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IMPROVEMENT IN DIRECT TORQUE CONTROL OF INDUCTION MOTOR USING FUZZY LOGIC DUTY RATIO CONTROLLER

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ABSTRACT

This paper shows the application of fuzzy logic based duty ratio control technique to reduce torque ripple in an induction motor employing Direct Torque Control (DTC). This technique increases the number of voltage vectors beyond the available eight discrete voltage vectors without any increase in the number of semiconductor switches in the inverter. Look-up Table based on-line tuning PI controller is proposed for outer speed control loop to achieve swift response, less overshoot and precision speed control to have wide torque-speed characteristics. A new algorithm for optimized value of stator flux based on the maximum reference value of electromagnetic torque is proposed to operate in conjunction with duty ratio control. The performance of the proposed drive system is evaluated through digital simulation using MATLAB-SIMULINK package. The simulation results clearly depict the superiority of devised method over the existing methods of DTC.

Keywords: direct torque control, fuzzy logic duty ratio controller, induction motor.

1. INTRODUCTION

The Induction Motor (IM) drives controlled with the vector control method has found wide acceptance in the industry. However, this control technique requires complex coordinate transformation, inner current control loop and accurate system parameters [3]. On the other hand, the Direct Torque Control (DTC) method [7, 12] provides robust and fast torque response without such coordinate transformation, PWM pulse generation and current regulators [20]. Moreover, DTC minimizes the use of motor parameters [7, 10].

Despite, this technique suffers from a major disadvantage of steady state ripple in torque and flux, because none of the inverter-switching vector is able to generate the exact stator voltage at proper instants as well as in space. These torque and flux ripples affect the accuracy of speed estimation; result in high acoustic noise and harmonic losses [26]. There are many methods to reduce this torque and flux ripple: (a) the alternative inverter topologies [11], multilevel inverters [6, 28] and matrix converters [4] which increase the number of switches, and thus cost and complexity; (b) the higher switching frequencies reduce the harmonic content of stator current and thus torque and flux ripple. However, such higher switching frequencies lead to increased switching losses and stress on semiconductor switches of the inverter [22, 23]; (c) yet, another method of reducing torque and flux ripples is space vector modulation [9, 16, 18] that has disadvantage of variable switching frequency [14]. Moreover this method requires complex control schemes than classical DTC and is machine parameter dependent; (d) the Discrete Space Vector Modulation [5, 10] overcomes the disadvantages of SVM technique with an accurate switching Table and five level hysteresis bands, but this method cannot guarantee its functionality at low speed range, especially with heavy load [20].

Some more solutions available in literature include modified switching Table based DTC [15], variable amplitude control of flux and torque hysteresis bands [13], open loop control of hysteresis band amplitude [27], and fuzzy logic based variable amplitude control of flux and torque hysteresis bands [8]. But these are complex in nature for easy implementation. The ripple in the torque and flux can be easily reduced by applying the selected inverter vector only for the part and not for the entire switching period unlike that in the classical DTC. This technique, also known as duty ratio control, increases the number of voltage vectors beyond the available eight discrete ones, without any increase in the number of semiconductor switches in the inverter [21, 23]. The work in [2] refers to fuzzy logic duty ratio control but fails to give any details. Similar work presented in [19, 24] claims reduction in ripple to one-third value. However, simulation results were shown for low speed operation only using a fuzzy controller with three membership functions for inputs and output. They have shown an algorithm for optimized value of reference flux based on reference load torque.

The work presented in this paper considers the design of new fuzzy logic controller with five membership functions for the inputs and output along with the optimized flux algorithm based on maximum reference value of the electromagnetic torque to adjust the "duty ratio" of inverter switching vectors. The present work shows much better performance (reduced ripple) though it has some similarities with those in [2, 19, 23]. A significant reduction in the ripple than that in [19, 24] has been achieved in the present work. The adaptive PI controller that is based on look-up Table is used for outer speed loop for precision speed tracking. A series of simulation tests are conducted using MATLAB-SIMULINK package to validate the performance of the devised algorithm.

The complete paper is organized as follows: Section 2 explains strategy of torque ripple minimization. Section 3 discusses design of fuzzy logic duty ratio controller. The simulation results, comparison and discussion are presented in Section 4. Section 5 concludes the work.

