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Self–Tuning Fuzzy Logic Controller for a Dual Star Induction Machine

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Abstract – This paper proposes a simple but robust self-tuning fuzzy logic controller for the speed regulation of a dual star induction machine based on indirect field oriented control. For feed the two star of this machine, two voltage source inverters based on sinus-triangular pulse-width modulation techniques are introduced. The simulation results show the robustness and good performance of the proposed controller.

Keywords: Dual star induction machine (DSIM), Indirect field oriented control (IFOC), PI-type self-tuning-fuzzy logic controller (PI-ST-FLC), Scaling factor (SF), PWM-VSI

1. Introduction

Multi-phase machines or those with more than three phases have been introduced a long time ago [1]-[3]. Compared with three-phase machines, this type of machine presents several advantages. First, there is reduction of the torque pulsations at a high frequency and of rotor harmonic currents, thereby minimizing rotor losses and the phase current in the machine and inverter without increasing the phase voltage. Other potential advantages are their high reliability and the possibility to divide the controlled power on more inverter legs [4].

The concept of reliability means that the loss of one or more of the stator winding excitation sets allows multi-phase induction machines to continue to be operated with an asymmetrical winding structure and unbalanced excitation [3]-[5]. This multi-phase characteristic enables these machines to be used in several applications such as in pumps compressors, rolling mills, mine hoist, and cement mills to name a few.

The most common multi-phase machine structure is the dual star induction machine. This structure has been studied and developed for high-power applications [6], [7]. The stator constructed from this model forms two three-phase windings sets shifted by 30 electrical degrees, whereas the rotor is a conventional structure (squirrel cage). The variable speed control of the AC machine is difficult because of the nonlinear and multivariable nature of machine dynamics [8]. Therefore, a variety of control techniques to overcome these problems have been developed [9]. Among these techniques, the field oriented control (FOC) has been used in many kinds of AC machine control. The control objective is to produce a decoupled control of the flux linkage and the electromagnetic torque. Both direct and indirect FOC have been successfully established in theory and practice. The IFOC method is the most popular because of its relative simplicity and low cost of implementation compared with the direct method.

Conventional (PID) controllers are used to regulate the rotor speed and/or electromagnetic torque. Compared with other fuzzy controllers [10], the traditional controller has the main advantages in terms of simple implementation and low cost. However, PID has an inferior performance compared with the fuzzy logic controller (FLC) in terms of sensitivity to parameter variations, load disturbances, and so on.

FLCs are useful tools for solving nonlinear and complex process control problems, such as the speed control of AC machines. This is attributed to the capability of FLCs to control nonlinear, uncertain systems and the lack of a mathematical model for the controlled system. FLCs handle qualitative knowledge in the control design [11]. Various velocity-types FLC generate incremental control output. Therefore, PI-type FLCs are more common and practical than PD- and PID-type ones because of their advantages of inherent stability of the proportional controllers and the offset elimination capability of integral controllers [12], [14].

A standard FLC of Mamdani is made up of parameters such as rules base, database, membership functions (MFs) and input, and output scaling factor (SF). Based on analogy with the human operator, the output SF should be considered a very important parameter of the FLC because its function is similar to that of the controller gain, and it is directly related to the stability of the control system. For the successful design of FLCs, there should be proper selection of the input and/or output (SFs) and/or the tuning of other controller parameters such as the determination of the shape and position of the membership functions [13], [14].

FLCs with fixed parameters may be insufficient in controlling systems, and they cannot achieve ideal performance under severe perturbations of model parameters and

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operating conditions [15], [16]. More sophisticated controllers are required. A solution to this problem is addressed using adaptive FLCs such as self-tuning. Self-organizing controllers have also been developed for more robust control processes, and they can modify their parameters in order to maintain the desired dynamic behavior of the system. Among various tunable parameters, SFs are most commonly adopted due to their desirable effects on the performance and stability of systems [14], [17].

For these reasons, only an adaptation of the output SF independent of a PI-type FLC by an adjusted gain online with the help of fuzzy rules is proposed. The proposed scheme is applied to the speed control of a DSIM based on IFOC.

The details of the IFOC and the model machine are provided in [5], [18].

