Speed Sensorless based Sliding Mode Control of BLDC Motor Drivefor Electric Vehicle

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Abstract: Electric vehicles are having significant priority in transportation including goods, public transport etc. among many technologies in electric vehicle, brushless DC (BLDC) motors operated eclectic drives are mostly used. Speed sensorless control is required to implement for obtaining a best performance. At the same time, a sliding mode controller (SMC) can be able to produce the ultimate response under various conditions. Hence sensorless speed control with SMC of BLDC motor is implemented in this paper to drive the electric vehicle. In order to develop speed sensorless of motor, a model reference adaptive control (MRAC) system is developed. However, obtaining a fastest response is very important in electric vehicle speed control. Hence a TS-Fuzzy model is developed to use in the place of conventional PI controllers. Extensive results are collected for presentation by establishing Hardware – in the – Loop (HIL) with the help of two OPAL-RT devices.

Keywords: BLDC Motor, Sliding Mode, MRAC, Electric Vehicle.

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1. INTRODUCTION

Transportation is playing a key role in development of any organization or nation. Generally vehicles are used to transport goods and people from one location to another. However, conventional vehicles consume much diesel/petrol which release toxic gases during burning process in the vehicle. Global warming is increasing day by day due to conational vehicles. In order to overcome these issues, concept of an electric vehicle is introduced which is running by electric motor with the help of electric power.

Electric vehicles are running mainly on electric drives. Hence, the selection of electric drives is very important in any electric vehicle. At very beginning, DC motors are using. The performances of DC motors are very well but there are many disadvantages over comparing with AC motors. However, AC motors are suffering with poor sped torque characteristics as compared with separately excited DC motor. Hence, a vector control is proposed to work an AC motor as a separately excited DC motor.

Among many AC motors, induction motors and BLDC motors are commonly used in vehicles because of their simplicity as well as wide verity of applications. In the commercial electric vehicles, usually BLDC motors prefer. Hence, novel control methods need to be implemented on the BLDC motor to make an efficient drive for flexible operation. A battery bank is used in the electric vehicles as power sources. Therefore an inverter is interfaced between battery bank and BLDC motor to work as an electronic commentator to drive the motor. Various control methods are implemented on BLDC motor, apart from them; a sliding mode control (SMC) technique is one of the best methods. The control method (i.e., SMC) is implemented based on regulating dc-link current.

Further, sensorless speed control method of the motor is developed and implemented control method with the help of T-S fuzzy controllers. Voltage fault diagnosis for electric vehicles is discussed by authors in [8]. Vehicle to vehicle charging management system of electric vehicle is implemented by authors in [9]. A detailed design and implementations of elective vehicles is presented by authors in [10]. LCA indicator system of electric vehicles is implemented by authors in [11]. A comparative economic analysis between conventional and plugged in electric vehicles is presented by authors in [12]. Authors in [13] discussed about charging safety of electric vehicles. Modeling of electric vehicles and their simulation results are presented by authors in [14].

Proper inverter control technique is required for BLDC motor to drive the vehicle effectively. Because measuring speed with a sensor will be problematic, a speed sensorless technique is devised in this study using a model reference adaptive controller (MRAC). To regulate the motor speed, a dc-current regulation-based sliding mode controller (SMC) combined with the MRAC approach is used.By comparing Proportional and Integral (PI) with T-S Fuzzy controllers, T-S Fuzzy controllersare more effective under variable inputs [2]. Hence, T-S Fuzzy controllers based controltechnique is considered in this paper.

This work is prepared by presenting the description of the system in Section-II. TS-Fuzzy controller is given in Section-III. A detailed modeling of BLDC motor is given in Section-IV. Control of the BLDC motor is presented in Section-V. Hardware – in the – Loop (HIL) based results are included in Section-VI. Conclusionsare presented in Section-VII. Valuable list of references is listed at the end of the paper.

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2. System Description

Proposed drive of an electric vehicle isdepicted in Fig. 1 which consists of power source, BLDC, converter, control unit etc. it is very difficulty on sensing the speed of the vehicle duringthe operations. To avoid this problem, sensorless speed control methodhas been implemented with the help of MRAC method. A SMC is implemented to track the motor at its reference values which is adjusted by driver of the vehicle. The detailed design and modeling of various components are discussed in net sections.

