced in the matrix of resistances by the addition of the matrix of the rotor resistance [R_r] with the default matrix [R_d].

$$[R_d] = \begin{bmatrix} 0 & 0 & 0 & \cdots & 0 \\ \vdots & 0 & \cdots & \cdots & 0 \\ \vdots & R_{k,k} & R_{k,k+1} & 0 & \vdots \\ 0 & R_{k+1,k} & R_{k+1,k+1} & \vdots & \vdots \\ 0 & \cdots & \cdots & 0 & 0 \end{bmatrix} \quad (11)$$

In case of the broken bar, the resistance value of this bar is multiply by M = 10^3, with:

$$R_{k,k} = R_{k+1,k+1} = (M+1).R_b + 2.R_e \quad (12)$$

$$R_{k+1,k} = R_{k,k+1} = (-M).R_b \quad (13)$$

Therefore, the rotor cage resistance matrix, with considering of the broken bars fault is defined as following:

$$[R_{rd}] = [R_r] + [R_d] \quad (14)$$

3. RESULTS AND DISCUSSION WAVELET PACKET METHOD

3.1. Decomposition level

The decomposition level of the approximation signal, which includes the left side band harmonic, is the integer n_{Ls} given by:

$$n_{Ls} = int\left(log\left(\frac{f_s}{f}\right)/log(2)\right) \quad (15)$$

For this approach, further decomposition of this signal has to be done, so that the frequency band $[0 - f]$ will be decomposed in more bands. Usually, two additional decomposition levels (that is, n_{Ls} +2) would be adequate for the analysis [16]:

$$n_{Ls} + 2 = int\left(\frac{log\left(\frac{10000}{50}\right)}{log(2)}\right) + 2 = 9\ levels \quad (16)$$

3.2. Energy level of the wavelet decomposition

The multilevel decomposition of the stator current was performed using Daubechies wavelet, the appropriate level of decomposition is calculated according to Eq. (14), when the faulty rotor is on the stator current phases of the induction machine appears, the faults information in stator current is integrated on each frequency band determined by the wavelet decomposition or in wavelet packet. Through calculated the associate energy of each nodes of decomposition level, for build one effective diagnosis and monitoring tools. The energy proper value for each frequency band is defined by [17, 18]:

$$E_j = \sum_{k=1}^{k=n} \left| D_{j,k}(n) \right|^2 \quad (17)$$

Based on the energy eigen value, the eigen vector is set up as:

$$T = \left[\frac{E_0}{E}, \frac{E_1}{E}, \frac{E_2}{E} \dots \dots \frac{E_{2^m-1}}{E} \right] \quad (18)$$

Where D_j is the amplitude in each discrete point of the wavelet signal coefficient in the corresponding frequency band.

$$E = \sum_{j=0}^{2^m-1} \left| E_j \right|^2 \quad (19)$$

The proper value T has information on the stator current signal for a machine behavior. In addition, the amplitudes of the deviation of some proper values indicate the severity of the faults, which makes a high quality of damaged bars supervision.

4. ADAPTIVE NEURO-FUZZY INFERENCE SYSTEM

ANFIS is a hybrid controller structure using fuzzy logic inference system and the architecture of a neural network having five-layer feed-forward structure [19-21]. Thus, the ANFIS offers the advantages of learning capability of neural networks and inference mechanism of fuzzy logic. The typical architecture of ANFIS has *n* inputs, *one* output (*f*), and *m* rules as illustrated in Figure. 3.

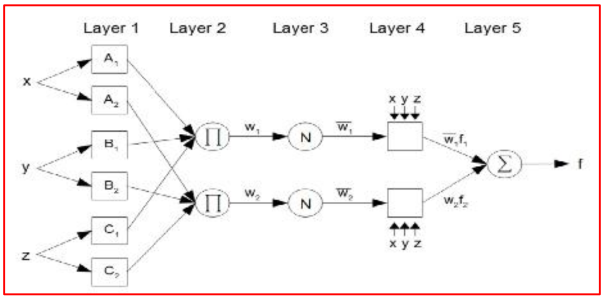

Fig.3. Typical ANFIS structure

In the structure *x*, *y*, *z* and up to *n* are inputs, the output is *f*, the circle signify the fixed node functions and the square signify the adaptive node functions. This is a Sugeno type fuzzy system, where the fuzzy *If-Then* rules have the following form:

- Rule1: If x is A_1 and y is B_1,……………..n is k_1
  Then $f_1 = (p_1x+q_1y+r_1z+\dots\dots v_1)$
- Rule 2: *If* x is A_2 and y is B_2,……………..n is k_2
  Then $f_2 = (p_2x+q_2y+r_2z+\dots\dots v_2)$.
- Rule m: *If* x is A_m and y is B_m,……………n is k_m

Then $f_m = (p_m x + q_m y + r_m z + \ldots\ldots v_m)$.