2. TORQUE RIPPLE MINIMIZATION STRATEGY

Despite of the available complex solutions [4-6, 9-11, 14, 16, 18, 26, 28] the duty ratio scheme presents best remedy to minimal torque and flux ripple, by overshadowing the above-mentioned existing methods. In the classical DTC, a voltage vector is applied for the entire switching period, and this causes the stator current and electromagnetic torque to increase over the whole switching period. Thus for small errors, the electromagnetic torque exceeds its reference value early during the switching period, and continues to increase, causing a high torque ripple. This is then followed by switching cycles, where the null switching vectors are applied to set the electromagnetic torque to its reference value.

The ripple in the torque and flux can be easily reduced by applying the selected inverter vector only for the part and not for the entire switching period unlike that in the classical DTC IM drive. The time for which an active voltage vector has to be applied is chosen just to increase the electromagnetic torque to its reference value and the null voltage vectors are applied for the rest of the switching period. During the application of the null vectors the motor absorbs no power, and thus the electromagnetic torque is almost constant or decreases slightly. But this decrease should be small to have minimum torque ripple. Since this decrease in torque also depends on the modulus of the reference stator flux, an optimized value for the flux has to be used, which is large enough to generate the reference torque. This implies that the maximum electromagnetic torque reference has to be found and the optimized stator flux reference corresponds to this, as follows: The expression of stator current space vector in stator flux oriented reference frame can be obtained as,

$$\bar{i}_s = \frac{\left(L_m/L_s\right)\left|\bar{\psi}_s\right|\left(R_r + j\omega_{sl}L_r\right)}{\left(R_r + j\omega_{sl}\sigma L_r\right)} \tag{1}$$

The imaginary part of the above equation gives the torque producing stator current $\left(i_{sy}\right)$, and maximum value of this occurs at $\omega_{sl,\max} = 1/T_r'$ (T_r' denotes the rotor transient time constant). By substituting the corresponding $i_{sy,\max}$ value in the electromagnetic torque expression, $T_e = 3/2\left(P/2\right)\bar{\psi}_s \times \bar{i}_s$ of induction motor, the maximum torque can be evaluated as follows:

$$T_{e,\max} = 3/2\left(P/2\right)\left|\bar{\psi}_s\right|i_{sy,\max} \tag{2}$$

The maximum electromagnetic reference torque can be found from the above equation by substituting $T_e = T_{e,ref}$, as shown in equation (3).

$$T_{e,ref}^{\max} = \frac{3}{4}\frac{P}{2}\left(\frac{L_m}{L_s}\right)^2\frac{\left|\bar{\psi}_s\right|^2}{\sigma L_r} \tag{3}$$

The optimized reference flux linkage for the given maximum electromagnetic torque reference can be calculated by setting $\left|\bar{\psi}_{s,ref}\right| = \left|\bar{\psi}_s\right|$ as in equation (4).

$$\left|\bar{\psi}_{s,ref}\right| = \sqrt{\frac{8T_{e,ref}^{\max}L_s^2\sigma L_r}{3PL_m^2}} \tag{4}$$

When the above optimized stator flux linkage value is used in DTC induction motor drive along with duty ratio control, the torque ripples reduce significantly. But, the duty ratio of each switching period is a non-linear function of the electromagnetic torque error (E_{Te}), stator flux-linkage error ($E_{\psi s}$), and the position of the stator flux-linkage space vector (ρ_s). It is difficult to model such non-linear function. However, the characteristics (such as, model free nature and non-dependence on mathematical equations [17]) of fuzzy logic controller make the duty ratio determination possible and easier during every switching period.

3. PROPOSED METHODOLOGY

Figure-1 shows the schematic of proposed DTC IM drive with fuzzy logic based duty ratio control. Two Mamdani type fuzzy logic controllers (FLC-1 and FLC-2) that contain fuzzifier, inference engine, rule base, and defuzzifier are chosen. The FLC-1 and 2 are used for positive and negative flux error respectively. In classical DTC, outer loop speed regulators are conventional PI controllers, which require precise math model of the system and appropriate value of PI constants to achieve high performance drive. Therefore, unexpected change in load conditions or environmental factors would produce overshoot, oscillation of the motor speed, oscillation of the torque, long settling time and, thus causes deterioration of drive performance. To overcome this problem, a look-up Table is designed from the experiences of speed response of classical DTC. According to the speed error and change of speed error, the proportional and integral gains are adjusted on-line.

