DIRECT TORQUE CONTOL OF PERMANENT MAGNET SYNCHRONOUS MOTOR USING SVPWM

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Abstract — Recent research has shown that for high performance servo applications Permanent magnet Synchronous motor could become a serious competitor to the induction motor (IM). In this paper Direct Torque Control (DTC) of Permanent Magnet Synchronous Motor (PMSM) using SVPWM is studied. It was observed that DTC based control of PMSM using SVPWM gives better performance of speed control. The method is verified with simulation using MATLAB/SIMULINK.

Keywords — Direct Torque Control , Park transform , Clarke transform, Vector control, SVPWM. Introduction

Permanent magnet (PM) synchronous motors are progressively replacing dc motors in high-performance applications like robotics, aerospace actuators and industrial applications. The PMSM is more efficient and has a larger torque inertia ratio and power density when compared to the IM for the same output capacity. The PMSM is smaller in size and lower in weight that makes it preferable for certain high performance[1][2][4].

The conventional DTC of PMSM has received considerable investigation for its advantage of quick change of torque, robustness and simplicity [1]. However, only six valid voltage vectors are available in conventional DTC which induce such problems as large torque ripple and variable switching frequency [2]. Hence the space vector modulation -direct torque control (SVM-DTC) was presented in which the along with hysteresis control of torque and stator flux hysteresis controller in conventional DTC, reference voltage calculator and space vector modulation unit are used. The SVM-DTC can provide constant switching frequency and more accurate Stator flux and torque control[1][3][5][6].

How to calculate reference voltage vector is an important issue in SVM-DTC.

This paper investigates an improved method of SVM-DTC in which the reference voltage is calculated with the flux position, errors of flux and torque. The method is simple to implement and robust. The improved SVM-DTC is verified by simulation and proved to decrease torque ripple effectively and be strong[7][9][20][21].

I. MATHEMATICAL MODEL OF PMSM

The model of surface-mounted Permanent magnet synchronous motor in the rotating reference frame(d,q) can be expressed as follows:

$$v_{sd} = R_s i_{sd} + \frac{d\Psi_d}{dt} - \omega_r \Psi_{sq}$$

$$v_{sq} = R_s i_{sq} + \frac{d\Psi_q}{dt} - \omega_r \Psi_{sd} \qquad (1)$$

$$\Psi_{sd} = L_{sd} i_{sd} + \Psi_f$$

$$\Psi_{sq} = L_{sq} i_{sq} + \Psi_f$$

$$T_e = \frac{3}{2} n_p i_{sq} \Psi_f$$

Where and are direct and quadrature axis voltage, and are direct and quadrature axis current, is the stator resistance, and are direct and quadrature flux, and are direct and quadrature axis inductance, is the permanent magnet flux, is the electrical rotor speed, number of pole pair[11][12][13].

II. CONTROL SCHEME

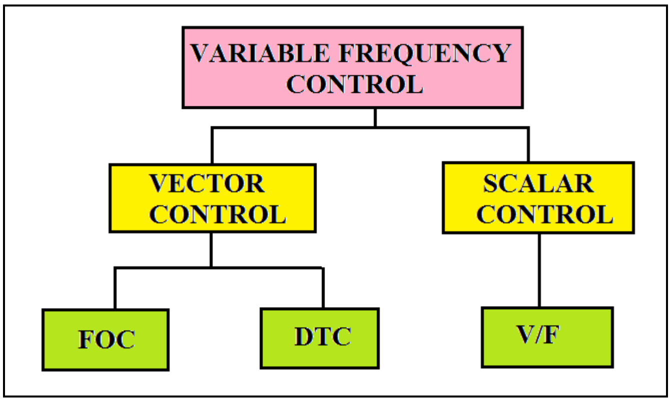

Figure 1 Types of speed control

Scalar control, as the name indicates, is due to magnitude variation of the control variables only, and disregards the coupling effects of the machine. For example, frequency or slip of a machine can be controlled to control the torque and the voltage can be controlled to control the flux,. However, torque and flux are also functions of voltage and frequency, respectively. Vector control or field oriented control is in contrast to scalar control, where both the magnitude and phase alignment of vector variables are controlled[9][10]. Because of the superior performance of vector controlled drives which is demanded in many applications, scalar-controlled drives giving somewhat inferior performance has diminished recently. [4][5].