2. The Proposed Self-Tuning Fuzzy Controller for a DSIM

The block diagram of a self-tuning fuzzy logic speed controller based on IFOC for a dual star induction motor is depicted in Fig. 1. The principal structure of a self-tuning fuzzy logic controller as illustrated in Fig. 1 is made up of the following elements:

2.1 Scaling Factors

The PI-ST-FLC inputs are the speed error E and change in speed error ΔE defined by

$$E = \Omega^* - \Omega_r \quad (1)$$

$$\Delta E(k) = E(k) - E(k-1) \quad (2)$$

where Ω^* is the reference speed, Ω_r is the actual rot-or speed, and k is the sampling instant.

The chosen input SFs G_E and $G_{\Delta E}$ indicate the normalized values of speed error and the change in speed error E and $\Delta E(k)$, respectively, i.e., G_E and $G_{\Delta E}$ are mapped onto the universe of discourse [-1, 1]. Similarly, the normalized output value is mapped into the physical domain by defuzzification and the output SF G_T. The output SF is a very important parameter of the FLC [14]. Therefore, the output SF (λG_T) is adjusted online according to the current states of the controlled machine by a gain tuning mechanism.

The relationships between the SFs and the input and output variables of the self-tuning FLC are as follows:

$$E_N = G_E . E \quad (3)$$

$$\Delta E_N = G_{\Delta E} . \Delta E \quad (4)$$

$$\Delta T^*_{em} = (\lambda . G_T) \Delta T_N \quad (5)$$

2.2 Fuzzification

The inputs to the PI-ST-FLC have to be fuzzified before being fed into the control rule and gain rule determinations. The triangular MFs used for the input (E_N, ΔE_N) and the singleton MFs for the output (ΔT_{em}) and gain updating factor (λ) are shown in Fig. 2(a), 2(b), and 2(c), respectively. Linguistic variables are represented by (positive big (PB), positive medium (PM), positive small (PS), zero environ

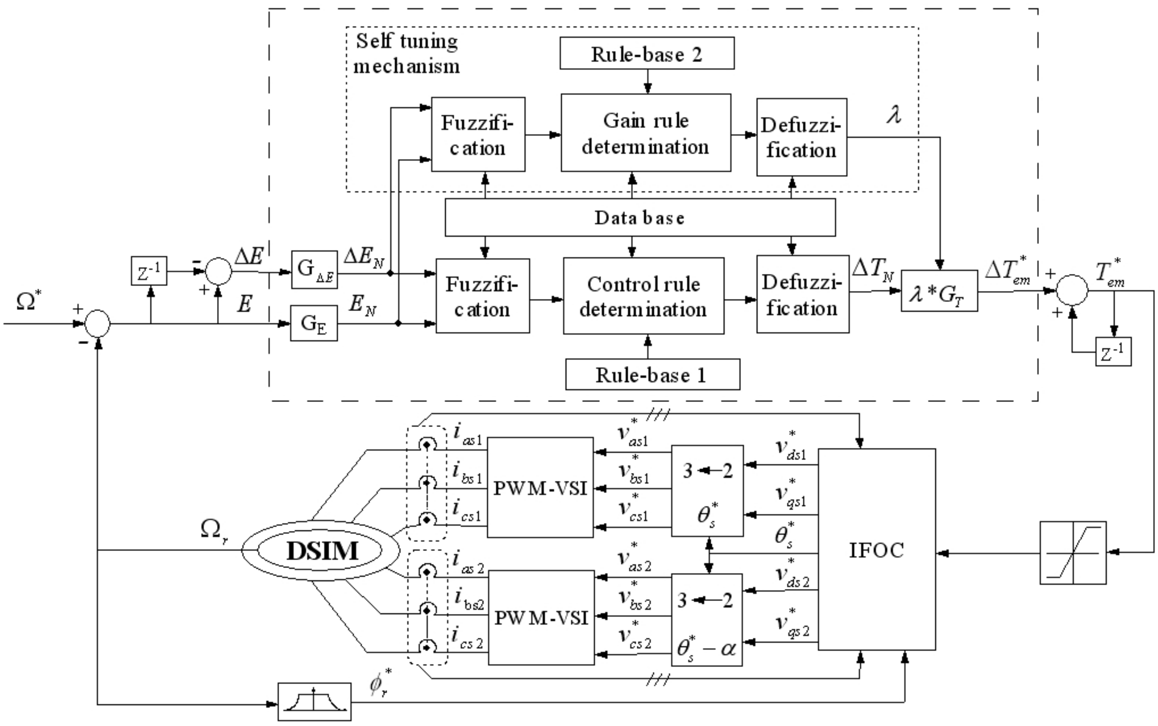


Fig. 1. Block diagram of the proposed self-tuning fuzzy speed controller.