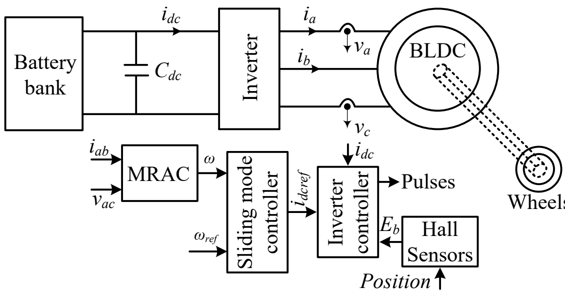

Fig. 1: BLDC Drive for Electric Vehicle.

3. T-S Fuzzy Controllers

Membership function of voltage errors (x_i) & its derivatives ($\dot{x}_i$) are implemented to develop a conventionalT-S Fuzzy controllers as shown in Fig. 2.
The mathematical expression for functions of membershipsof system is as follows:

$$\mu_P(x_i) = \begin{cases} 0, & x_i < L_1 \\ \dfrac{x_i + L_1}{2L_1}, & -L_1 \le x_i \le L_1 \\ 1, & x_i > L_1 \end{cases} \text{ and } \mu_N(x_i) = \begin{cases} 1, & x_i < L_1 \\ \dfrac{-x_i + L_1}{2L_1}, & -L_1 \le x_i \le L_1 \\ 0, & x_i > L_1 \end{cases}$$

$$\mu_P(\dot{x}i) = \begin{cases} 0, & \dot{x}_i < L_2 \\ , & L_2 \le \dot{x}_i \le L_2 \\ 1, & \dot{x}_i > L_2 \end{cases} - \frac{\dot{x}_i + L_2}{2L_2} \text{ and } \mu_N(\dot{x}_i) = \begin{cases} 1, & \dot{x}_i < L_2 \\ \dfrac{-\dot{x}_i + L_2}{2L_2}, & -L_2 \le \dot{x}_i \le L_2 \\ 0, & \dot{x}_i > L_2 \end{cases}$$

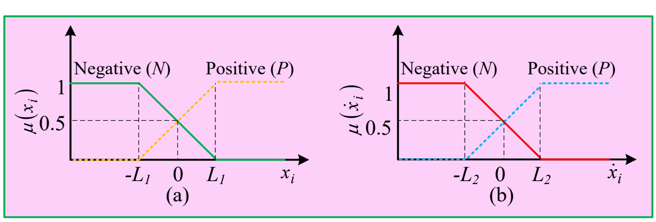

Fig. 2: T-S Fuzzy represents.

Table-1: Rules of a T-S Fuzzy controllers.

Rules	x_i(t)	$\dot{x}_i$(t)	Values
Rule1.	*N*	*N*	$Z_1 = k_1 x_i(t) + k_2 \dot{x}_i(t)$

Rule2.	*N*	*P*	$Z_2 = \mathrm{k}_3 Z_1$
Rule3.	*P*	*N*	$Z_3 = \mathrm{k}_4 Z_1$
Rule4.	*P*	*P*	$Z_4 = \mathrm{k}_5 Z_1$

The Table-3 compressed with list of rules of designed T-S Fuzzy controllers. The parameters of Z_1, Z_2, Z_3, and $Z_4$are tuned at particular instant. The 'k' is asample instant.k_1, k_2, k_3, k_4 and k_5 are the fuzzy variables. Theseparameters are arranged by any tuning method. The following equation is expressed the output.

$$Y = \frac{Z_1 B_1 + Z_2 B_2 + Z_3 B_3 + Z_4 B_4}{Z_4 + Z_3 + Z_2 + Z_1} \tag{1}$$

Here,B_1= min.{ $\mu_p(\dot{x}_i)$, $\mu_p(x_i)$ }.B_2= min.{ $\mu_N(\dot{x}_i)$, $\mu_p(x_i)$ }.B_3= min. { $\mu_p(\dot{x}_i)$, $\mu_N(x_i)$ }.B_4= min.{ $\mu_N(\dot{x}_i)$, $\mu_N(x_i)$ }.

a. Development of MRAC, BLDC, & SMC [4].

