Speed Control of BLDC Motor Drive under Direct Torque Control Scheme with Modified Integrator

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Abstract— **In this paper, speed control of Brushless DC (BLDC) motor drive under Direct Torque Control scheme with modified integrator for flux estimation is investigated. The initial transient in flux linkage in first switching is reduced by the modified integrator. Here the drive is operated in the constant torque region under the DTC scheme. The speed control operation is achieved using PI controller and sensing the speed. The electrical rotor speed and the back EMF in dq- reference frame is used for the torque estimation. The inverter DC-link voltage and two line currents are measured for control. In DTC, two, two level hysteresis controllers are used for torque and flux control. The validity of the introduced scheme is verified through extensive simulation under MATLAB/Simulink environment. Simulation results indicate good speed regulation of BLDC motor.**

Keywords— Brushless DC (BLDC) motor, Direct Torque Control (DTC), permanent magnet motor, PI Controller, fast dynamic response

I. Introduction

Recently the permanent magnet motors are widely used for many of applications due to the emergence of fast digital controllers. The permanent magnet motors are available in BLAC and BLDC motors. Even though the advantages such as higher efficiency, high speed operation, high torque to volume ratio, noiseless operation, and long operating life etc. make BLDC motor as a best choice for many applications ranging from servos to traction drives [1]-[4]. Considering the high performance application of BLDC motor, one of the major issue is the torque ripple. There are several researches in the field of torque ripple reduction [5]-[7]. The Direct Torque Control is one of the suitable method to reduce the torque ripple for high performance applications. Basically DTC is developed for induction motors drives that directly control the electromagnetic torque and the flux [8].

This paper focus on the speed control of the BLDC motor with direct torque control scheme for high performance applications. This method provides fast torque response rather than the vector control with good speed regulation. Hysteresis controllers are used for the torque and flux control. A speed control scheme with PI control is investigated.

II. DTC Scheme For BLDC Drive

The idea behind the DTC of AC drive, from the name itself, is to control the electromagnetic torque and flux linkage directly and independently by the use of six or eight voltage space vectors. DTC includes two hysteresis controllers, one for torque error correction and other for flux linkage error correction. In this scheme two level hysteresis controllers are used for keeping the torque and flux error within the predefined value. The flux controller makes the stator flux rotate in a circular fashion along the reference trajectory. The electromagnetic torque estimation T_{em} for a balanced system in *d-q* reference frame is given by:

$$T_{em} = \frac{3P}{4w_{re}}\left(e_{qs}i_{qs} + e_{ds}i_{ds}\right) \tag{1}$$

Where P is the number of poles, W_{re} is the electrical rotor speed e_{ds}, e_{qs}, i_{ds} and i_{qs} are the *d-q* axis back EMF's and currents respectively, the speed W_{re} which is sensed from the machine thus the drive system makes a sensored DTC. The stator flux linkage vector can be estimated from the stationary αβ - reference frame stator voltages and currents which are directly measured.

During the sampling interval time, out of the six voltage vectors one is applied. Stator flux linkage in stationary reference frame [9] can be depicted with initial condition, and can be written as:

$$\left.\begin{aligned} \varphi_{s\alpha} &= V_{s\alpha}t - R_s\int i_{s\alpha}\,dt + \varphi_{s\alpha}(0) \\ \varphi_{s\beta} &= V_{s\beta}t - R_s\int i_{s\beta}\,dt + \varphi_{s\beta}(0) \end{aligned}\right\} \tag{2}$$

Where $V_{s\alpha}$, $V_{s\beta}$, $i_{s\alpha}$ and $i_{s\beta}$ are the stationary reference frame voltages and currents. $\varphi_{s\alpha}(0)$ and $\varphi_{s\beta}(0)$ are the initial stator flux linkage at the instant of first switching. The approximate initial starting flux values at initial zero position is $\varphi_{s\alpha}(0) = 0$ and $\varphi_{s\beta}(0) = 2K_b\pi/(3\sqrt{3})$ Where K_b is the back EMF constant.