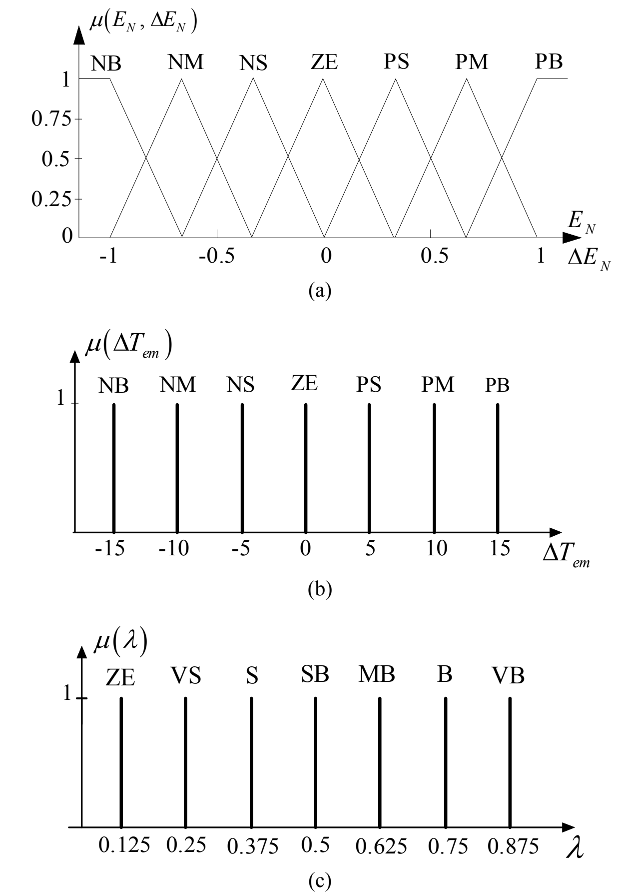


Fig. 2. Membership functions of (a) E, ΔE (b) ΔT_{em}, and (c) λ.

(ZE), negative small (NS), negative medium (NM), and negative big (NB)) for E_N, ΔE_N and ΔT_{em}. Zero environ (ZE), very small (VS), small (S), small big (SB), medium big (MB), Big (B), and very big (VB) are used for the gain updating factor (λ).

2.3 Control Rule Determination

The reference torque rule determination is represented by the fuzzy IF (conditions)-THEN (action) rules of the following form:

R_i IF (E_N is PB and ΔE_N is NS), THEN (ΔT_{emi} is PM). The entire rule base is given in Table 1. A total of 49 (7×7) rules are obtained to achieve the desired speed trajectory.

Table 1. Fuzzy rules for the computation of ΔT_{em}

	ΔT_{emi}	ΔE_N						
		NB	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
E_N	**NB**	NB	NB	NB	NB	NM	NS	ZE
	NM	NB	NB	NB	NM	NS	ZE	PS
	NS	NB	NB	NM	NS	ZE	PS	PM
	ZE	NB	NM	NS	ZE	PS	PM	PB
	PS	NM	NS	ZE	PS	PM	PB	PB
	PM	NS	ZE	PS	PM	PB	PB	PB
	PB	ZE	PS	PM	PB	PB	PB	PB

2.4 Inference and Defuzzification

The present paper uses MIN operation for the calculation of the degree $\mu(\Delta T_{emi})$ associated with every rule, for example, $\mu(\Delta T_{emi})$=Min[$\mu(E_N)$, $\mu(\Delta E_N)$], the appropriate E_N and ΔE_N can be easily obtained using this type of inference method under the singleton type of MFs while maintaining the accuracy of the results [19]. In the defuzzification stage, a crisp value of the electromagnetic torque is obtained by the normalized output function

$$\Delta T_N = \frac{\sum_{i=1}^{m} \mu(\Delta T_{emi}) \Delta T_{emi}}{\sum_{i=1}^{m} \mu(\Delta T_{emi})} \tag{6}$$

where m is the total number of rules, $\mu(\Delta T_{emi})$ is the membership grade for the i^{th} rule, and ΔT_{emi} is the position of the singleton in rule i^{th} in U (-15, -10, …,15), Fig. 2(b).