DIRECT TORQUE CONTROL

The working principle for the basic DTC is to select a voltage vector based on the error between requested and actual (sensed and estimated) values of torque and flux, rotor position estimation. DTC has the capability to work without any requirement of external measurement sensor for the mechanical position of rotors. The flux and torque references are tracked using hysteresis comparators and a switching table implemented with look up tables is used for selecting the optimum converter's output.

The advantages of the DTC is to eliminate the direct and quadrature axes current controllers, associated transformation circuits, and the rotor position sensor. The disadvantages are difficulty of torque control at low speed, high current and torque ripple value, variable switching frequency, high noise level at low speed range.

DTC Process

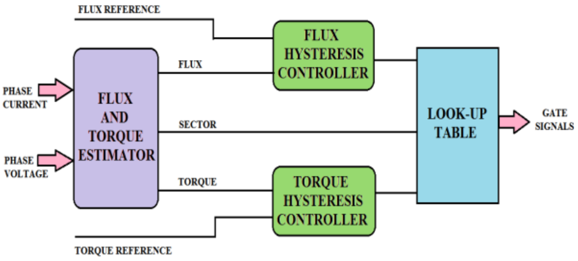

Figure 2 DTC flow

- Voltage transform
- Flux estimator
- Torque calculation
- Sector Calculation
- Torque and flux hysteresis comparators
- Look-up tables
- Voltage source inverters

Voltage transform

The voltage is estimated from the inverters switching state and the DC-link voltage in the reference frame by the voltage equation.

$$v_{set}(S_{abc}) = \sqrt{\frac{2}{3}}\frac{V_{dc}}{2}\left(S_a e^{0i} + S_b e^{2\pi i/3} + S_c e^{4\pi i/3}\right) - \sqrt{\frac{2}{3}}\left(v_a e^{0i} + v_b e^{2\pi i/3} + v_c e^{4\pi i/3}\right) \qquad (2)$$

where Sabc is the state of the switches and uabc is the voltage loss in the switches.

Flux and Torque Estimation

Accurate flux estimation in DT controlled PMSM system is required to have proper drive operation, it's stability. Most of the flux estimation techniques known is based upon voltage modelling, current modeling, or combination of both of these[16].

$$\Psi_{s\alpha} = \int (V_{s\alpha} - R_s i_{s\alpha})dt$$

$$\Psi_{s\beta} = \int (V_{s\beta} - R_s i_{s\beta})dt \qquad (3)$$

Angle Determination and Sector Calculation

By the help of flux linkage vector in the αβ coordinates, location of the sector of the stator flux linkage vector is possible. The sign of the finds us the quadrant of the stator flux linkage vector and the given equation gives us the exact angular position of flux vector.

$$\theta_s = \tan^{-1} \Psi_\beta / \Psi_\alpha$$

Torque and Flux Hysteresis Comparator

To find out the correct commands for control purpose a flux and a torque hysteresis comparators can be used. The comparators calculate the error between the required values and estimated values, and hence obtain if the flux and torque vectors should be

1. Increased - Output is 1

2. Decreased - Output is -1

3. Constant - Output is 0

The torque comparator works with three levels, but the flux comparator works with only two levels, as the stator flux mustn't be kept constant while operating the permanent motor[16][17].

VECTOR CALCULATION (SVPWM)

The SVPWM scheme is more complicated than that of the conventional SPWM. It requires the determination of a sector, calculation of vector segments, and it involves region identification based on the modulation index and calculation of switching time durations[17][22].

For state (++- / 110)

Va0=Vdc, Vb0=Vdc, Va0=0

$$V_s = V_{a0} + V_{b0} e^{2\pi i/3} + V_{c0} e^{-2\pi i/3}$$

$$V_2 = V_{dc}\left(\frac{1}{2} + \frac{j\sqrt{3}}{2}\right) \quad (4)$$

$$V_2 = V_{dc}\angle 60$$

Similarly the switching vectors can be computed for the rest of the inverter switching state