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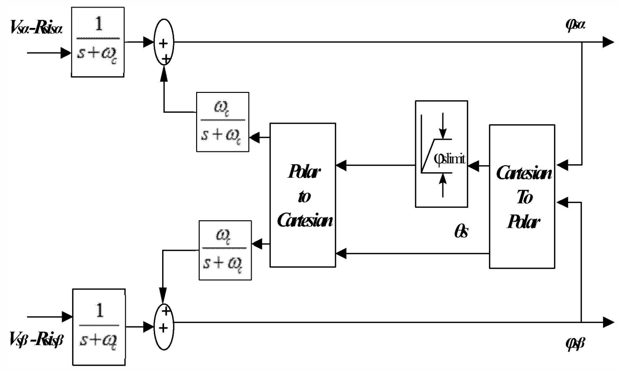

Fig. 1. Stator flux linkage estimation with modified integrator [10].

To solve the above common problems for integrators, an appropriate integration algorithm for estimating the stator flux linkage in [10] is used.

Even though the modified integrator is designed for sine wave systems, the algorithm is befitting to a BLDC motor with variation in the stator flux linkage amplitude. The modified integrator with an amplitude limiter is used here for flux estimation is shown in Fig.1

where ω_c is the cut-off frequency and θ_s is the stator flux linkage position. Here instead of magnitude of φ_s, its amplitude is indirectly controlled by d-axis current in constant torque region, the i_d controlled as zero.

The stator flux linkage vector position is obtained by:

$$\theta_s = \tan^{-1}\left(\frac{\varphi_{s\beta}}{\varphi_{s\alpha}}\right) \tag{3}$$

The voltage vector selection table for controlling the stator flux is given in Table I. Depending upon the status of torque, flux and sector angle, voltage vector is selected from the Table I. During the sampling interval, out of the six voltage vector from the switch selection table one is applied. In each sector, four of the six non-zero voltage vectors may be used. Zero vectors are also allowed.

Electrical rotor position θ_{re}, which is needed in the modified line-to line Park transformation and torque computation algorithm can be found by:

$$\theta_{re} = \tan^{-1}\left(\frac{\varphi_{s\beta} - L_s i_{s\beta}}{\varphi_{s\alpha} - L_s i_{s\alpha}}\right) \tag{4}$$