A. Selection of input/output variables

The design starts with assigning mapped input/output variables of FLC. In this work, the first input variable is the torque error ($E_{Te} = T_{e,ref} - T_e$) and the second input variable is the stator flux vector position (ρ_s) at a sampling time t_s. The output variable is duty ratio (δ).

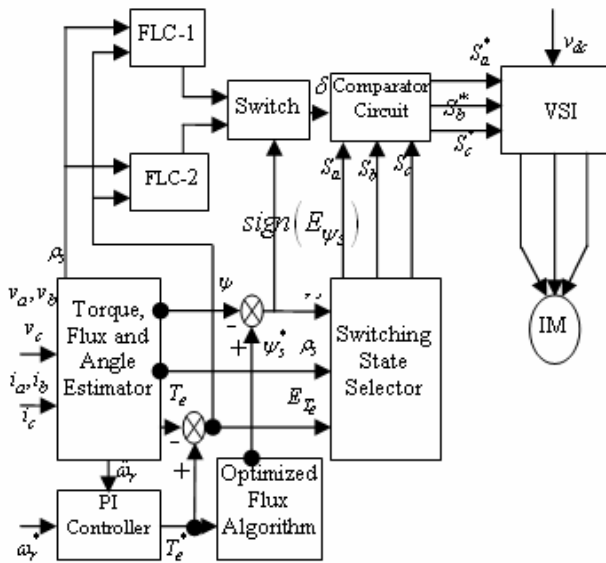**Figure-1.** Schematic diagram of proposed DTC with fuzzy
logic duty ratio controller.

B. Fuzzification

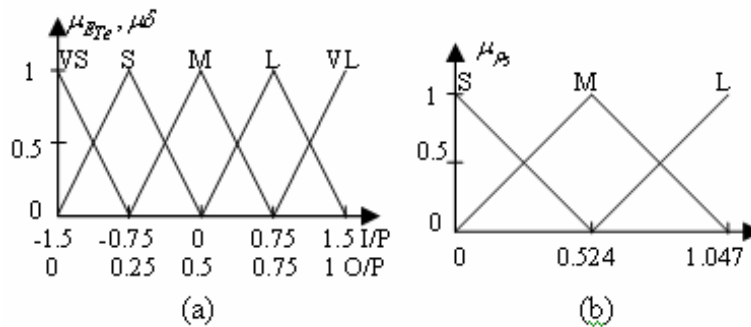The success of robust fuzzy controller design mainly depends upon this stage. In this stage the crisp variables of the inputs $E_{Te}(t_s)$ and $\rho_s(t_s)$ are converted into fuzzy variables E_{Te} and ρ_s that can be identified by the levels of membership in the fuzzy set. Each fuzzy variable is a member of the subsets with a degree of membership μ varying between 0 (non-member) and 1 (full member).

To make the torque and duty ratio variations smaller, the universe of discourse of torque error and duty ratio are divided into five overlapping fuzzy sets. However, to reduce the complexity of design, the stator flux position is defined with three overlapping fuzzy sets only. The universe of discourse of all the variables, covering the whole region is expressed in per unit values. The fuzzy subsets are defined with triangular membership functions as shown in Figure-2. The linguistic labels are defined as VS = Very Small, S = Small, M = Medium and L = Large, VL = Very Large.

Figure-2. Membership functions for (a) torque error and duty
ratio (b) stator flux position.

C. Rule base and fuzzy inference engine

The Rule base involves defining the rules in IF-THEN form, which govern the relation between input and output variables in terms of membership functions. In this stage the input variables are processed by the inference engine that executes 15 rules (5x3) as shown in Table-1. These rules are generated from the knowledge of control systems and the simulation results of classical DTC induction motor using different switching states.

The inference engine also includes the application of fuzzy operator (AND, OR), product operation of fuzzy implication and maximum aggregation. The relation between different conditions in the same rule is done by means of 'AND' operator. On the other hand, the relationship between different rules is done by means of 'OR' operator.