Voltage Vector	a	b	c	V_α	V_β	Vector
V_0	0	0	0	0	0	0
V_1	1	0	0	$2V_{DC}/3$	0	$V_{0°}$
V_2	1	1	0	$V_{DC}/3$	$V_{DC}/\sqrt{3}$	$V_{60°}$
V_3	0	1	0	$-V_{DC}/3$	$V_{DC}/\sqrt{3}$	$V_{120°}$
V_4	0	1	1	$2V_{DC}/3$	0	$V_{180°}$
V_5	0	0	1	$-V_{DC}/3$	$-V_{DC}/\sqrt{3}$	$V_{240°}$
V_6	1	0	1	$V_{DC}/3$	$-V_{DC}/\sqrt{3}$	$V_{300°}$
V_7	1	1	1	0	0	0

It is necessary to know in which sector the reference output lies in order to determine the switching time and sequence. The identification of the sector where the reference vector is located is straightforward. The phase voltages correspond to eight switching states: six non-zero vectors and two zero vectors at the origin[18][19]. Depending on the reference voltages and , the angle of the reference vector can be used to determine the sector as per Table.

SECTOR	DEGREES
1	$0 < \theta \le 60°$
2	$60 < \theta \le 120°$
3	$120 < \theta \le 180°$
4	$180 < \theta \le 240°$
5	$240 < \theta \le 300°$
6	$300 < \theta \le 360°$

The reference voltage vector rotates in space at an angular velocity ω = 2πf , where f is the fundamental frequency of the inverter output voltage. When the reference voltage vector passes through each sector, different sets of switches in Table will be turned on or off[17][18]. As a result, when the reference voltage vector rotates through one revolution in space, the inverter output varies one electrical cycle over time[14][15][16].

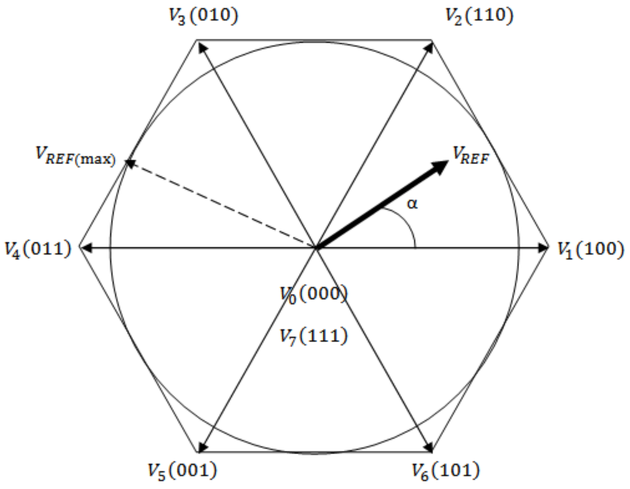

Figure 3 Space Vector

III. SIMULATIONS

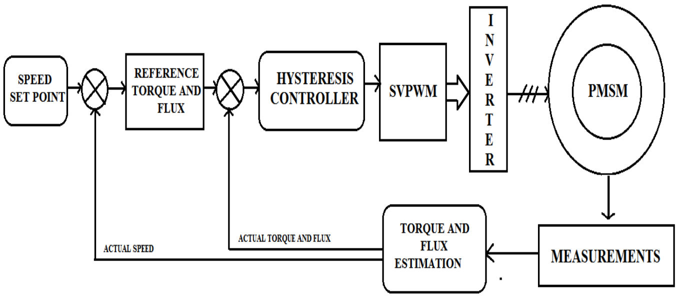

Figure 4 DTC Block Diagram

Matlab Model of PMSM is used for simulation purpose with following parameters

Bus Voltage =300V

Pole pairs (p) = 3

Magnetisation ( ) = 0.1546 Wb

Moment of Inertia (J) = 0.000141 kg-sq.m

Resistance (Rss) = 0.86Ω

Direct axis Inductance (Ld) = 0.00665 H

Quadrature axis Inductance (Lq) = 0.00665 H

Coeff. of Friction(B) = 0.0038 Ns

Synchronous Speed (ωn) = 500 rpm

Nominal Torque (Mn) = 14 N-m

Each block used in DTC simulation is shown below

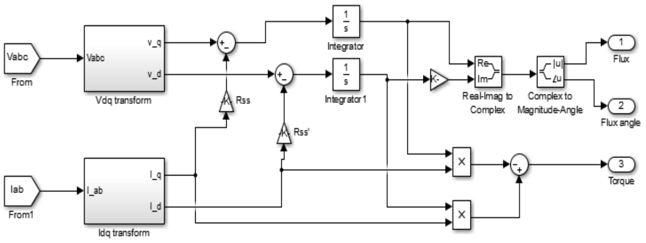

Figure 5 Flux and Torque Estimation

Voltage (Va, Vb, Vc) and current (Ia,Ib) are taken from the measurement block shown in Fig 6 for estimation of torque and flux