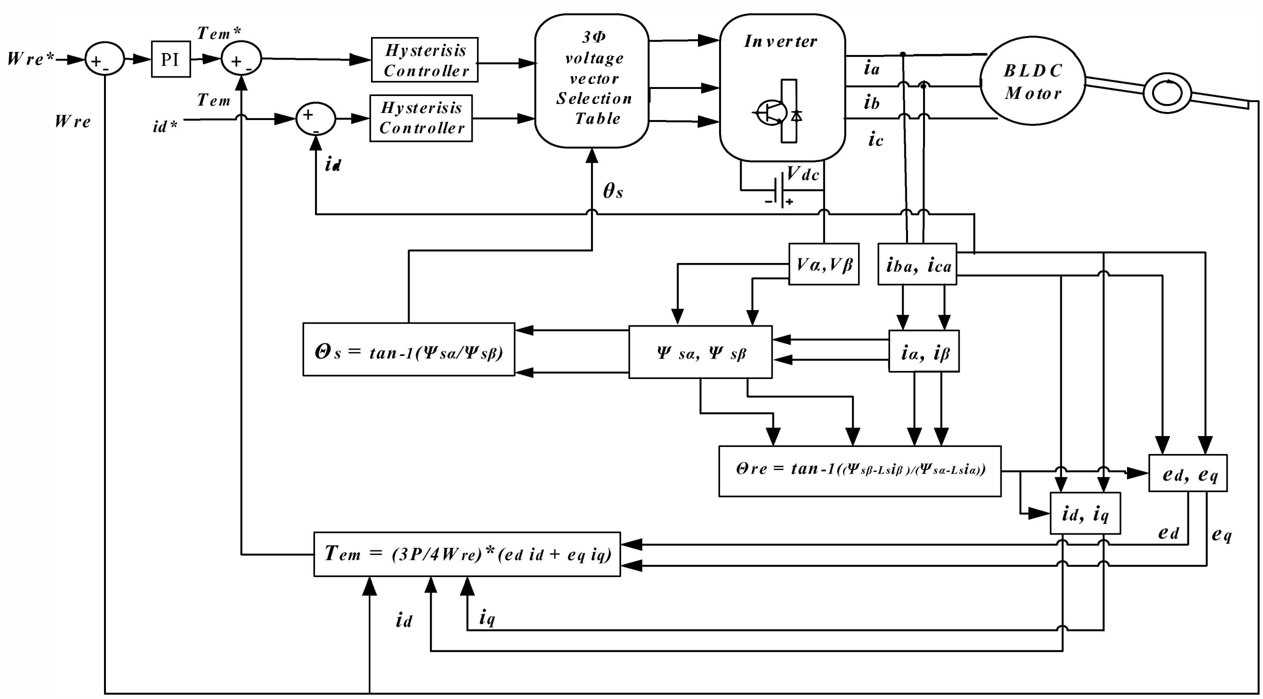

Fig. 2. Block schematic of DTC based speed control of BLDC motor Drive

TABLE I

THREE PHASE VOLTAGE VECTOR SELECTION TABLE FOR BLDC MOTOR FOR DTC SCHEME

φ	τ	Θ_s					
		Θ(1)	Θ(2)	Θ(3)	Θ(4)	Θ(5)	Θ(6)
φ=1	τ = 1	$\mathbf{V}_2$(110)	$\mathbf{V}_3$(010)	$\mathbf{V}_4$(011)	$\mathbf{V}_5$(001)	$\mathbf{V}_6$(101)	$\mathbf{V}_1$(100)
	τ= -1	$\mathbf{V}_6$(101)	$\mathbf{V}_1$(100)	$\mathbf{V}_2$(110)	$\mathbf{V}_3$(010)	$\mathbf{V}_4$(011)	$\mathbf{V}_5$(001)
φ=-1	τ = 1	$\mathbf{V}_3$(010)	$\mathbf{V}_4$(011)	$\mathbf{V}_5$(001)	$\mathbf{V}_6$(101)	$\mathbf{V}_1$(100)	$\mathbf{V}_2$(110)
	τ= -1	$\mathbf{V}_5$(001)	$\mathbf{V}_6$(101)	$\mathbf{V}_1$(100)	$\mathbf{V}_2$(110)	$\mathbf{V}_3$(010)	$\mathbf{V}_4$(011)

The output of the torque hysteresis comparator is denoted as τ, the output of the flux hysteresis comparator as φ and the flux linkage sector is denoted as θ_s. The status of torque hysteresis comparator i.e. τ = -1 or τ =1 indicates that whether the actual value of torque lies above or below the reference value respectively. The same is adapted to the flux hysteresis comparator.

III. SIMULATION RESULTS

The drive system shown in Fig.2 has been simulated using MATLAB®/Simulink® environment. Table II shows the ratings and parameters of the BLDC motor considered is given in appendix. The sampling interval is selected as 20µs. The magnitudes for the torque and flux hysteresis bands are selected as 0.0001 Nm and 0.0001Wb respectively. The switch selection table for the inverter that is given in Table I is employed for the DTC scheme.

Figure.3. shows the actual torque and estimated electromagnetic torque when a load of 2.2 Nm is applied at 0.1sec. From the figure it is clear that the estimated electromagnetic torque is exactly matching with the actual one, also a fast dynamic torque response is obtained.

