Predictive Torque Control of Three Phase Axial Flux Permanent Magnet Synchronous Machines

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ABSTRACT:
This paper presents a predictive strategy to control torque and flux of an axial flux permanent magnet (AFPM) machine. Unlike conventional direct torque control (DTC) for permanent magnet machines that only six actives voltage vectors of the inverter are used to control the torque and flux of the machine, in predictive torque control (PTC), zero voltage vectors are used to control too. Thus, the number of voltage vectors to control AFPM increases and leads to faster dynamic torque response and lower ripples of torque and flux. In predictive torque control presented in this paper, responses of torque and flux are computed for all possible switching states of the inverter at every sample time according to the discrete time model of the machine and then the switching state that optimizes ripples of torque and flux will be applied in the next discrete-time interval. Simulation results, which confirm the good performance of the proposed predictive torque control are presented.

KEYWORDS: Permanent magnet (PM) machine, predictive control, axial flux motor drives, torque ripple.

1. INTRODUCTION

Recently, permanent magnet (PM) machines due to the advantages such as small size with high efficiency and high reliability, have been receiving many attention. PM machines are divided to two general groups, including Radial Flux Permanent Magnet (RFPM) machine and Axial Flux Permanent Magnet (AFPM) machine. AFPMs have higher torque to inertia ratio and thus, faster dynamic torque response with respect to RFPMs [1, 2].

Two widely used commercial control schemes are field-oriented control (FOC) and direct torque control (DTC). DTC technique was developed for induction motor drivers in the middle of 1980s [3]. It was applied to permanent magnet drives in [4, 5]. DTC has a faster dynamic torque response with respect to FOC. In DTC, the appropriate inverter configuration is selected from a switching table, according to the signs of the errors between the references of torque and stator flux and their actual values to keep the torque and stator flux within a hysteresis band. The main advantage of DTC in comparison with FOC is a faster dynamic torque response. Furthermore, DTC is independent of motor parameters except for stator resistance. There are some disadvantages like torque ripple, current distortion and mainly needing a high sampling frequency for digital implementation that is due to the hysteresis based scheme and therefore, due to the variable switching frequency. Many studies have been done to solve these problems [6- 9].

Predictive control is a control theory that was developed at the end of the 1970s [10]. Variant types of this control strategy have been used for power conversion and motor drive control that mainly associated with modulation techniques [11-16]. The application of this family of nonlinear control techniques for torque and flux control in induction machines (IMs) has received attention from researchers due to the technique's qualities of fast dynamic torque response, low torque ripple, and reduced switching frequency [17-20]. In [21, 22] predictive method has been used for control of PM synchronous machine. An alternative technique for controlling the torque and flux of an IM based on state space models has also been investigated [23].

A Predictive direct torque control method has been proposed in [24] to overcome the drawbacks of DTC for PMSM. In this approach, the torque ripple is supposed to be constant. At every sample time, active time (the interval of exerting active voltage vector) and the zero time (the interval of exerting zero voltage vector) are calculated for every 6 active voltage vectors according to discrete time model of machine's torque as if that voltage vector is used in the next interval, the torque won't exceed from the band limit. Then the voltage vector that leads to minimum ripple in flux will be applied in the next discrete-time interval. So, in this method, two voltage vectors (active voltage vector and zero voltage vector) and therefore, two switching states are applied in every time interval.

But another approach for predictive torque control has been presented in [25] for an induction machine fed by a matrix converter. In this method, torque and flux are evaluated for every valid switching state of the converter based on predictions obtained from a discrete time model of the system. Then the best switching state that minimizes the cost function will be used in next time interval.

The objective of this paper is to present a new predictive torque control for a 250V and 0.5HP surface mounted axial flux permanent magnet synchronous machine.

2. PM MACHINE EQUATIONS

The equations of the AFPM synchronous machine are same as PMSM. Therefore the machine equations in the rotor reference frame are [26],

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - L_q \omega i_q \tag{1}$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} + L_d \omega i_d + \omega \varphi_m \tag{2}$$

$$T_e = \frac{3}{2} p \left[\varphi_m i_q - (L_q - L_d) i_d i_q \right] \tag{3}$$

where

v_d , v_q stator voltage on d and q and axes;

i_d , i_q stator current on d and q axes;

R_s stator armature resistance, Ω ;

L_d , L_q direct and quadrature inductance, H;

ω rotor speed in electrical rad/s;

T_e electromagnetic torque, N.m;

p pole pairs;

φ_m rotor magnet flux linkage.e included.