Permanent magnets are placed in a rotor of the BLDC motor, hence no need of supply in the rotor. Usually, only 2-phases are having current in BLDC motor at a time [1]. The basic equations for modeling of the motor are listed below.

$$v_{ab} = e_a - e_b + (i_a - i_b)R + \frac{d}{dt}(i_a - i_b)L \tag{2}$$

$$v_{ca} = e_c - e_a + (i_c - i_a)R + \frac{d}{dt}(i_c - i_a)L \tag{3}$$

$$v_{bc} = e_b - e_c + (i_b - i_c)R + \frac{d}{dt}(i_b - i_c)L \tag{4}$$

$$T_e = \frac{i_a e_a + i_b e_b + i_c e_c}{\omega} \tag{5}$$

Where, line voltages are v_{ab}, v_{bc} and v_{ca}. The $i_{a,b,c}$ are the 3-phases currents. Three phase back EMFs are represented bye_a, e_b, &e_c.The 'R'and$L$=L_s-$L_m$are resistances and inductancs.

4. Modeling of BLDC Motor

The term T_e represents electromagnetic torque produced bymotors. The vehicle speed is representedby ω.

Generally, $i_a = -i_b \quad \& \quad i_c = 0$ (6)

Below equations shows back EMFs.

$$e_c = 0 \quad \& \quad e_a = -e_b$$

Hence, $T_e = \frac{2 i_a e_a}{\omega_r}$ (7)

The speed of the vehicle is directly proportional to itsback EMFs.

$$e_a = k_e \omega \tag{8}$$

$$\omega = \frac{2L\frac{di_a}{dt} - 2Ri_a - v_{ab}}{2K_e} \tag{9}$$

In steady state, $\frac{di_a}{dt} = 0$, hence $\omega = \frac{v_{ab} - 2i_a R_s}{2k_e}$ (10)

Here, coefficientof back EMF is considered by 'k_e'.

The following equations of motor are represented 'DQ'reference frame.

$$\psi_{ds} = \psi_{fd} + L_{ad} i_{dr} + + L_{ds} i_{ds} \quad (11)$$

$$\psi_{qs} = (L_{aq} i_{qr} + L_{qs} i_{qs}) \quad (12)$$

$$\psi_{dr} = (L_{ad} i_{ds} + \psi_{fd} + L_{dr} i_{dr}) \quad (13)$$

$$\psi_{qr} = (L_{qr} i_{qr} + L_{aq} i_{qs}) \quad (14)$$

Where, $L_{ds} = L_{ad} + L_{sl}$, $L_{dr} = L_{ad} + L_{rl}$, $L_{qr} = L_{aq} + L_{rl}$, $L_{qs} = L_{aq} + L_{sl}$, ψ_{fd} denotes permanent magnetic flux linkage.

The i_{ds}&$i_{qs}$are playing a major role while regulating the speed of the BLDC motor. The parameter lists of BLDC motor are provided in Table-2.

Table-2: BLDC motor ratings.

S.No	Parameters	Values
1	Power.	5hp
2	voltage.	440V_{rms}
3	current.	7.5Amp
4	Speed.	1500rpm
5	Range of DC voltage.	240-850V
6	Start up voltage.	500V_{dc}
7	Rated torque.	31Nm
8	Frame model.	90MB
9	Motor model.	PE1R112M4
10	Efficiency.	92.31
11	Power factor.	0.99
12	Inertia constant.	0.012kgm^2
13	Phase resistance.	0.9Ohm
14	Magnetizing inductance.	10.5mH
15	Leakage inductance.	2.5mH
16	Magnetizing reactance.	3.3Ohm
17	Leakage reactance.	0.8Ohm
18	Weight.	37kg

5. Control of BLDC Motor

A MRAC method is implemented for a closed loop speed control of the motor by using basic below mathematical equations [2].