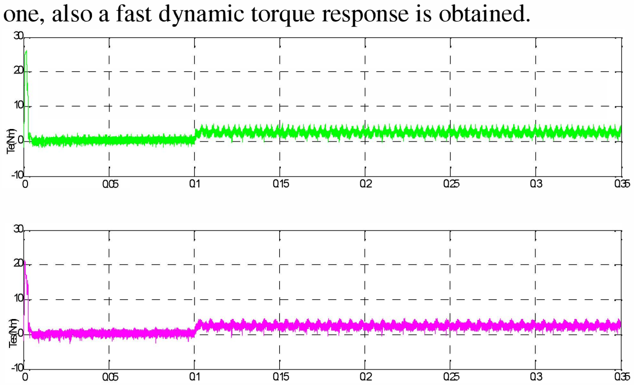

Fig. 3. Actual torque and Estimated electromagnetic torque when rated load torque is applied at 0.1sec

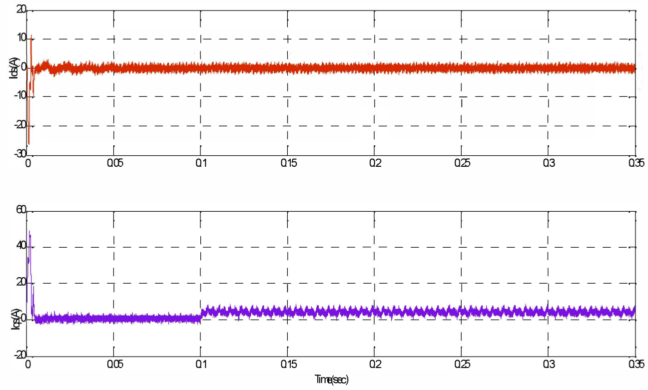

Fig. 4. Steady state and transient behavior of the d-axis and q-axis stator currents under 2.2Nm load torque at 0.1sec.

In Fig.4, the d-axis current fluctuates around at its reference value which is set at zero value. In order to provide the required motor torque, the q-axis current changes to 5 A when load is applied at 0.1sec. The q-axis current which oscillates around the dc offset value ensures the smooth torque response.

Initially the motor runs at no load with a speed of 500 rad/s. When the load is suddenly increased the q-axis current amplitude also increases and fast speed response is achieved as shown in Fig.5 (a). In Fig. 5(b) normally motor runs at 400 rad/sec and suddenly speed reference changed to 300 rad/sec, the machine try to attain reference speed with short span of time. Simulation results shows good speed regulation.

When the load torque changes abruptly, there is a dip in the speed response. However the motor tracks the reference speed of 500 rad/s within 0.0125sec. Thus high dynamic performance achieved by this scheme. The ripple seen in the torque and current can be minimized by properly selecting the torque hysteresis band size.

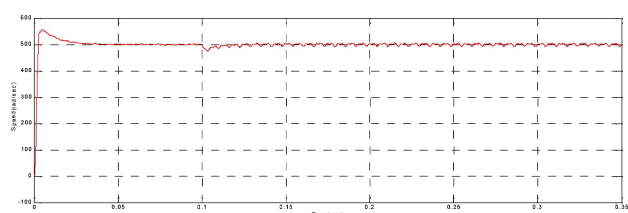
Fig. 5.(a) speed when the system is subjected to rated torque at 0.1sec

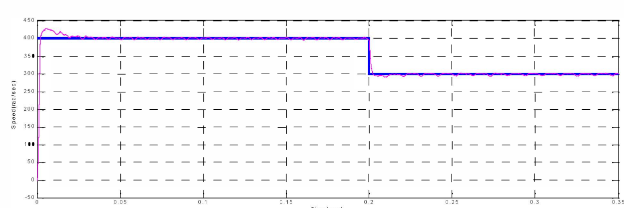
Fig. 5.(b) speed when the system is subjected to different speeds at constant torque of 1Nm

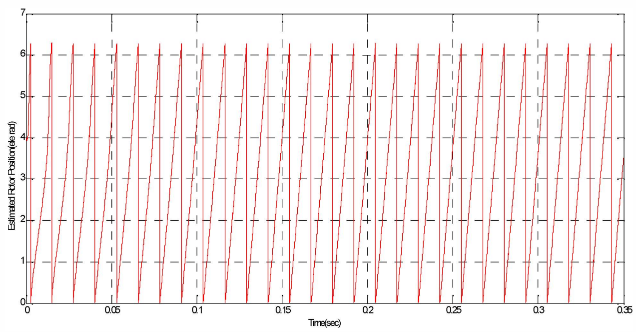

Fig. 6. Estimated rotor position

The estimated electrical rotor position is shown in Fig.6. The electrical rotor position estimated using stator flux and currents. The estimated rotor position tracks the actual rotor position. Fig.7. shows the flux sector of the drive. The steady state and transient response of phase current and back EMF are shown in Fig.8. Up to 0.1sec, the motor draws only the no load current. When the load is applied, the current rises to meet the applied torque.

