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Analysis of Three Phase Space Vector PWM Voltage Source Inverter for ASD's

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Abstract **– This paper comprehensively analyses the design of Space Vector PWM (SVPWM) using *Simulink* and presents the comparative analysis of improved quality three phase PWM-VSI for Adjustable Speed Drives (ASD's). In SVPWM the complex reference voltage phasor is processed as a whole, therefore, interaction between three motor phases is exploited, and this strategy reduces the switching losses by limiting the switching. The performance of three phase Space Vector PWM based VSI for ASD's using fuzzy logic controller are verified through simulation model and a good consistency is achieved.**

Keywords **— Adjustable Speed Drive (ASD); Total Harmonic Distortion (THD); Space Vector Pulse Width Modulation (SVPWM); Fuzzy Logic Controller (FLC), Sinusoidal Pulse Width Modulation (SPWM)**

I. INTRODUCTION

The most economical induction motor speed control methods are realized by using frequency converters. A converter consisting of a diode rectifier, a DC-link and a Pulse Width Modulated (PWM) voltage inverter is the most applied in the industry. Today pulse Width Modulation based variable speed drives are increasingly applied in many new industrial applications that require superior performance. Recently, developments in power electronics and semiconductor technology have lead improvements in power electronic systems. Hence, different circuit configurations of inverters have become popular and considerable interests by researcher are given on them. Although the basic circuit for an inverter may seem simple, accurately switching these devices provides a number of challenges for the power electronics engineer. Space vector pulse width modulation prevent unnecessary switching hence provides excellent output performance, optimized efficiency, high reliability and easier digital realization compared to similar inverters with conventional pulse width modulators. Presently among various applications, the ASD's has been used to save energy consumption by matching supply with demand. By supplying the exact amount of flow, all the energy losses associated with over supplying are eliminated.

II. SPACE VECTOR PWM VSI

Space Vector Modulation (SVM) technique was originally developed as vector approach to pulse-width modulation (PWM) for three-phase inverters (Figure 1). This technique confines space vectors to be applied according to region where the output voltage vector is located. The determination of switching instants may be achieved using space vector modulation technique based on the representation of switching vectors in α-β plane. Space Vector Modulation increases the output capability of Sinusoidal PWM (SPWM) without distorting output voltage waveform; and prevents un-necessary switching.

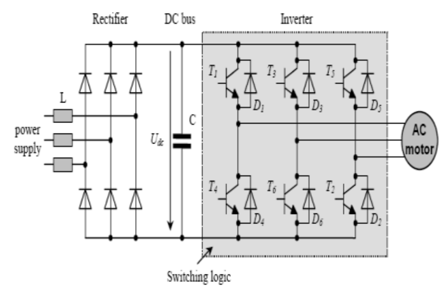

Figure1. Basic Three-Phase Voltage-Source Converter circuit connected to Power Supply

III. REALIZATION OF SPACE VECTOR PWM

In SVPWM each desired position on the circular locus can be achieved by an average relationship between two neighboring active vectors. Zero state vectors are used to fill-up the gap to a constant sampling interval. An optimum space vector modulation is expected if the maximum deviation of the current vector for several switching states becomes as small as possible, and the cycle time is as short as possible [1]. Here the space vector PWM is realized based on the following steps [2] –

A. Step 1. Determination of V_d, V_q, V_{ref}, and (α) [3]:

Coordinate transformation (a-b-c to d-q). The Voltage Space vector and its components in d-q plane.

$$\begin{bmatrix} v_d(t) \\ v_q(t) \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} \quad (1)$$

$$\left|\bar{V}_{ref}\right| = \sqrt{V_d^{\,2} + V_q^{\,2}} \quad (2)$$

$$\theta = \tan^{-1}\left(\frac{V_q}{V_d}\right) = \omega_s t = 2\pi f s\, t \quad (3)$$