In this paper we are using the stator current signals as the input nodes, and the output is the estimated machine state for classified the rotor broken bars fault The ANFIS model provides the output value which can be used for advance decision making, also to go for preventive maintenance or to program of the maintenance. The suggested model for monitoring system is developed under *MATLAB/Simulink*. Database that collected from off-line is used to associate the energy to each node of decomposition level of stator current signal. The inputs are translated into 8 different Gaussian membership functions and 64 rule bases.

5. RESULTS AND DISCUSSION

The Figure 4 and Figure 5 show, respectively, the stator current phase “I_{sa}” in healthy case and the stator current phase “I_{sa} “ in broken rotor bar with Zoom, the presented result presented shows the appearing of the envelopes on the ends of the current .

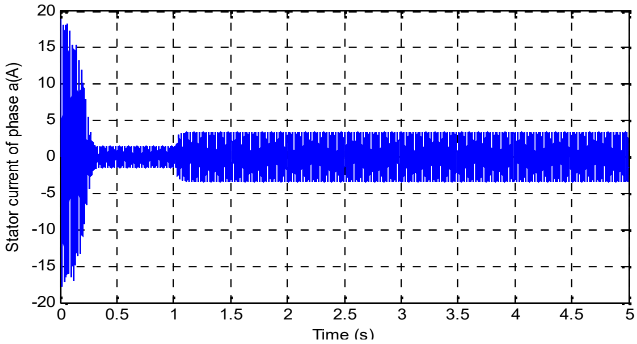

Fig.4. Stator current in healthy case

Figure 6 presents the variation of decomposition energy level of wavelet in the 16 frequency bands for healthy function case and with the presence of fault broken rotor bars in the induction machine. The ANFIS model generates eight input membership functions of Gaussian structure and it runs for 500 Epochs.

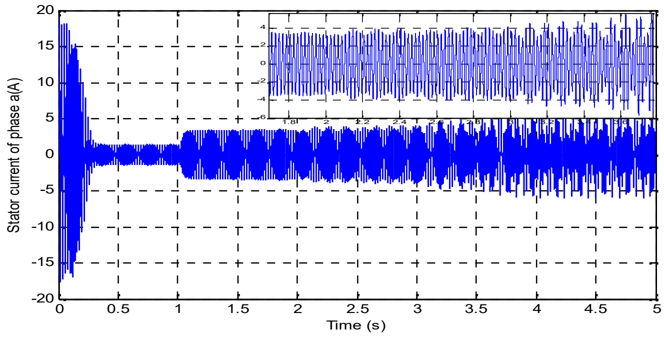

Fig.5. Stator current in broken 5 rotor bars case

The error for the training and checking output is found to be 0.004 % as shown in Figure.7. The trained and checked ANFIS output for different types of fault diagnosis are shown in Figure. 8.

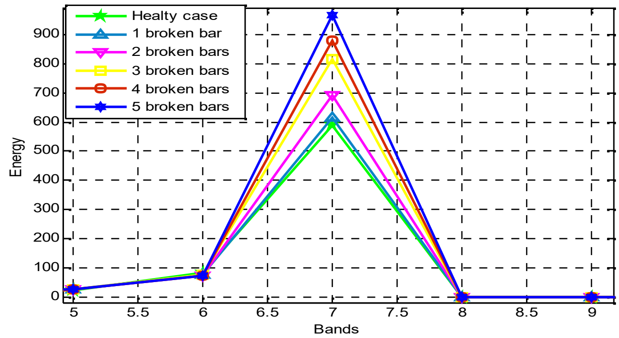

Fig. 6. Variation of the energy levels in the frequency bands

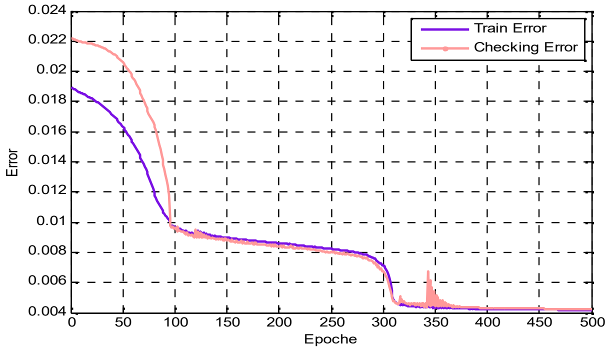

Fig. 7. Error curve of the ANFIS controller (Rotor broken bars)

The input relationships or dependency for the ANFIS output are in addition analyzed. These are the unique characteristics of adaptive neuro-fuzzy inference system. The mapping is optimized by neuro adaptive learning techniques by fuzzy modeling procedure to learn information about the data set for monitoring the stat of induction machine in our case study.