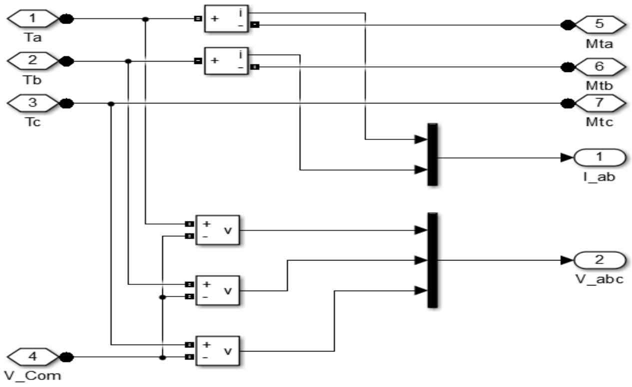

Figure 6 Measurement Block

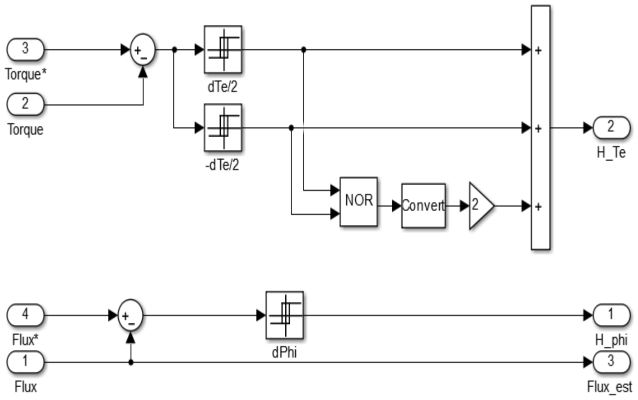

Figure 7 Flux and Torque Hysteresis Comparator

Actual and reference torque are compared and given to the 3- Level Hysteresis Comparator as shown in Fig 7. Similarly actual and reference flux are compared and given to the 2-Level Hystersis Comparators.

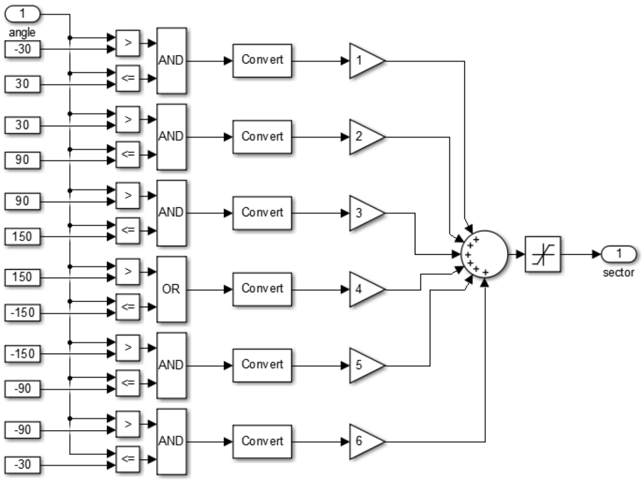

Figure 8 Sector Calculation

Flux angle is calculated from the direct and quadrature axis flux component. It acts as a input to sector calculation block. Sector is calculated based on location of angle in space vector. For example if angle is 75° then sector 2 gets selected. The Logic is based on ANDing operation.

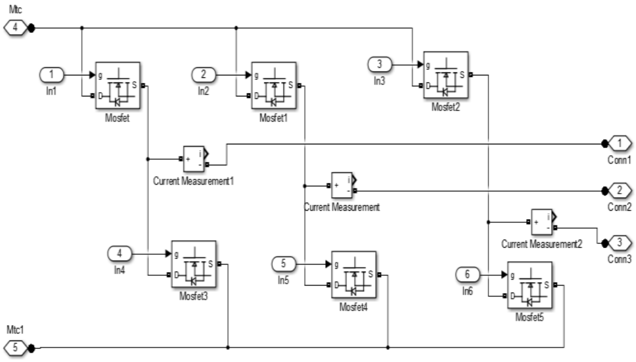

Figure 9 Inverter

Fig 9 shows the Inverter designed to drive the PMSM. This inverter uses MOSFET as a switches which receives its gate pulses from the Look-up-Table.