3. PROPOSED PREDICTIVE TORQUE CONTROL

This predictive torque control (PTC) consists of choosing one of the 8 feasible switching states of the inverter, at fixed sampling intervals. The strategy to select the switching state for every time interval is based on minimization of a quality function. The quality function QF represents the evaluation criteria in order to select the best switching state for the next sampling interval. For the computation of QF , by means of the mathematical model of the AFPM, the electric torque T_e , and the stator flux φ_s on the next sampling interval are predicted, for each valid switching state. These predicted values are indicated by the superscript “p” and are compared with their reference values denoted by the superscript “*” within QF . A proportional–integral (PI) controller is used to generate the reference torque T_e^* for the predictive algorithm.

3.1. Quality Function QF

The quality function represents the evaluation criteria used to decide which switching state is the best to apply. The function is composed of the absolute error of the predicted torque, the absolute error of the predicted flux magnitude, resulting in

$$QF = \lambda_T \left| T_e^* - T_e^p \right| + \lambda_\varphi \left\| \varphi_s^* \right| - \left| \varphi_s^p \right\| \tag{4}$$

where λ_T and λ_φ are weighting factors that handle the relationship between torque and flux conditions. To maintain QF as a magnitude without a physic interpretation, λ_T is measured in Newton.meter inverse and λ_φ in weber inverse. The quality function QF must be calculated for the each of 8 feasible switching states. The state that generates the optimum value, in this case a minimum, will be chosen and applied during the next time interval. The state that generate the higher predictions of torque error and flux error will be penalized with higher values of QF , and thus, will not be selected. In this sense, the technique assigns costs to the objectives reflected in QF , weighted by λ_T and λ_φ and then chooses the switching state that presents the lowest cost.

3.2. Models Used to Obtain Predictions

In this section, a mathematical discrete-time model is derived to predict the behavior of the system under a given switching state, based on the well-known equations of the surface-mounted AFPM synchronous machine. The voltage equations in a d-q system of coordinates are expressed as (1) and (2).

For simplicity a surface mounted AFPM is considered $(L_q = L_d = L_s)$. Therefore, the electromagnetic torque expressed in (3) is simplified to

$$T_e = \frac{3}{2} p \varphi_m i_q \tag{5}$$

The derivative of electromagnetic torque is:

$$\frac{dT_e}{dt} = \frac{3}{2} p \varphi_m \frac{di_q}{dt} \tag{6}$$

Resolving for the derivative of i_q in (2)

$$\frac{di_q}{dt} = \frac{1}{L_q}[v_q - R_s i_q - L_d \omega i_d - \omega \varphi_m] \qquad (7)$$

In order to predict the current and torque values for the next sampling instant $t(k+1)$, a discrete-time set of equations can be derived from the continuous-time model. For small values of the control sampling time T_s, the quadrature axis current i_q at $t(k+1)$ can be calculated as follows

$$i_q(k+1) = i_q(k) + \frac{d}{dt} i_q(k) T_s \qquad (8)$$

Substituting in (7) yields

$$i_q(k+1) = i_q(k) + \frac{T_s}{L_q}[v_q(k) - R_s i_q(k) - L_d \omega(k) i_d(k) - \omega(k)\varphi_m] \qquad (9)$$

Substituting (9) in (5), the electromagnetic torque at instant $t(k+1)$ is obtained as follows [27]:

$$T_e(k+1) = \frac{3}{2} p \varphi_m \{ i_q(k) + \frac{T_s}{L_q}[v_q(k) - R_s i_q(k) - L_d \omega(k) i_d(k) - \omega(k)\varphi_m] \} \qquad (10)$$