$$e_a = F(\theta_e)\omega_m \times \frac{k_e}{2} \quad (15)$$

$$e_b = (\omega_m \frac{k_e}{2} \times F\left(\theta_e - \frac{2\pi}{3}\right)) \quad (16)$$

$$e_c = (F\left(\theta_e + \frac{2\pi}{3}\right) \times \omega_m \frac{k_e}{2}) \tag{17}$$

$$T_e = \frac{k_t}{2}\left[F(\theta_e)i_a + F\left(\theta_e - \frac{2\pi}{3}\right)i_b + F\left(\theta_e + \frac{2\pi}{3}\right)i_c\right] \tag{18}$$

$$\frac{d}{dt}\begin{pmatrix} i_a \\ i_b \\ \omega_m \\ \theta_m \end{pmatrix} = \begin{pmatrix} -\frac{R}{L} & 0 & 0 & 0 \\ 0 & -\frac{R}{L} & 0 & 0 \\ 0 & 0 & -\frac{k_f}{J} & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}\begin{pmatrix} i_a \\ i_b \\ \omega_m \\ \theta_m \end{pmatrix} + \begin{pmatrix} \frac{2}{3L} & \frac{1}{3L} & 0 \\ -\frac{1}{3L} & \frac{1}{3L} & 0 \\ 0 & 0 & \frac{1}{J} \\ 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} v_{ab} - e_{ab} \\ v_{bc} - e_{bc} \\ T_e - T_{pm} \end{pmatrix} \tag{19}$$

$$\frac{d\omega_{ref}}{dt} = b_m \upsilon_x - a_m \omega_{ref} \tag{20}$$

$$T_e = (\sum_{n=1}^{3} \frac{2}{3} I_m M i_m \sin^2(2\theta + \pi_n) = I_m \hat{M} i_n) \tag{21}$$

$$\frac{de}{dt} = (\left(a_m - \frac{B}{J}\right)\omega + \frac{\hat{M}i_m}{J} I_m^* - b_m \upsilon_x + -a_m e) \\ \frac{Tpm}{J} + \frac{1}{J}\sum_{n=1}^{Nr}\left(h_n \sin(2n\theta) + g_k \cos(2k\theta)\right) \tag{22}$$

Here, ‘J’ is ainertia constant of rotor. Friction coefficient is assumed as ‘k_f’. ‘M, b_m, a_m, h_n, g_k, n’, and ‘k’ are constants. Gains of PI are K_p and K_i.
Finally,

$$I_m^* = \frac{J}{\hat{M}i_m}\left[\begin{matrix} \left(\frac{B}{J} - a_m\right)\omega + b_m \upsilon_x - \frac{T_{pm}}{J} - \\ \frac{1}{J}\sum_{n=1}^{Nr}\left(g_k \cos(2k\theta) + h_n \sin(2n\theta)\right) \end{matrix}\right] \tag{23}$$

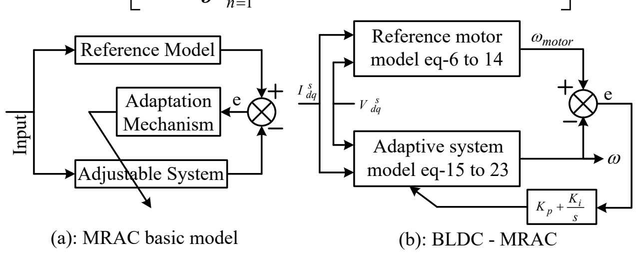

Fig. 3: MRAC block of a BLDC motor.

Fig. 3(a) shows the basic model of the MRAC method. The speed of the BLDC motor is estimated and presented in 3(b). The estimated speed from MRAC block is further compared withthe motor reference speed. Variousparameters used in estimating the speed of the motor are updatebased on the PI controller.

The amount of required power is decided the value of voltage at dc-link.
Generally voltage at dc-link is depending on power flow from batteries into electric vehicles. Therefore, the motor can be set at its reference value through SMC. A model of theSMC is shown in Fig. 4. The model for generating required pulses is depicted in Fig. 5.

Tables 3 and 4 are prepared with variables used in SMC and constants of T-S Fuzzy controllers.

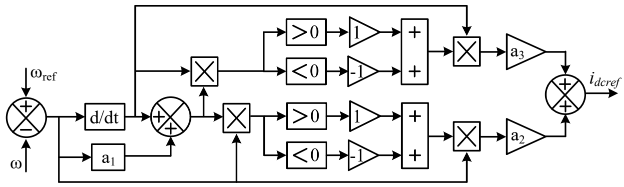

Fig. 4: Model represents of SMC.