B. Step 2. Switching Time Duration T_a, T_b and T_0 [3]:

1) Switching Time Duration at Sector 1: Let T_s is the sampling Period, T_z is switching Period and considering that T_S is sufficiently small, and then the V_{ref} (reference voltage) could be constant during $T_{S.}$ Within sampling Period (T_s) reference voltage (V_{ref}) is sampled at regular interval. If T_s (2^*T_z) is the sampling period then for switching period T_z, V_1 is applied for T_a, V_2 is applied for T_b, and Zero vector is applied for the rest of sampling period i.e. $T_0 = (T_z - T_a - T_b)$. When the reference voltage V_{ref} falls into sector I. The reference voltage V_{ref} can be found by two adjacent active vectors V_1 and V_2 and zero vectors (V_0, V_7), for sufficiently high switching frequency the reference space vector is assumed constant during one switching cycle.

$$\begin{aligned} \vec{V}_{ref}\, T_z &= (\vec{V}_1 T_a + \vec{V}_2 T_b + \vec{V}_{0,7} T_0) \\ T_z &= (T_a + T_b + T_0) \end{aligned} \quad (4)$$

T_a, T_b, and T_0 are the time for V_1 and V_2 and $V_{0,\,7}$ respectively.

$$\begin{aligned} &\vec{V}_{ref} = V_{ref}\, e^{j\alpha}, \\ &V_1 = \frac{2}{3}V_d\,,\ \vec{V}_{0,7} = 0\,,\ \text{and}\ \vec{V}_2 = \frac{2}{3}V_d\, e^{j\frac{\pi}{3}} \end{aligned} \quad (5)$$

As each switching period T_z starts and ends with zero vectors i.e. there will be two zero vectors per T_z or four null vectors per Ts, duration of each null vector is $T_0/2$.Therefore, the space vector can be written as follows-

$$\begin{aligned} \textbf{Re:}\quad & V_{ref}(\cos\alpha)T_z = \frac{2}{3}V_{dc}T_a + \frac{1}{3}V_{dc}T_b \\ \textbf{Im:}\quad & V_{ref}(\sin\alpha)\,T_z = \frac{1}{\sqrt{3}}V_{dc}T_b \end{aligned} \quad (6)$$

$$T_a = \frac{\sqrt{3}\,T_z V_{ref}}{V_{dc}}\sin\left(\frac{\pi}{3} - \alpha\right) = T_z * m_a * \sin\left(\frac{\pi}{3} - \alpha\right) \quad (7)$$

$$T_b = \frac{\sqrt{3}\,T_z V_{ref}}{V_{dc}}\sin\alpha = T_z * m_a * \sin\alpha \quad (8)$$

and $T_0 = (T_z - T_a - T_b)$,

$$\text{where Modulation Index } m_a = \frac{\sqrt{3}\,V_{ref}}{V_{dc}} \quad [0 \le \alpha \le 60°] \quad (9)$$

To reduce the number of the inverter switching, it is necessary to distribute the switching sequence in such a way that the transition from one state to the next is performed by switching only one inverter leg at a time. This results in starting the sampling period with one zero state and ending at the other state. The two possible methods shown in Figure 2 are [4] -

Method 1: equal sharing of the zero vector intervals on each sampling interval

Method 2: use of only a zero vector interval within each sampling period.

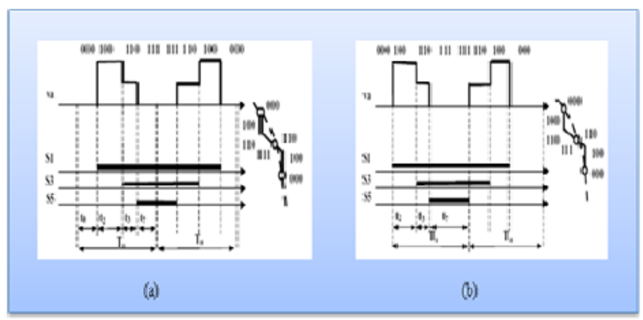

Figure 2. Pulse Generation with (A) method 1 (B) method 2

The time intervals can be shared in different ways between V_0 and V_7 and the way we are placing the active states within the sampling period influences the content in fundamental or the Total Harmonic Distortion coefficient. Equal sharing provides a good compromise between simplicity and THD. (Figure 2(A)). The process is now straightforward it is only necessary to calculate the portions of sampling period allocated to V_1,V_2, and $V_{0,7}$.The time weighted sum of these vectors taken over the sampling period, T_S, should give the desired voltage vector V_{ref}.