Table-1. Fuzzy control rules for duty ratio determination.

$E_{\psi s}$	E_{Te} / ρ_s	**VS**	**S**	**M**	**L**	**VL**
	S	S	M	M	L	VL
$\|\bar{\psi}_s\| < \|\bar{\psi}_{s,ref}\|$	M	VS	S	M	L	VL
	L	VS	S	M	L	VL
	S	VS	S	M	M	VL
$\|\bar{\psi}_s\| > \|\bar{\psi}_{s,ref}\|$	M	VS	S	M	L	VL
	L	S	M	L	VL	VL

D. Defuzzification

This stage introduces different inference methods that can be used to produce the fuzzy set values for the output fuzzy variables. In this paper, the center of gravity

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(COA) or centroid method is used to calculate the final fuzzy value. The COA expression with a discretized universe of discourse can be written as,

$$\delta = \frac{\sum\limits_{i=1}^{n} \delta_i \, \mu_{out}(\delta_i)}{\sum\limits_{i=1}^{n} \mu_{out}(\delta_i)} \qquad (5)$$

Where, n denotes the total number of rules. The comparator circuit as shown in Figure-1, compares the

duty ratio determined during each switching period with a triangular signal, whose period is equal to that of switching period and thus determines the duration for which active vector should be applied. The modified symmetrical switching vectors fed to the inverter would improve the performance of drive.

4. RESULTS COMPARISON AND DISCUSSIONS

A series of simulation tests are conducted on a 4KW, 4pole inverter-fed IM to evaluate the performance of proposed DTC method.
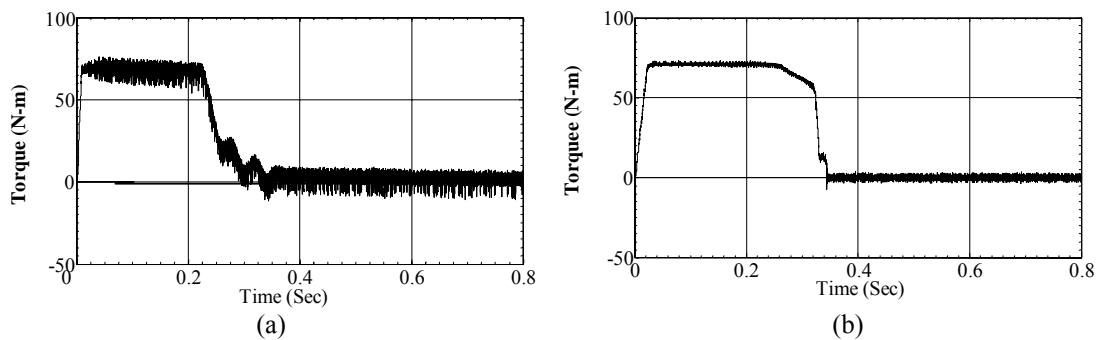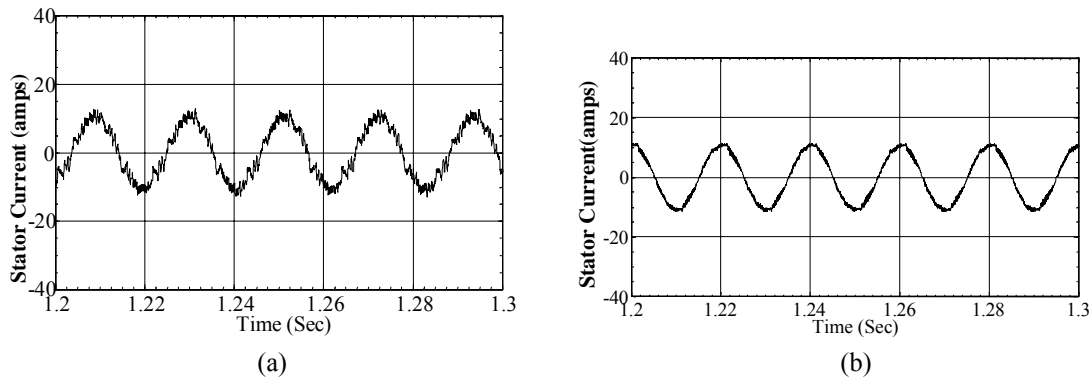