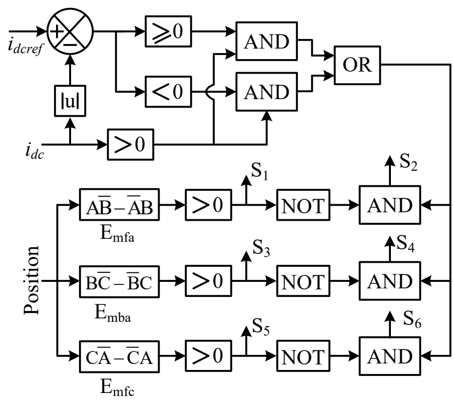

Fig. 5: model for generating pulses to the inverter.

Table-3: variables of SMC.

S.No	Constants	Values
1	a_1	540
2	a_2	358
3	a_3	186

Table-4: Gains of T-S Fuzzy& PI.

Controller	Value
T-s Fuzzy	a_1=3.9, a_2=3.25, a_3=-1.6, a_4=1.8, a_5=4.002.
PI gains in DC block	K_p=0.46, K_i=18.01.
PI gains of MRAC	K_p=4.16, K_i=17.79.

6. RESULTSAND DISCUSSIONS

The performance of the system is increased utilizing real-time simulators (RTS) in this study [2, 21-22]. To achieve HIL configuration in the laboratory, RTS modules such as OPAL-RT devices are attached. Two OPAL-RT devices are utilized to create HIL for real-time testing of proposed complicated controllers. The planned electric vehicle system plant is dumped in OPAL-RT module 1 (i.e., OPAL RT-1). OPAL-RT module 2 contains all of the controllers. Through data cards, analog signals from the plant are transformed to digital for input to the controller unit (i.e., OPAL RT-2). The controller module may act as planned controllers and creates switching pulses for the plant's converters.The digital pulses will be translated to analog signals and sent into the plant via external data cards. For better visibility, the essential findings are performed using a laptop rather than an oscilloscope. Figure 6 depicts the basic HIL configuration with two OPAL-RT dev

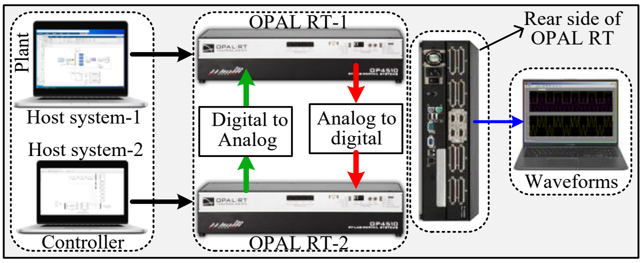

Fig. 6: HIL setup for results.

Various analogue signals of the electric vehicle dynamic model (OPAL RT-1) are going as input to the control unit (OPALRT-2). On the other hand, the digital signals are coming to vehicle model from the controller unit. Hence, this method can be formed a HIL loop [2, 21] effectively. The detailed HIL implementation of proposed system with proper colour coding is depicted in Fig. 7. Other dynamics of BLDC motor are adopted from [22].

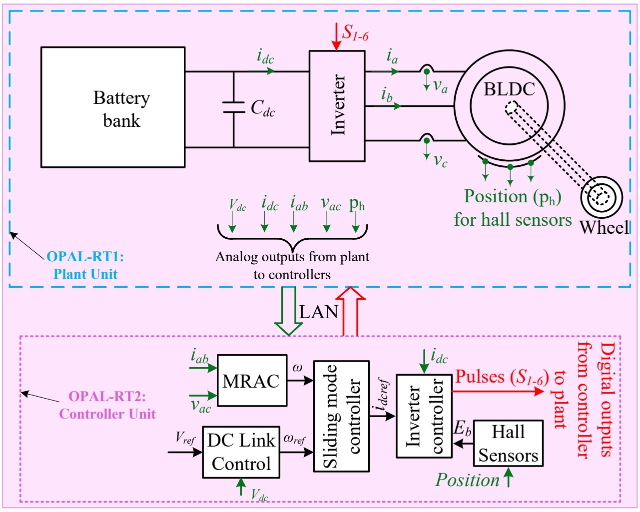

Fig. 7: HIL implementation with plant and controller units.