2) Switching Time Duration at any Sector [3] –

$$\begin{aligned} T_a &= \frac{\sqrt{3}\,T_z V_{ref}}{V_{dc}}\left(\mathrm{Sin}\left(\frac{\pi}{3} - \alpha + \frac{n-1}{3}\pi\right)\right) \\ &= \frac{\sqrt{3}\,T_z V_{ref}}{V_{dc}}\left(\mathrm{Sin}\left(\frac{n}{3}\pi - \alpha\right)\right) \end{aligned} \quad (10)$$

$$T_b = \frac{\sqrt{3}\,T_z V_{ref}}{V_{dc}}\left(\mathrm{Sin}\left(\alpha - \frac{n-1}{3}\pi\right)\right) \quad (11)$$

$$T_0 = (T_z - T_a - T_b) \quad (12)$$

where, $n = 1$ to 6 (i.e. sector 1 to 6) $0 \le \alpha < \pi/3$

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3) Determine switching time of each transistor (S_1 to S_6):

By selecting the space vectors and their times calculated, switching sequence is going to be the next step to arrange. A typical seven-segment switching sequence and inverter output voltage waveforms for V_{ref} in sector I is shown in Figure 3 where $V_{1,}$ V_2 and $V_{0,7}$ synthesize V_{ref}. The sampling period T_S for selected vectors can be divided into the seven segments. The construction of symmetrical pulse pattern for two consecutive T_z intervals are shown in Figure 2(A) and $T_s = 2T_z = 1 / f_s$ (f_s = Switching frequency) is the sampling time. Note that the null time has been conveniently distributed between the V_0 and V_7 vectors to describe the symmetrical pulse width (to produce minimal output harmonics.) [3], [5]

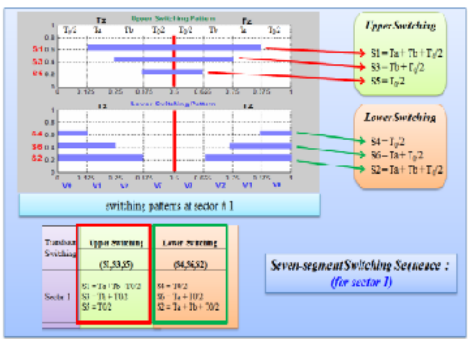

Figure 3. Seven Segments Switching Sequence

TABLE I. SWITCHING SEQUENCE FOR EACH SWITCH IN EACH LEG

Sector	Upper Switching (S1,S3,S5)	Lower Switching (S4,S6,S2)
Sector 1	S1 = Ta +Tb +T0/2 S3 = Tb + T0/2 S5 = T0/2	S4 = T0/2 S6 = Ta + T0/2 S2 = Ta + Tb + T0/2
Sector 2	S1 = Ta + T0/2 S3 = Ta +Tb +T0/2 S5 = T0/2	S4 = Tb + T0/2 S6 = T0/2 S2 = Ta +Tb +T0/2
Sector 3	S1 = T0/2 S3 = Ta +Tb +T0/2 S5 = Tb + T0/2	S4 = Ta +Tb +T0/2 S6 = T0/2 S2 = Ta + T0/2
Sector 4	S1 = T0/2 S3 = Ta + T0/2 S5 = Ta +Tb +T0/2	S4 = Ta +Tb +T0/2 S6 = Tb + T0/2 S2 = T0/2
Sector 5	S1 = Tb + T0/2 S3 = T0/2 S5 = Ta +Tb +T0/2	S4 = Ta + T0/2 S6 = Ta +Tb +T0/2 S2 = T0/2
Sector 6	S1 = Ta +Tb +T0/2 S3 = T0/2 S5 = Ta + T0/2	S4 = T0/2 S6 = Ta +Tb +T0/2 S2 = Tb + T0/2

Table I shows seven-segments switching sequence for all sectors and Table 2 shows switching sequence time for each switch in each leg of SVPWM based VSI. The algorithm proposed in this work is based on approach taken in [6]. Here we calculate the phase turn-on and turn-off times directly instead of calculating the effective times (ta, tb and tc) along with identification of the sector to activate them and explore the decoupling between the angle and amplitude of the command voltage vector in the calculation of turn-on and turn-off times.