2.5 Self Tuning Mechanism

The output SF is modified in each sampling time by the gain updating factor λ depending on the state of the controlled process; λ is computed using a model independent fuzzy rule base defined in terms of E_N and ΔE_N.

A nonlinear function between the normalized inputs (EN, ΔEN) and the gain updating factor (λ) is described by the rule base shown in Table 2 and the associated inferencing scheme.

Table 2. Fuzzy rules for the computation of λ

	λ	ΔE_N						
		NB	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
E_N	**NB**	VB	VB	VB	B	SB	S	ZE
	NM	VB	VB	B	B	MB	S	VS
	NS	VB	MB	B	VB	VS	S	VS
	ZE	S	SB	MB	ZE	MB	SB	S
	PS	VS	S	VS	VB	B	MB	VB
	PM	VS	S	**MB**	B	B	VB	VB
	PB	ZE	S	SB	B	VB	VB	VB

The same operations (fuzzification, inference, and defuzzification) used in the computation of ΔT_N are used to calculate λ, except for the fuzzy rules and the MFs for the gain updating factor defined in [0, 0.875] and presented in Fig. 2(c).

The expert human operator plays a crucial role in the selection of 49 rules based on the response of a conventional controller PI. In the case of a PI-type FLC, the actual value of the controller output (T^*_{em} reference electromagnetic torque) is obtained by the following equation [12], [14]:

$$T^*_{em}(k) = T^*_{em}(k-1) + \Delta T^*_{em}(k) \tag{7}$$

where $\Delta T^*_{em}(k)$ is the incremental change in controller output. Accumulation (7) of the controller output takes place outside PI-ST-FLC and is not reflected in the rules themselves.

3. Simulation Results

To verify the validity of the proposed PI-ST-FLC, several simulation tests under various operating conditions and parameter disturbances were conducted. Computer simulations were performed using MATLAB. To solve the differential state equation of DSIM drives, the fourth-order *Runge-Kutta* method was used. Table 3 shows the parameter of the DSIM for simulation. The general specifications of the DSIM are 4.5 *kW*, 2753 *rpm*, 220/380 *V*, 2 poles, and the parameters of the self-tuning fuzzy speed controller.

Table 3. DSIM Parameters used for Simulation

Stator resistance Rs	3.72Ω
Rotor resistance Rr	2.12Ω
Stator leakage inductance ls	0.022H
Rotor leakage inductance lr	0.006H
Resultant magnetizing inductance Lm	0.3672H
Moment of inertia J	0.0662kg.m2
Viscous friction coefficient Kf	0.001kg.m2/s
Input scaling factors GE, GΔE	GE=0.0038,GΔE=0.222
Output scaling factors GT	GT=3