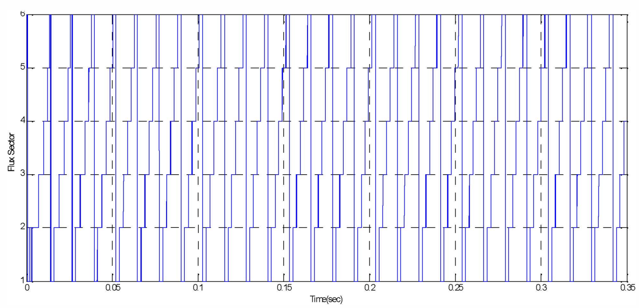

Fig.7. Stator Flux Sector

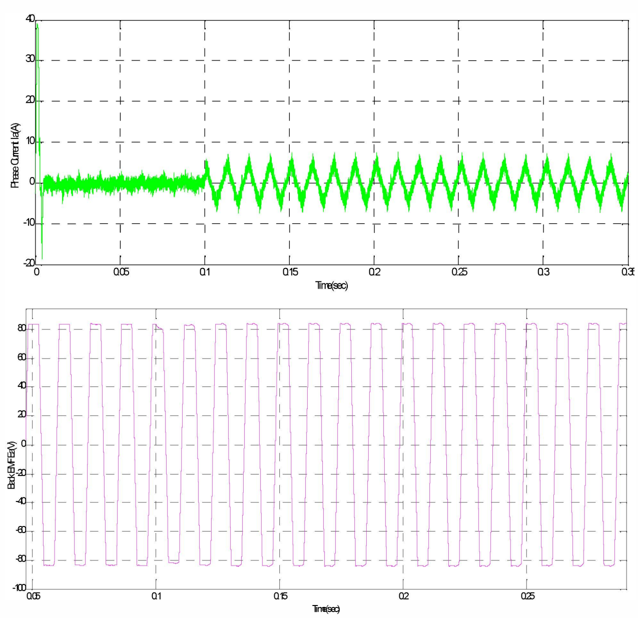

Fig. 8. Steady state and transient behavior of the phase current and back EMF under 2.2Nm load torque at 0.1sec

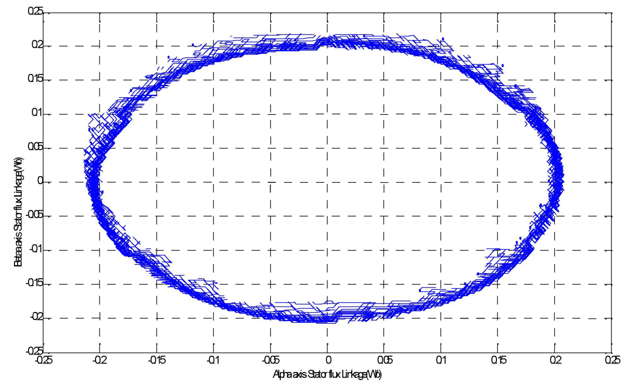

Fig. 9. αβ - axis flux linkage trajectory BLDC Drive

Figure.9. Shows the αβ - axis stator flux linkage locus under the zero and loaded condition of the motor. Here the speed is controlled and hence a better circular flux trajectory is obtained. The amplitude of the stator flux linkage is the amplitude of the flux linkage of the permanent magnet itself, and it is indirectly controlled at its optimum value by means of d-axis current.