The stator flux linkage of an AFPM in the stationary reference frame can be expressed as

$$\varphi_s = \int (v_s - R_s i_s) dt \qquad (11)$$

During the switching interval, each voltage vector is constant, and (11) is then rewritten as

$$\varphi_s = v_s t - R_s \int i_s dt + \varphi_s \big|t = 0 \qquad (12)$$

For prediction of stator flux, we should calculate stator flux components in the $\alpha - \beta$ system of coordinates. Since the calculations are realized in the $\alpha - \beta$ stator frame of coordinates, (1) and (2) are transformed into the $\alpha - \beta$ coordinates. The flux in each stator fixed axis can be split into one term depending on the rotor position and the PM flux and a second originated by the current in the corresponding axis as follow

$$\varphi_{s\alpha} = R_s i_{s\alpha} + \varphi_{m\alpha} \ , \ \varphi_{m\alpha} = \varphi_m . \cos(\theta) \qquad (13)$$

$$\varphi_{s\beta} = R_s i_{s\beta} + \varphi_{m\beta} \ , \ \varphi_{m\beta} = \varphi_m . \sin(\theta) \qquad (14)$$

Thus, the voltage equations result in

$$v_\alpha = R_s i_{s\alpha} + L_s \frac{di_\alpha}{dt} - \omega \varphi_m \sin(\theta) \qquad (15)$$

$$v_\beta = R_s i_{s\beta} + L_s \frac{di_\beta}{dt} + \omega \varphi_m \cos(\theta) \qquad (16)$$

According to (12), the components of stator flux in $\alpha - \beta$ stator frame at instant $t(k+1)$ are

$$\varphi_{s\alpha}(k+1) = \varphi_{s\alpha}(k) + v_\alpha(k) T_s - R_s \int i_\alpha dt \qquad (17)$$

$$\varphi_{s\beta}(k+1) = \varphi_{s\beta}(k) + v_\beta(k) T_s - R_s \int i_\beta dt \qquad (18)$$

The current within a switching interval has the trajectory shown in Fig. 1. So, i_α and i_β during the time interval [$t(k)$ $t(k+1)$] are

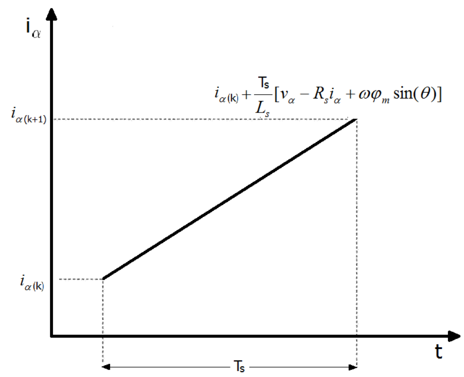


Fig. 1. Current i_α during a switching interval.

$$i_\alpha(t) = i_\alpha(k) + \frac{di_\alpha}{dt} t \qquad (19)$$

$$i_\beta(t) = i_\beta(k) + \frac{di_\beta}{dt} t \qquad (20)$$

Resolving for the derivative of i_α and i_β in (15) and (16),

$$\frac{di_\alpha}{dt} = \frac{1}{L_s}[v_\alpha - R_s i_\alpha + \omega \varphi_m \sin(\theta)] \qquad (21)$$

$$\frac{di_\beta}{dt} = \frac{1}{L_s}[v_\beta - R_s i_\beta - \omega \varphi_m \cos(\theta)] \qquad (22)$$

According to (17)-(22),

$$\varphi_{s\alpha}(k+1) = \varphi_{s\alpha}(k) + v_\alpha(k) T_s - \{ R_s T_s i_\alpha(k) + \frac{R_s T_s^2}{2L_s}[v_\alpha - R_s i_\alpha(k) + \omega \varphi_m \sin(\theta)] \} \qquad (23)$$

$$\varphi_{s\beta}(k+1) = \varphi_{s\beta}(k) + v_\beta(k) T_s - \{ R_s T_s i_\beta(k) + \frac{R_s T_s^2}{2L_s}[v_\beta - R_s i_\beta(k) + \omega \varphi_m \cos(\theta)] \} \qquad (24)$$

Equations (10), (23) and (24) are used to obtain the predictions of torque and flux for the each of 8 valid switching combinations. Then the switching state that minimizes (4), will be applied in the next time interval.