Case-1: Comparison betweenPI &T-S Fuzzy Systems:

Let'sassume30% decrease in speed of the motorat t = 3 sec. du to this reference speed, the control of the motor try to adjust the motor actual speed. The performance of control method is compared with PI and T-S Fuzzy controllers. Due to fixed gains of PI controllers, the T-S Fuzzy controller exhibits its superior performance during particular change in reference speed. Under these circumstances, the power consumption of the motor is depicted in Fig. 8. Moreover, due to constant gains of PI adjusted at change in speed,oscillations will become more in voltage at dc-link.

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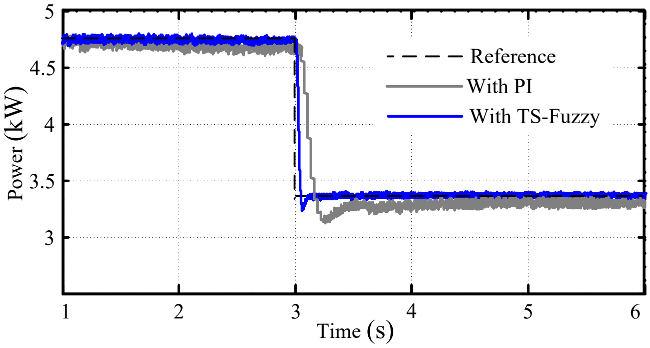

Fig. 8: Power consumption with PI and T-S Fuzzy.

Case-2: Response of motor torque and speed:

The proposed method is tested during changesin reference speed suddenly at t=3sec. During this sudden decreasing in reference speed, the motor speed must be reduced. Under this condition, the reference speed is estimated through the MRAC model of the BLDC motor. The designed SMC is generated required pulses to maintain speed at its reference value. Corresponding response of speed is presented in Fig. 9. Anyhow, the torque of the motor should be maintain at constant during steady state which is depicted by Fig. 10.

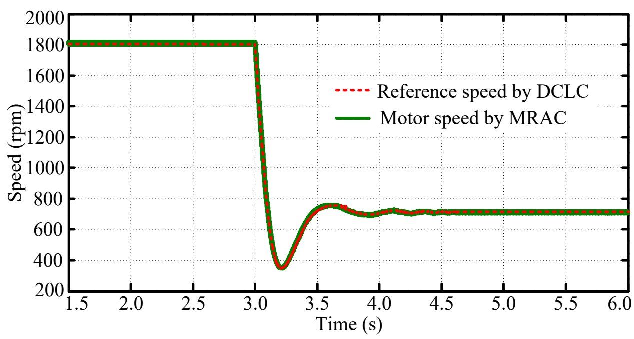

Fig. 9: BLDC motor speed with DCLC & MRAC.

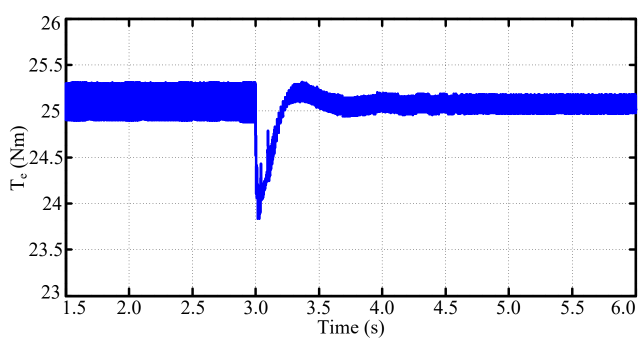

Fig. 10: Torque generated by the motor under decreeing its speed.

7. Conclusions

A motor control is implemented in this paper to drive an eclectic vehicle with the help of BLDC. A hybrid control method is developed to achieve the best response during sudden change happen in the vehicle. Various results are examined under different case studies with the help of HIL established by OPALRT modules. The T-S Fuzzy based control model is developedfor achieving fast tracking behaviorthe drive.The T-S Fuzzy controller is able to adjust the gains according to changes in the system. Hence, there is a significant priority of proposed method than PI controllers. By using HIL, required results are included in this paper by using OPAL-RT devices.

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