IV. RESULTS AND DISCUSSIONS

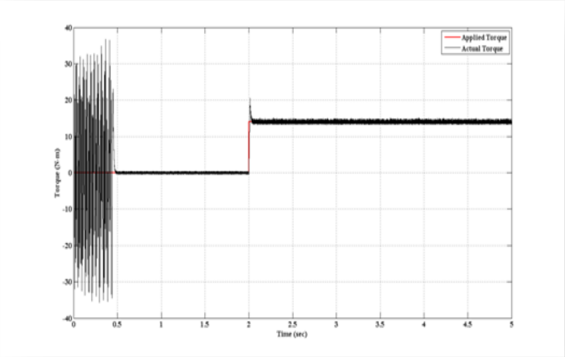

Figure 10 Step Torque input and Actual Torque

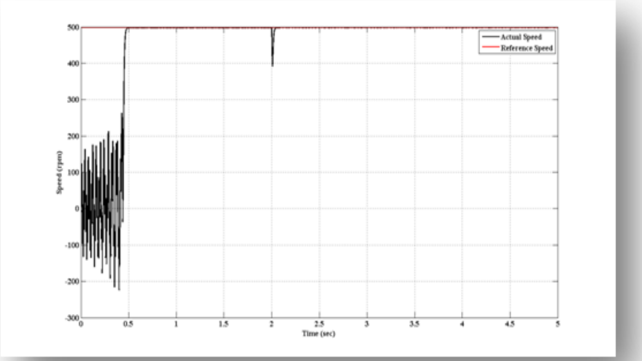

Figure 11 Speed Response for step torque

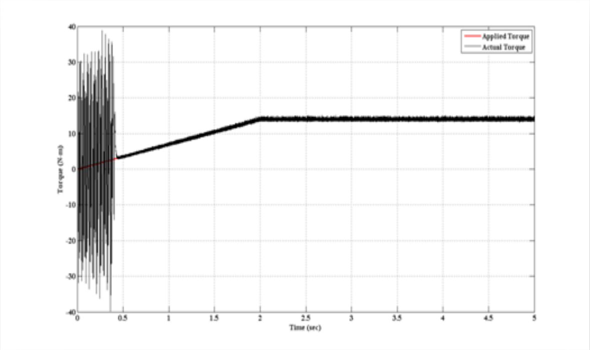

Figure 12 Ramp Torque input and actual Torque

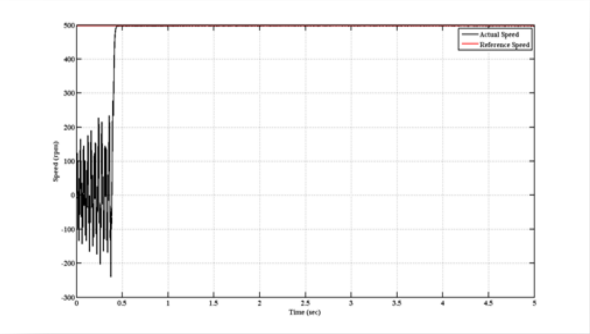

Figure 13 Speed response for ramp torque

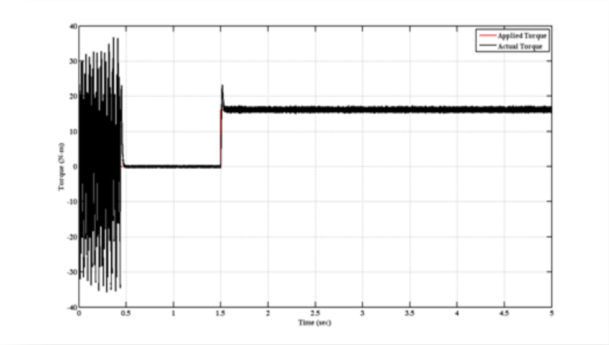

Figure 14 Maximum torque input

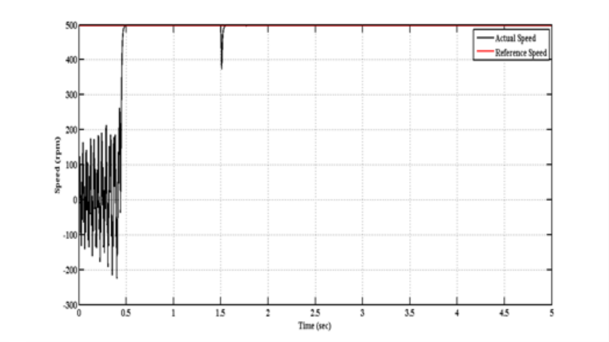

Figure 15 Speed response for maximum torque

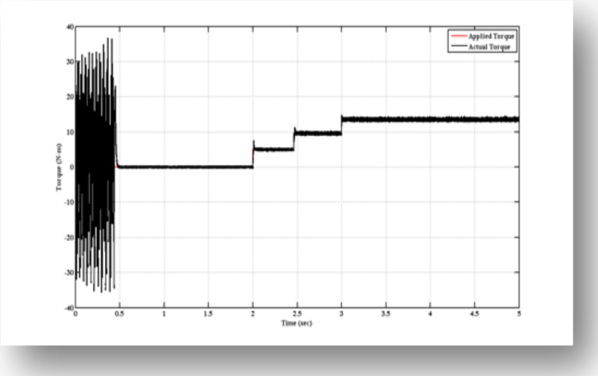

Figure 16 Staircase torque input and actual torque

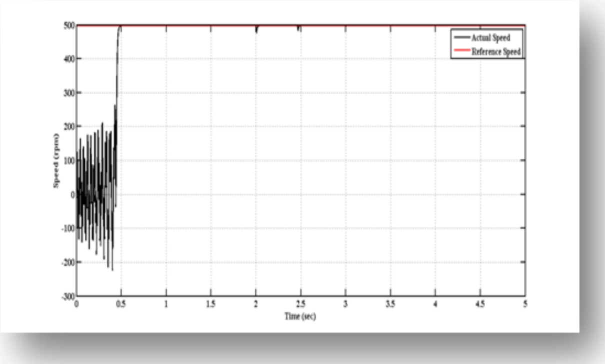

Figure 17 Speed response for staircase torque of DTC

Fig 10 shows actual and reference torque at rated value of 14N-m with respect to time. Here step torque is applied at 2 sec. Fig 11 shows the speed plot for the torque applied shown in Fig 10.For DTC during the staring and transitions high torque ripple can be seen. This is because of current ripples during transients. But DTC gives a better speed response and have less settling time.

Fig 12 shows ramp function of Torque with respect to time. Torque is kept constant at rated value after 2 sec. Fig 13 shows speed curve for torque applied in Fig 12. Torque has high ripples but I can be seen that speed is constantly maintained at rated value.

Fig 13 shows Torque applied in step function greater than rated value at 18 N-m. Fig 14 shows speed curve for the torque applied at fig 13.

Fig 15 shows Torque as staircase function of time. Its value is increased at 2, 2.4 and 3sec at 5, 10 and 14N-m respectively. Fig 16 shows the speed curve for the torque applied in Fig 15 .In this Torque is increased in 3 steps which gives drops in the speed.

V. CONCLUSIONS

DTC is used for efficient control of the torque and flux without varying the motor parameters and load value. The flux and torque can be directly controlled by the inverter voltage vector in DTC.

It can be concluded that DTC can be applied for the PMSM and is useful for a wide range of speed. Applications which require good dynamic performance demand DTC as it has a greater advantage over other control methods because of its property of fast torque response. For the sake of increase of the performance indices, control period must be as short as possible.

PMSM offers some advantages over IM like increased efficiency and smaller size. Modeling of the PMSM in both stationary and rotating reference frames were made and a Simulink model of the PMSM was proposed in the stationary reference frame in order to be used in the DTC system. Explanation of each part in the DTC-PMSM system was given. Simulation works of the DTC system showed its effectiveness even over the FOC in terms of the torque and flux dynamics.

Torque/flux ripples and the variable switching frequency are the main drawbacks of the DTC system. Many methods were proposed to solve those problems but increased complexity is a major demerit facing them.

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