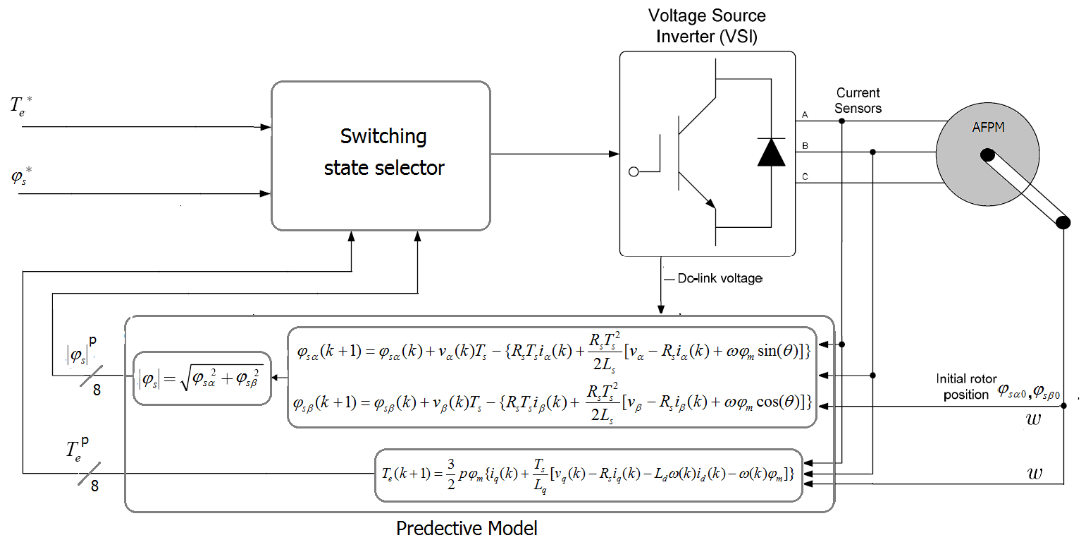


Fig. 2. Block diagram for proposed Predictive Torque Control of AMFM drive.

It should be noticed that the change of the reference flux amplitude between no-load and rated torque conditions is not large; nevertheless, its correction according to the actual torque enhances the overall efficiency of the system. Thus, the amplitude of the stator flux results from the constant value of the PM flux as

$$\left|\varphi_s^*\right| = \sqrt{\varphi_m^2 + \left(\frac{2}{3}\frac{T_e^* L_s}{p\varphi_m}\right)^2} \tag{25}$$

4. SIMULATION RESULTS

A SIMULINK model was used to verify the behavior of the proposed predictive torque control. Simulation parameters (such as AFPM and voltage source inverter) have been listed in Table 1.

Table 1. PMSM parameters in simulation model

Parameter	Description	Value
p	number of pole pairs	4
R/Ω	stator resistance	0.2
$L_d, L_q\ /mH$	stator inductance	8.5
$\varphi_m\ /Wb$	rotor magnet flux	0.175
$j/(kg.m^2)$	rotor inertia	0.089
B	damping coefficient	0.005
$V_{DC}\ /V$	DC voltage	250
$\omega_r\ /rpm$	rated speed	300
$T_N\ /(N.m)$	rated torque	11
-	power switches	IGBT

The block diagram of the proposed predictive torque control has been shown in Fig. 2. As shown in this figure, unlike DTC this control method doesn't need switching table and the proper switching state in each

Time interval is selected according to flowchart that has been shown in Fig. 3.

The reference torque is obtained from the output of the speed controller and the reference flux is generated by (25).

To calculate the torque and flux for each possible switching state the discrete time model of the machine is used that has been presented in part 2.

The motor torque response with this control method has been shown in Fig. 4. In order to show the performance of the proposed controller, a sudden load change is applied to the AFPM. The reference torque changes abruptly from 11 to -11 Nm at $t = 0.075$ s and from -11 to 11 Nm at $t = 0.175$ s. As this figure shows the electrical torque tracks the mechanical load torque properly.

According to (12) it is clear that voltage magnitude of DC link and also sample time have important effect on torque and flux changes. Thus, simulation has been done for two different sample times, $T_s = 10\mu s$ and $T_s = 40\mu s$. As shown in this figure, smaller sample time leads to smaller ripples of torque. However, it should be notice that that less sample time needs more powerful processor for doing calculations practically.