IV. CLOSED LOOP SPEED CONTROL OF AC DRIVES

The closed loop speed control of AC Drive is obtained here by using slip speed control method. The speed error is processed through a PID based speed controller (Fuzzy Logic based) and a slip regulator. The fuzzy PID controller designing steps are as following 1. Formulate the PID control strategy and design the controller 2. Replace it with a fuzzy controller 3. Set the transfer gains and 4. Fine-tune the fuzzy controller. In present designing the FLC has two inputs which are: Error and the Error change. Figure 6(A) illustrates the method used in reaching the desired speed value. [7]

V. SIMULATION OF THREE PHASE SVPWM VSI FOR ASD

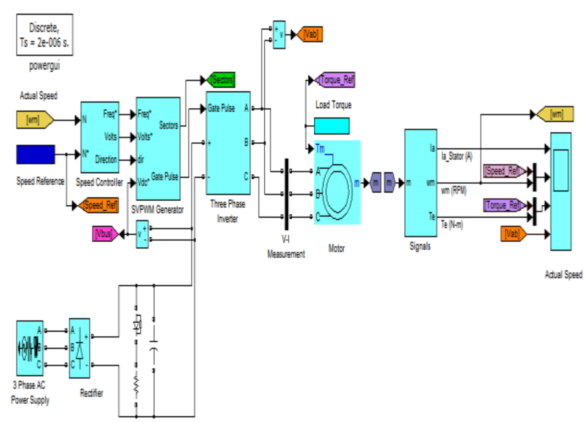

Figure 4. *MATLAB/Simulink* Model of three phase SVPWM-VSI for ASD

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VI. Speed Controller Subsystem

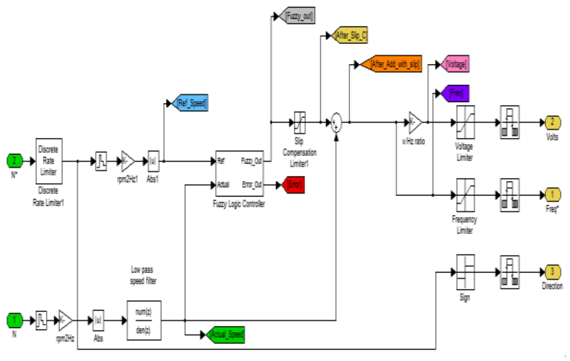
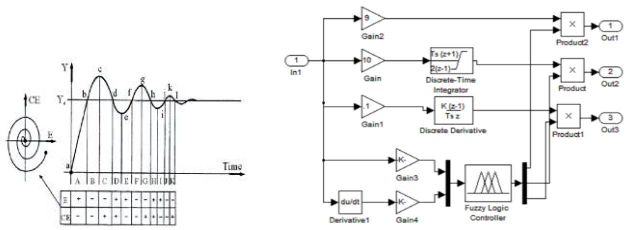


Figure 5. Realization and Design of Speed Controller Subsystem



(A) (B)

Figure 6. (A) Error and Error-Change approach in FLC
(B) Fuzzy PID Controller

VII. FIS Rule and Membership Functions for FLC

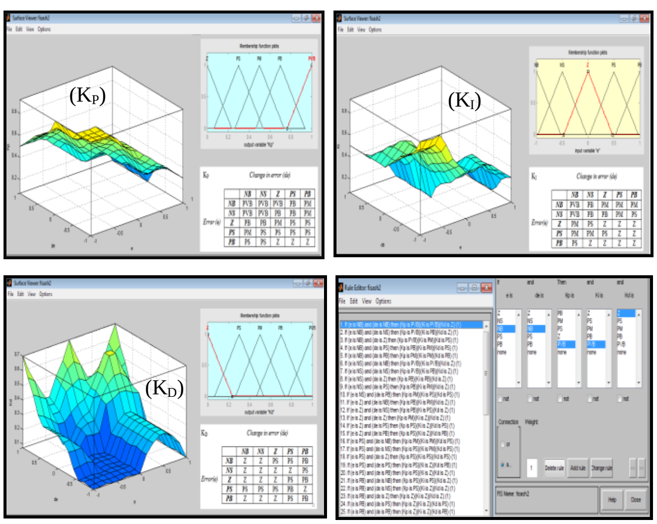


Figure 7. The surface Viewer, Membership Function & Rule-Base for Controller Subsystem (a) K_p (b) K_I (c) K_D