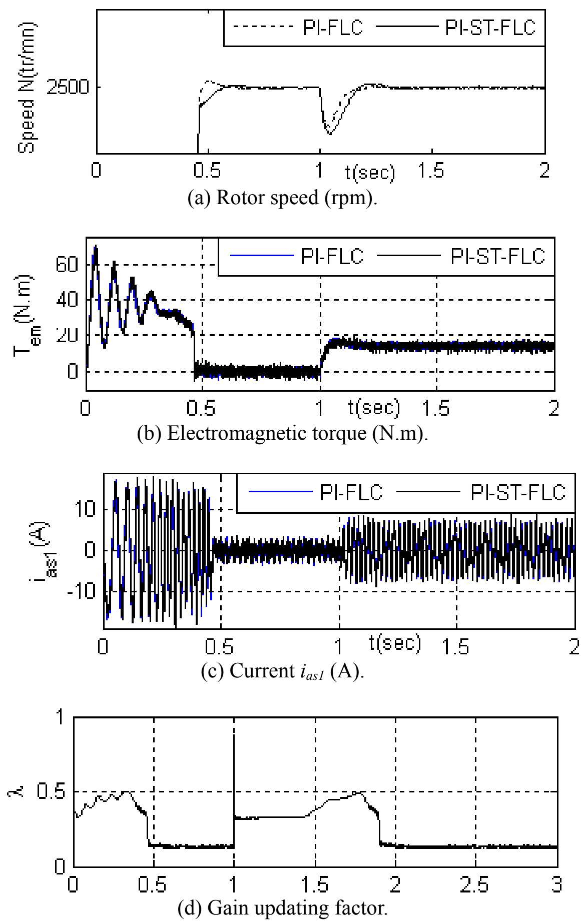
The Fig. 3 shows the transient responses for the IFOC of the DSIM drive using the proposed PI-ST-FLC in case of a sudden change in reference speed from 0 to 2500 rpm at 0.0 *sec* with the application of a step increase in load (from zero to the rated torque). Fig. 3(a) shows that the proposed controller allows the act-ual speed to follow the reference speed with no overs-hoot and rejects the load disturbance rapidly with a maximum drop of speed of 40 *rpm*. Fig. 3(b) shows that the compensation for disturbance and the effect of friction are achieved by the developed electromagnetic torque automatically. The developed torque can follow the load torque. The magnitude of current per phase i_{as1} at the start is 18 A, which is stabilized at 3 A in the steady state in the presence of load torque. The i_{as1} stabilizes at 6.5 A as shown in Fig. 3(c). Fig. 3(d) shows the evolution of the gains λ, which clearly con-forms to the desired variation 0.14 (i.e., zero environ). A variation of λ follows the variation of the speed at t=1 *sec* (applying the rated load torque).

The Fig. 5 shows the transient responses for the PI-ST-FLC of DSIM based on IFOC in case of reference speed reversal from 2500 *rpm* to -2500 *rpm* at 1 *sec* with no load torque.

The proposed PI-ST-FLC works properly for reference speed reversal as shown in Fig. 5(a). The actual speed N tracks the negative reference speed N^*=-2500 *rpm* at 1.9 *sec* with no overshoot. Fig. 5(b) shows that the electromagnetic torque decreases to stabilize environ -38*N.m* between 1 and 1.9*sec* (second transient response) for forcing the actual rotor speed to follow the desired reference trajectory. The magnitude of current i_{as1} in the second transient response is similar to that at the start as shown in Fig. 5(c). Fig. 5(d) shows the evolution of gain λ, with a peak at t=1 *sec* of 0.87, which stabilized at 0.32 between 1 and 1.44*sec* (decrease of speed from 2500 *rpm* to 0). An increase was observed followed by a decrease in λ between 1.4 and 1.9*sec* (speed reversal) and then stabilized at environ 0.14.

The Fig. 4, 6 show the rotor speed and the gain updating factor λ for the increased rotor resistance and moment of inertia, and sudden changes in rotor resistance and in moment of inertia from R_r to 1.5R_r and J to 1.5J, respectively, are applied at 1 *sec*.

A comparison of the performance of the PI-ST-FLC and PI-FLC controller is shown in Fig. 3(a), 4(a), and 6(a). The proposed self-tuning fuzzy controller offers significant improvements compared with PI-FLC. The proposed controller reacts perfectly and tracks the command speed with almost no steady state error and smaller overshoot/ undershoot. The self-tuning controller is more robust to the inertia and rotor resistance variation, and it has fewer harmonics in the electromagnetic torque in the case of reference speed reversal Fig. 5(b).



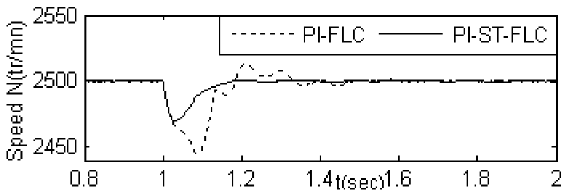
(a) Rotor speed (rpm).

(b) Electromagnetic torque (N.m).

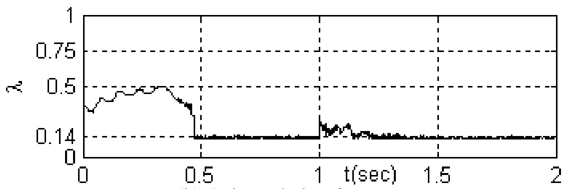
(c) Current i_{as1} (A).