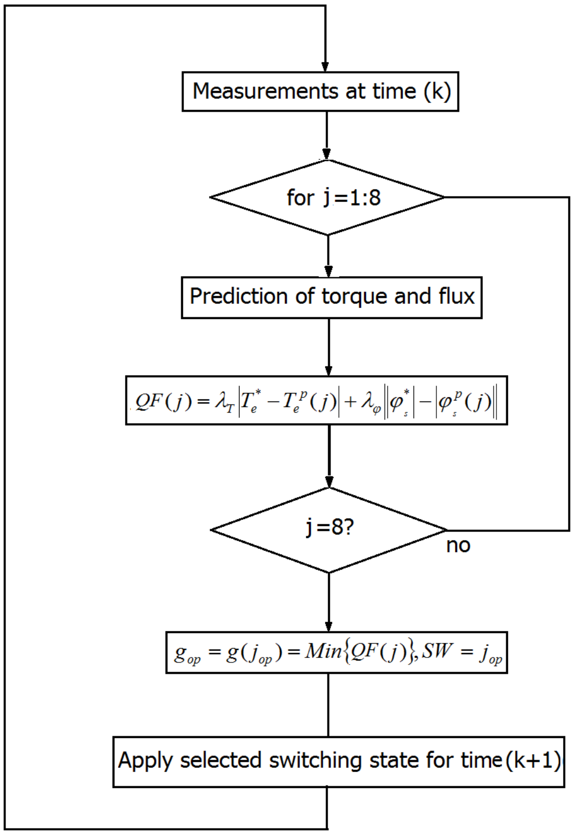
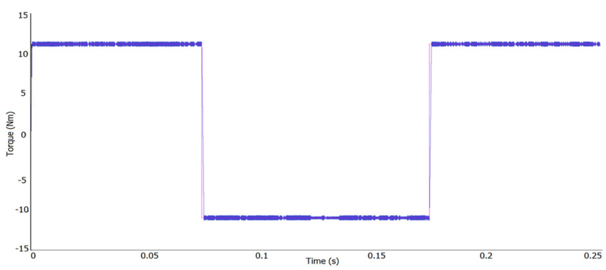
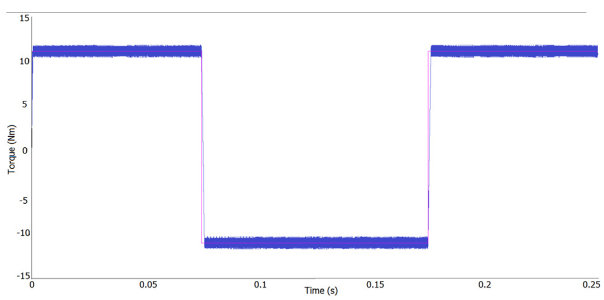


Fig. 3. Flowchart of the proposed predictive control.

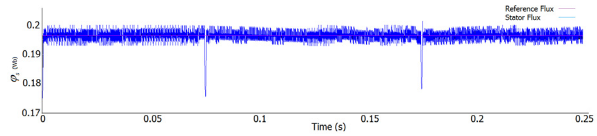


(a)

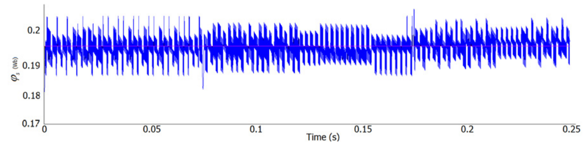


(b)

Fig. 4. Torque response of AFPM. (a) $T_s = 10\mu s$. (b) $T_s = 40\mu s$.



(a)



(b)

Fig. 5. Stator flux. (a) $T_s = 10\mu s$. (b) $T_s = 40\mu s$.

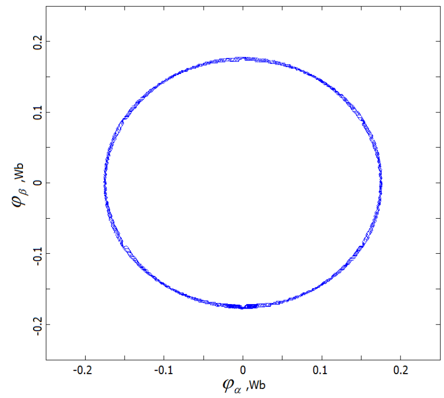


Fig. 6. The trajectory of φ_α and φ_β. ($T_s = 10\mu s$)