VIII. Space Vector PWM Generator Subsystem

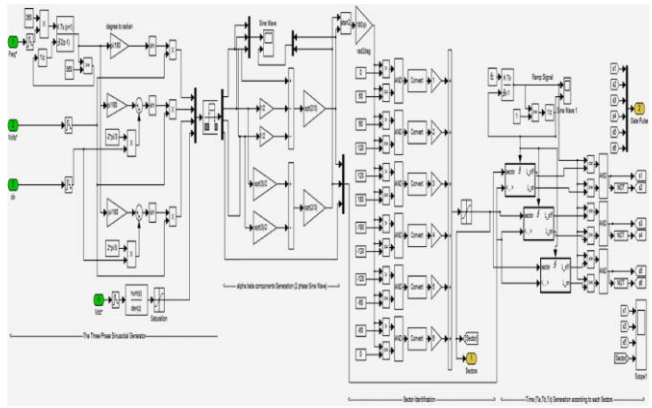


Figure 8. Realization of Space Vector PWM Generator Subsystem

IX. Simulation Results And Analysis

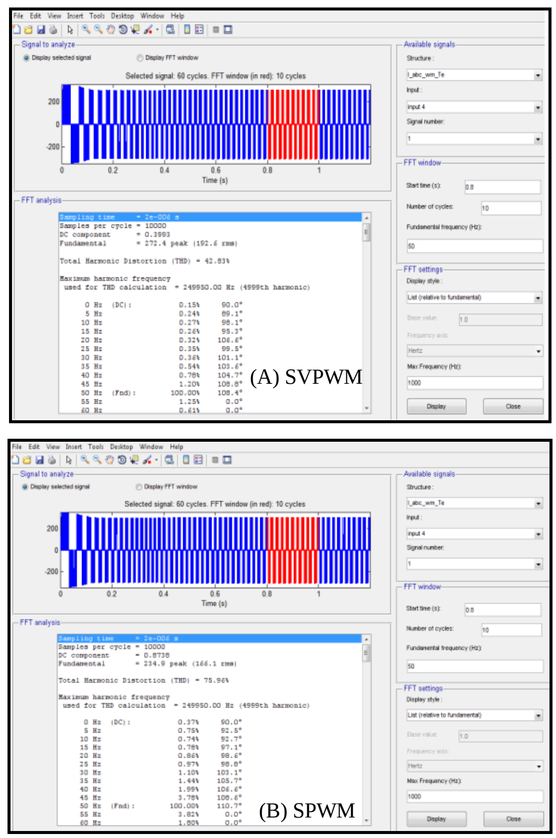


Figure 9. FFT analysis showing Fundamental (50 Hz) and THD at Speed 1500 RPM for (A) SVPWM (B) SPWM

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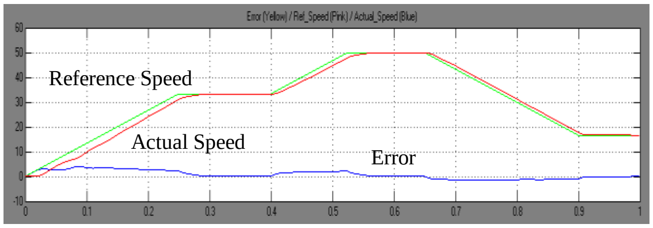