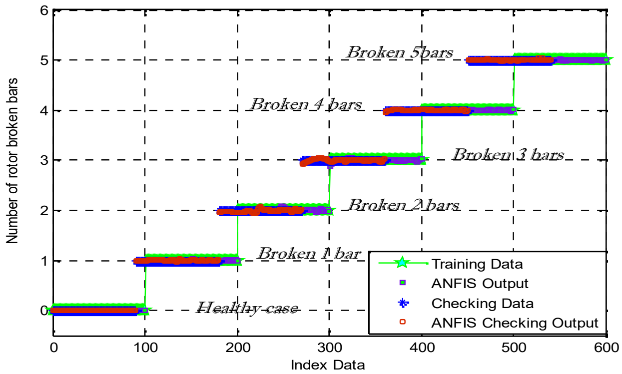

Fig.8. Training, Testing and Checking Output for the ANFIS controller (Rotor broken bars)

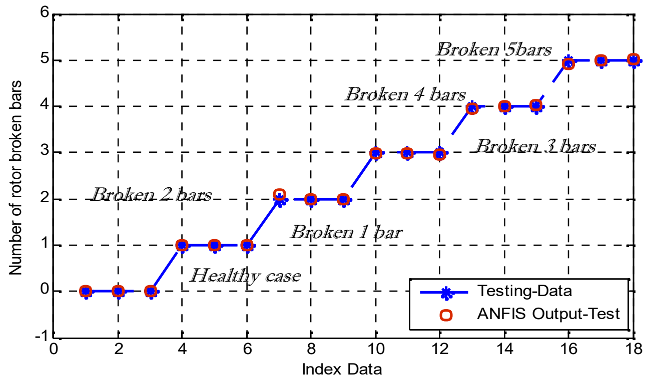

Fig.9. Testing Data and Testing Output for the ANFIS controller (Rotor broken bars)

To validate our network (shown the Fig.9), a test of recognition is carried out. The results are consigned in the following table (Show Tab.1).

Tabl 1. Numerical values of input-output for validate ANFIS

Inputs		Outputs		Observations of the Error
x	***y***	***Desired***	***Estimated***	
HEALTHY CASE				
95.5056	366.6240	0.0000	0.0000	0.0000
96.5848	380.2702	0.0000	0.0000	0.0000
98.1150	405.8460	0.0000	0.0000	0.0000
1 BROKEN BARS				
61.6177	351.4025	1.0000	1.0011	-0.0011
61.6177	366.5898	1.0000	0.9993	0.0007
65.3050	412.7210	1.0000	0.9987	0.0013
2 BROKEN BARS				
56.7994	381.6860	2.0000	1.9998	0.0002
58.1560	398.6990	2.0000	2.0022	-0.0022
59.3361	416.9158	2.0000	1.9877	0.0023
3 BROKEN BARS				
57.3547	434.1678	3.0000	3.0076	-0.0024
60.0000	480.0000	3.0000	2.9938	0.0062
62.5511	520.7533	3.0000	3.0009	-0 .0001
4 BROKEN BARS				
53.0000	462.0000	4.0000	3.9895	0.0205
55.8730	500.4854	4.0000	4.0011	-0.0011

59.0201	550.6706	4.0000	3.9993	0.0007
5 BROKEN BARS				
63.0000	552.0000	5.0000	4.8890	0.0210
65.8730	630.4051	5.0000	5.0000	0.0000
70.0111	645.0800	5.0000	5.9997	0.0003

6. CONCLUSION

In this paper, the development the healthy and the fault models of induction machine are presented; also the simulation of each models with application of the diagnosis approach for detection the presence of faults. The first part of this work presented the mathematical models of healthy and faulty machines with damaged rotor bars. In the second part; the ANFIS approach was used in aim to diagnose the broken bars in the induction machine. The adaptive neuro-fuzzy system inference indicator is based on the analysis of magnitude of energy level of the wavelet decomposition of stator current, this associate energy is used as inputs of ANFIS, and in addition, the off-line training and checking of ANFIS is used. The data bases are collected for different number of broken rotor bars. Finally, the performance of the ANFIS offered satisfactory results with high precision.

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