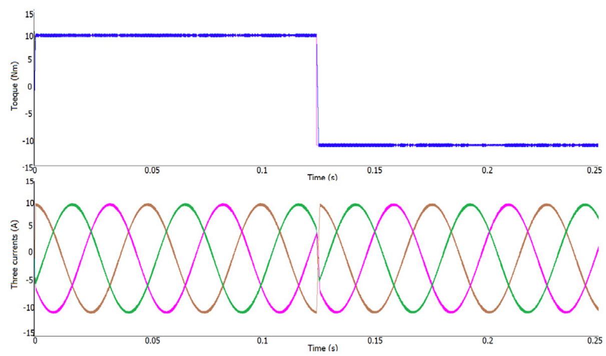
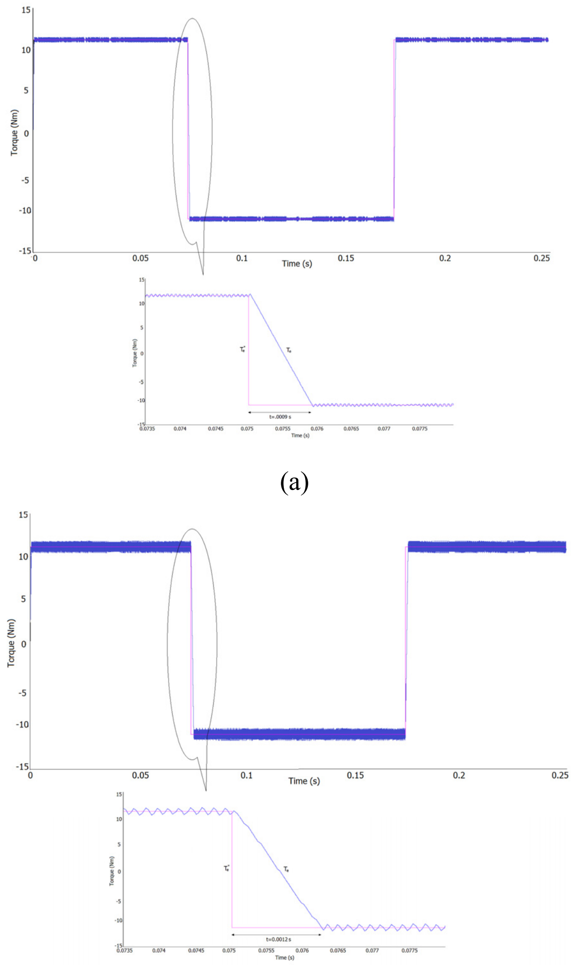


Fig . 7. Three phase stator currents of PMSM for Predictive torque control.

Stator flux for both sample times, have been shown in Fig. 5. It is seen that smaller sample time leads to the smaller ripple of flux too. The trajectory of φ_α and φ_β that is shown on Fig. 6, is a circle as expected.

The stator currents for the transient state and the steady state operations of the proposed method have been shown in Fig. 7. It can be seen that the three phase motor currents are symmetric with low ripple that leads to less harmonics and less losses in stator coil.

To examine the performance of proposed predictive torque control, simulations have been carried out under proposed PTC and under conventional DTC. The simulation results have been shown on Fig. 8. For both



(a)

(b)

Fig. 8. Torque response of PMSM. (a) conventional DTC. (b) Predictive torque control

Methods $T_s = 10\mu s$. As shown in Fig. 6, the torque response for both of steady state and transient state, has been improved with proposed PTC in comparison with DTC.

5. CONCLUSION

A new predictive torque control has been presented in this article. The mathematical equations for implementation of the proposed method have been presented. It has been shown that the proposed predictive torque control unlike conventional DTC uses zero vectors in addition to six active voltage vectors to control motor. Simulation results that verify the good performance of the proposed method, have been presented. Since sample time has an important effect on ripples of torque and flux, simulation has been done for two different sample times. To comparison the performance of proposed predictive torque control with previous method, simulations under proposed PTC and under conventional DTC have been carried out. The simulation results show that proposed predictive torque control has faster dynamic response with respect to conventional DTC. Furthermore, in steady state it has lower ripple of torque and flux that leads to less losses and thus more efficiency and more lifetime of the machine.

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