Figure 10 (A) Minimization of Error according to Variation in Speed

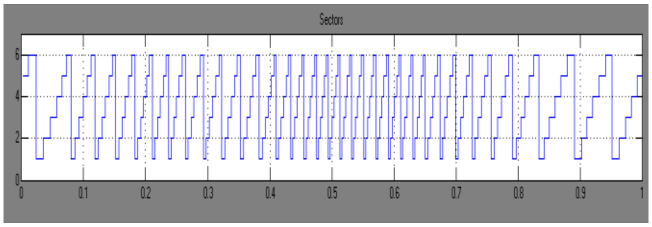


Figure 10 (B) Sectors according to Variation in Speed

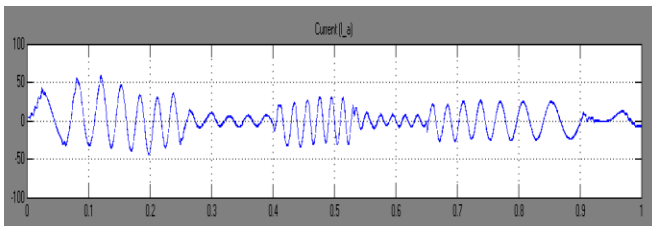
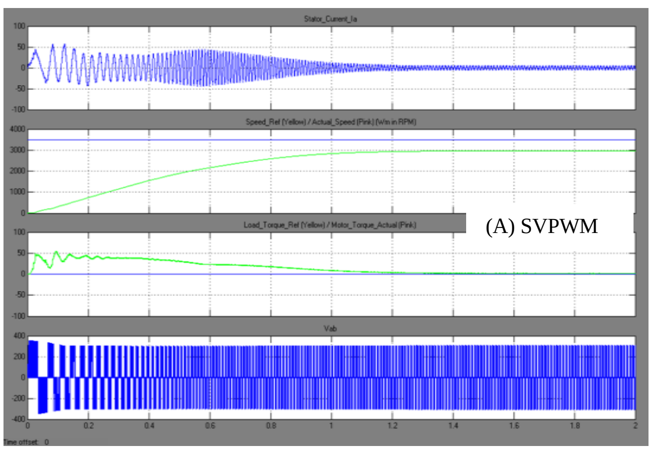


Figure 10 (C) Change in Current according to Variation in Speed

Figure 10: (A,B,C) Simulated Waveforms of SVPWM-VSI for ASD



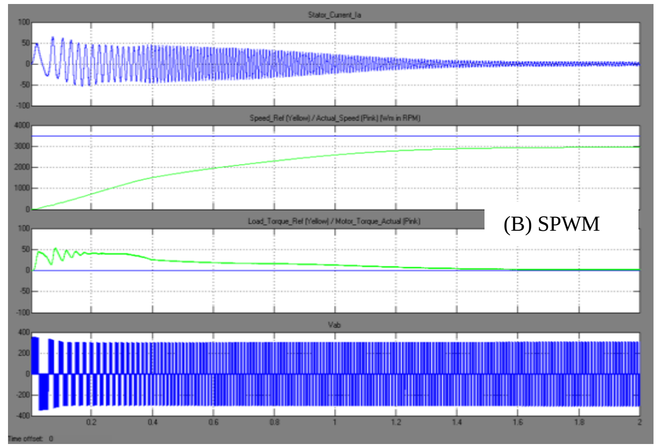


Figure 11. Simulation results showing Stator current, Settling time, Motor torque and V_{AB} at maximum speed for (A) SVPWM (B) SPWM

TABLE II: COMPARISON OF FUNDAMENTAL, THD & SETTLING TIME

Converter Topology	*fundamental (50 Hz)*	*THD*	*Settling time (max. speed)*
SVPWM	272.4 V	42.03 %	1.30 sec
SPWM	234.9 V	75.96 %	1.75 sec

TABLE III SIMULATION PARAMETERS

3Φ, 220V,50Hz	Solver =Ode 45	Bridge arm s=3	p = 2
V/f = 3.2	fc = ±4500 Hz	P = 2	Rs = 500Ω
Cs = 1e-9	Ts = 2e-6	Tm =10e-6	Tc = 50e-6

X. CONCLUSION

This paper has attempted to give the designing and comparative analysis of Three Phase improved quality Space Vector PWM based VSI for ASD's.

The simulation test results validate the effective utilization of DC link voltage, improvement in total harmonic quality, FLC robustness for different speed trajectories, acceptable steady state error and fast settling time for ASD using Space Vector PWM.

EXPLORING RESEARCH AND INNOVATIONS

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