Figure-3. Simulation results for torque response with reference speed of 157 rad/sec and no load (a) classical (b) proposed DTC.
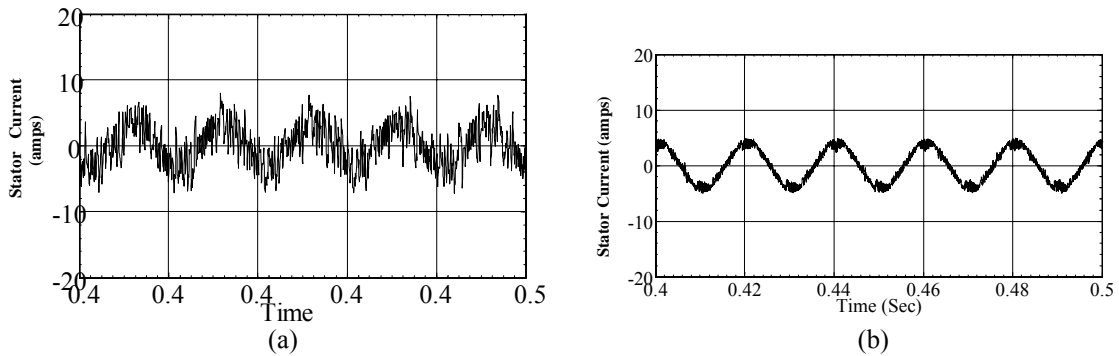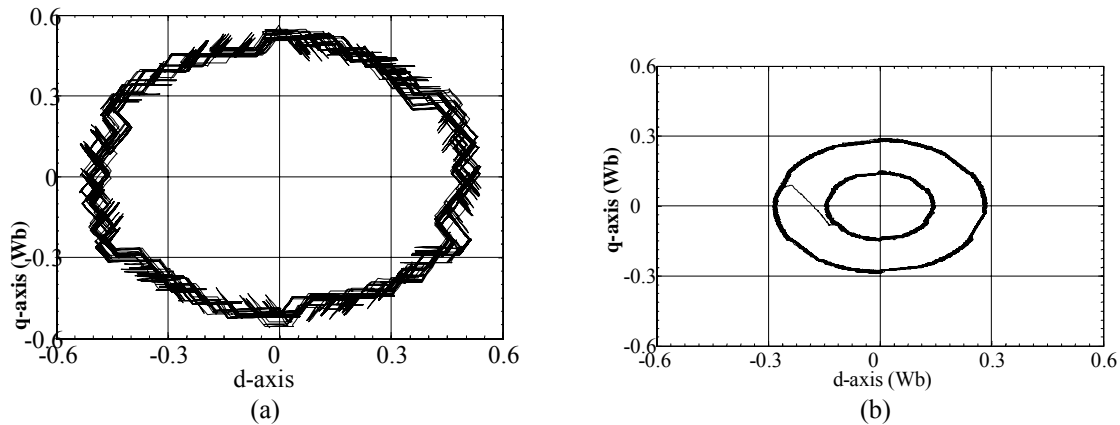

Figure-4. Simulation results for stator current with reference speed of 157 rad/sec and no load (a) classical DTC (b) proposed DTC.
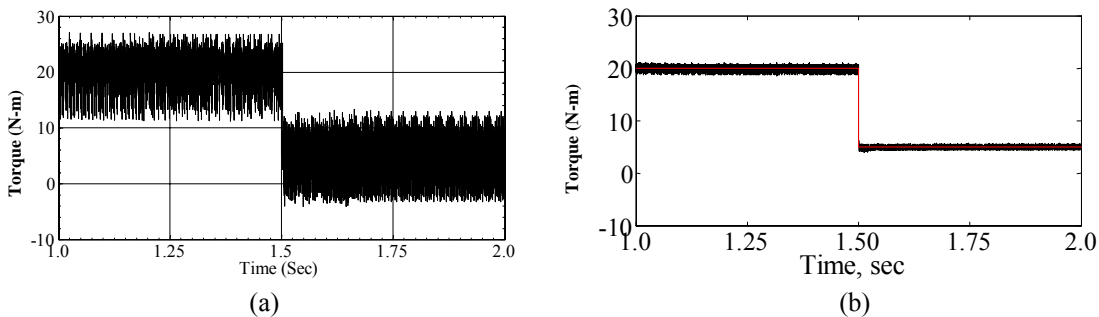
Figure-5. Simulation results for electric torque response (a) Classical DTC with reference speed of 157 rad/sec and step load (b) proposed DTC with reference speed of 157 rad/sec and step load.