IV. Conclusion

Speed control of BLDC motor drive, operated under DTC scheme, is discussed in this paper. In this scheme, torque is estimated in the rotating dq - reference frame. From the simulation results, it has been shown that this scheme can used for high performance applications. Also better dynamic performance can be achieved with variations in the load. The drive system is sensitive to resistance changes and hence parameter adaptation can be adopted for further improvements in the performance. Three phase conduction space vector pulse width modulation technique can also be combined with this scheme to reduce the current and torque ripples while keeping the robustness in the torque control. The scheme mentioned in this paper further extended to sensorless speed control by designing back EMF observer and instead of PI controller more advanced controllers such as Fuzzy controller or optimal controller can be adopted.

Appendix

Dynamic Model of BLDC Motor: A dynamic model of the BLDC motor is developed in terms of time derivative of current, speed, and position. The per-phase voltages (V_{an}, V_{bn}, and V_{cn}) of the BLDC motor are given as [11]

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = R_s \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} i_{an} \\ i_{bn} \\ i_{cn} \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} p \begin{bmatrix} i_{an} \\ i_{bn} \\ i_{cn} \end{bmatrix} + \begin{bmatrix} e_{an} \\ e_{bn} \\ e_{cn} \end{bmatrix} \qquad (5)$$

where e_{an}, e_{bn}, and e_{cn} are the phase back EMFs i_{an}, i_{bn}, and i_{cn} are the phase currents, , R_s is the per-phase resistance, L is the self-inductance, M is the mutual inductance of the stator's winding of the BLDC motor, and p is the time differential operator.

The sum of the currents in three phases is zero for a threephase star-connected BLDC motor given as

$$i_{an}+i_{bn}+i_{cn}=0 \tag{6}$$

Now, substituting (6) in (5), the VA relation is obtained as

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = R_s \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} i_{an} \\ i_{bn} \\ i_{cn} \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} p \begin{bmatrix} i_{an} \\ i_{bn} \\ i_{cn} \end{bmatrix} + \begin{bmatrix} e_{an} \\ e_{bn} \\ e_{cn} \end{bmatrix} \tag{7}$$

Now, by rearranging (7), the current derivatives are obtained as

$$p \begin{bmatrix} i_{an} \\ i_{bn} \\ i_{cn} \end{bmatrix} = \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix}^{-1} * \left(\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} - \begin{bmatrix} e_{an} \\ e_{bn} \\ e_{cn} \end{bmatrix} - R_s \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} i_{an} \\ i_{bn} \\ i_{cn} \end{bmatrix} \right) \tag{8}$$

Total torque can be represented as summation of product of each phase back EMF and currents divided by rotor speed,

$$T_{em} = \frac{e_{an} i_{an} + e_{bn} i_{bn} + e_{cn} i_{cn}}{\omega_r} \tag{9}$$

Moreover, back EMF is also defined as [11]

$$\left.\begin{aligned} e_{an} &= K_b f(\theta_{re}) \omega_r \\ e_{bn} &= K_b f\left(\theta_{re} - \frac{2\pi}{3}\right) \omega_r \\ e_{cn} &= K_b f\left(\theta_{re} + \frac{2\pi}{3}\right) \omega_r \end{aligned}\right\} \tag{10}$$

The electrical rotor angle θ is equal to the mechanical rotor angle θ_m multiplied by the number of pole pairs which is given by,

$$\theta = \frac{P}{2} \theta_m \tag{11}$$

The torque balance equation is expressed as

$$T_{em} - T_l = J \frac{d\omega_r}{dt} + B\omega_r \tag{12}$$

Where T_l is the load torque, J is the moment of inertia of the motor, and B is the frictional constant.

TABLE II

Motor Parameters

1HP, 310 V, 4 pole, 50Hz		
Rated current(I_{rated})	4.52	A
Rated speed (w_{rated})	4600	rpm
Rated torque (T_{rated})	2.2	Nm
Winding inductance(L_s)	3.285	mH
Winding resistance(R_s)	1.535	Ω
Rotor inertia constant(J)	$1.8e^{-4}$	Kg m^2
Frictional co-efficient(B)	0.001	Nm/rad/s
Back EMF constant(K_b)	51	V/krpm/min
Torque constant(K_t)	0.49	Nm/A

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