(d) Gain updating factor.

Fig. 3. Simulated responses for a step reference speed from standstill to 2500 *rpm* followed by the application of the rated load torque (14*N.m*) at 1 *sec*.

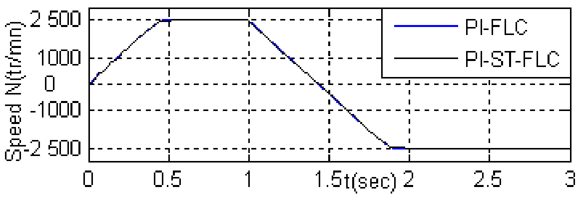


(a) Rotor speed (rpm).

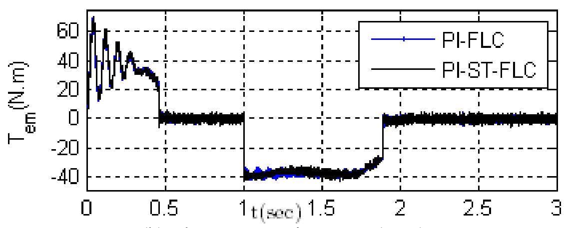


(b) Gain updating factor.

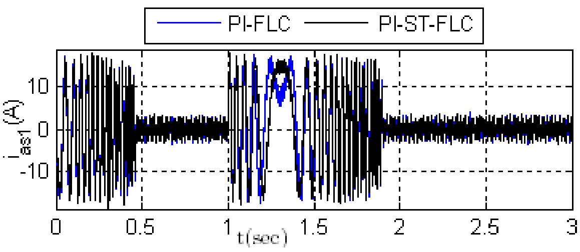
Fig. 4. Simulated responses for a step reference speed with an increased rotor resistance (ΔR_r %=+50 %) under a step increase in load (from zero to rated torque) at 1 *sec*.



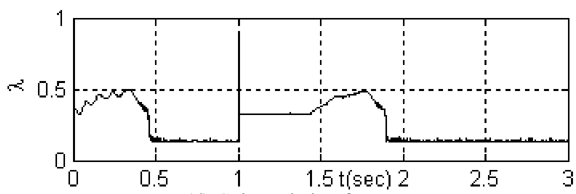
(a) Rotor speed (rpm).



(b) Electromagnetic torque (N.m).

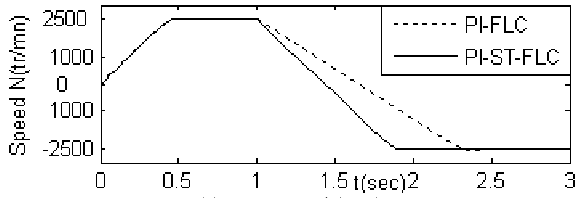


(c) Current i_{as1} (A).

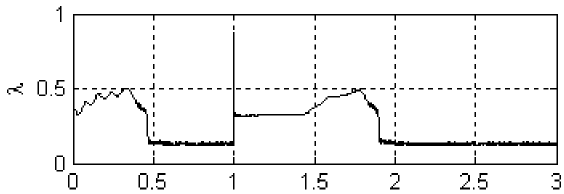


(d) Gain updating factor.

Fig. 5. Simulated responses for reference speed reversal from 2500 *rpm* to -2500 *rpm* at 1 *sec* with no load.



(a) Rotor speed (rpm).



(b) Gain updating factor.

Fig. 6. Simulated responses for a reference speed reversal with an increased moment of inertia (ΔJ %=+50 %) under no load.

4. Conclusion

This paper proposed a robust independent self-tuning fuzzy logic speed controller of DSIM based on indirect field oriented control. The proposed controller was tuned online by gain-updating factors for the output scaling factors of PI-FLC using independent fuzzy rules based on the speed error and change in this error.

The simulation results show the robustness and good performance of the proposed PI-ST-FLC in different operational conditions such as variation of the load torque, reference speed, moment of inertia, and rotor resistance.

The proposed controller offers a number of advantages over the conventional fuzzy controller.

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