Figure-6. Simulation results for stator current with reference speed of 157 rad/sec
and step load (a) classical DTC (b) proposed DTC.

Figure-7. Simulation results for stator flux trajectory with reference speed of 157 rad/sec
and step load (a) classical DTC (b) proposed DTC.

The torque response has been analyzed in steady state. These tests are carried out for 157-rad/sec speed operation, with sudden drop in load torque from 20N-m to 5N-m at 1.5sec. A constant un-optimized stator flux value of 0.5 Wb is used for classical DTC. Whereas, optimized stator flux values of 0.3734Wb (for 20N-m load) and 0.1867 Wb (for 5N-m load) are used for proposed one.

Figure-3(a) and 3(b) shows electric torque response for classical DTC and proposed DTC respectively for no load operation. In addition to the inherent disadvantage of classical DTC, the constant reference flux causes higher ripple at lower torque level because, the chosen 0.5 Wb is larger than the optimized flux value (0.1867Wbs). But, the proposed method causes lower ripple at lower torque level than at the higher torque level. Moreover, this method is able to eliminate the torque undershoot and overshoots. The average amount of ripple reduction in torque compared to classical DTC is observed to be $1/19^{th}$ (~11N-m for classical with peaks up to ~16N-m, and ~1.2N-m for proposed) and $1/15^{th}$ (~15N-m for classical with peaks up to ~19N-m, and ~1N-m for proposed) respectively for higher and lower torque levels of high-speed operation. Similarly, for low speed operation the reduction is observed to be more than $1/10^{th}$ (~9N-m for classical with peaks up to ~14N-m, and

~0.8N-m for proposed) and $1/17^{th}$ (~11N-m for classical with peaks up to ~15N-m, and ~0.6N-m for proposed) respectively for higher and lower torque levels. Figure-4 (a) and 4(b) shows no-load stator currents for classical and proposed DTC respectively for a reference speed of 157 rad/sec. Figure-5(a) and 5(b) shows electric torque response for classical DTC and proposed DTC respectively for a step load, Figure-6(a) and 6(b) shows stator currents for classical and proposed DTC respectively for a reference speed of 157 rad/sec for a step load and Figure-7(a) and 7(b) shows stator flux trajectory for classical and proposed DTC respectively for a reference speed of 157rad/sec and with a step load.

5. CONCLUSIONS

In this study, on-line PI tuning and torque ripple minimization strategy are brought to a common platform to alleviate the disadvantages of classical DTC employed to control an inverter-fed induction motor drive. The fuzzy logic duty ratio controller with optimized reference flux command is applied and verified. Low speed operation of the proposed method dictates the proper functionality of speed estimation as well as precision torque control. From the simulation tests the following justifiable conclusions are drawn against the existing solutions.

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a) The devised method is easier to understand, design and implement. The input/output scaling factors for fuzzy logic controller are absent;

b) Increased efficiency as well as lower acoustic noise for the induction motor drive is observed because of the significant reduction (~1/15th) in torque, flux and current ripples/harmonics. In addition to the torque ripple minimization, under (over) shoots are also eliminated;

c) The proposed method operates at a lower switching frequency, and thus reduces switching losses as well as stress on semiconductor switches of the inverter;

d) From the simulation results shown, it is clear that, the proposed method of DTC will reduce the torque and flux ripple considerably; and

e) The smoother flux trajectory for the proposed method of DTC confirms the ripple reduction in torque, flux, stator current and speed response.

Appendix

3-Phase Induction Motor Parameters
Rotor type: Squirrel cage, Reference frame: Stationary
4KW, 1440 rpm, 50Hz, 4 Poles, $R_s = 1.57\Omega$, $R_r = 1.21\ \Omega$, $L_s = 0.17$ H, $L_r = 0.17$ H, $L_m = 0.165$ H, $J = 0.06$ Kg-m^2.

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