A NOVEL ELECTRIC VEHICLE CONTROL-ELECTRONIC DIFFERENTIAL-STRATEGY USING FIVE PHASE INDUCTION MOTOR

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Abstract: Three phase Induction motors especially multiphase motor drives has proved to be much efficient for high power drives application such as Electric vehicles/Hybrid Electric vehicles. In this paper a simulated Electric Vehicle (EV) with four-wheel-drive with Electronic Differential System (EDS) is presented. The Electric Vehicle (EV) is controlled with five phase induction motor and the EDS distributes torque and power to each in-wheel motor according to the requirements, adapts the speed of motor to the driving conditions and simulates the behavior of a differential. The working conditions including the condition of the vehicle with the constant speed, accelerating and decelerating are studied , and the control strategy of the EDS for the vehicle with four in-wheel motors is designed and simulated. The simulation with Matlab/Simulink is made and the results are verified with the rationality of the EDS controller, and proved that the system has more favorable dynamic performance.

Index Terms: Eletric Vehicle, Electronic Differential System

I. INTRODUCTION

The principal constraints in vehicle design for transportation are the development of a non-polluting high safety and comfortable vehicle. Taking into account these constraints, our interest has been focused on the Electrical Vehicle, with independent driving wheel-motor drive shaft . This configuration is a conceivable solution, the pollution of this vehicle is strongly decreased and electric traction gives the possibility to achieve accurate and quick control of the distribution torque. Torque control can be ensured by the inverter, so this vehicle does not require a mechanical differential gear or gearbox. One of the main issues in the design of this vehicle (without mechanical differential) is to assume the car stability. During normal driving condition, all drive wheel system requires a symmetrical distribution of torque in the both sides. In recent years, due to problems like the energy crisis and environmental pollution, the Electric Vehicle (EV) has been researched and developed more and more extensively.

Three phase squirrel cage induction motor are well known for their simple and robust construction, reliability, ruggedness, low maintenance and low cost. The speed control of induction motor is complicated when used for variable speed application. However, due to the development in the power electronic devices, the control of induction motor have become easier and flexible. In addition to this, the numbers of phases have become a design parameter. The development of the solid-state inverter and control schemes has opened a new range of applications for induction machines in areas where dc machines were dominant. In almost any kind of application, three phase induction machines have been employed. However, when the machine is not directly fed from standard power sources, there is no need for specified number of phases. Higher numbers of phases are more advantageous. Multiphase machine has several advantages over the conventional three phase motor such as reduced torque pulsation, reduced per phase rotor harmonic current, high reliability and high fault tolerance.E.E. Ward and Harrer have presented the preliminary investigation on inverter fed five phase induction motor and suggested that the amplitude of the torque pulsation can be reduced by increasing the number of phases. H.A. Toliyat, J.C. White, and T.A.*et al* Lipo evaluated the performance of induction machine with different number of phases for operation with static converter in. Nelson and Krause *et al* derived the voltage equations in phase variables and the transformed in to d–q–o reference frame of a multi-phase machine with symmetrical phase displacement. G.K. Singh et al developed a two-axis (d–q) model of the multi-phase machine in an arbitrary reference frame analyzed the machine under balanced, and unbalanced (open circuit and short circuit both) operating condition.

II. PROBLEM FORMULATION AND ANALYSIS

A. ELECTRIC VEHICLE DESCRIPTION

According to Figure 1(a) the opposition forces acting to the vehicle motion are: the rolling resistance force F_{tire} due to the friction of the vehicle tires on the road; the aerodynamic drag force F_{aero} caused by the friction on the body moving through the air; and the climbing force Fslope that depends on the road slope

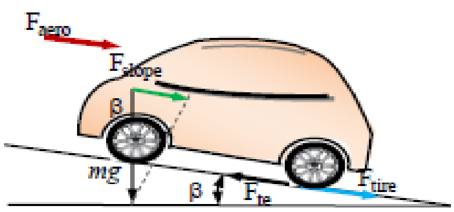

Figure 1

The forces acting on a vehicle moving along a slope.

$$F_r = F_{tire} + F_{aero} + F_{slope} \quad (1)$$

The total resistive force is equal to Fr and is the sum of the resistance forces, as in (1).
The rolling resistance force is defined by:

$F_{tire} = mgF_r$ (2)

The aerodynamic resistance torque is defined as follows

$F_{aero} = ½(\rho_{air} A_f C_d V^2)$ (3)

The rolling resistance force is usually modeled as:

$F_{slope} = m\ g\ \sin(\beta)$ (4)

The main purpose of the electronic differential is to substitute the mechanical differential in multi-drive systems providing the required torque for for each driving wheel

V1 =Wv(R-d/2) (5)

V2 = Wv(R+d/2) (6)

Where R= L/(tanδ)

δis the steering angle d is the width of the car where this angle is zero we are in the straight road. The angular speeds in the curved roads are

W1= ((L-(d/2)tanδ)/L) Wv (7)

W2= ((L+(d/2)tanδ)/L) Wv (8)

Where L is the length of the car and Wv is the centre of the turn angular speed's is given by

Wv = (W1+W2)/2 (9)

B.CONSTRUCTION AND WORKING PRINCIPLE OF MULTIPHASE INDUCTION MOTOR

Similar to the working of three phase induction motor, five phase induction motor works on the application of Faraday's law and Lorentz force on conductor. When five phase ac supply is given to the stator winding which are spatially and time displaced by displaced by 72°the rotating magnetic field is produce which rotates at synchronous speed. When short circuited rotor (squirrel cage) is placed in rotating magnetic field an EMF is induced in the rotor conductor due to electromagnetic induction. Due to this EMF, current starts flowing in the rotor conductor and sets up its own magnetic field. Due to interaction of these two magnetic fields, a torque is produced and conductor tends to move. The scheme of five phase motor drive is shown in Fig. (2). The field winding of the induction motor is housed in the stator which is excited by five leg inverter. Stator winding of an n-phase machine can be designed in such a way that the spatial displacement between any two consecutive stator phases equals,α = 2π n in this case a symmetrical multiphase machine results. This will always be a case if the number of phases is an odd prime number. In three phase induction machine the three phases are spatiallydisplaced by 120 degree whereas in five phase machine by 72 degrees as shown in Fig. (3) .

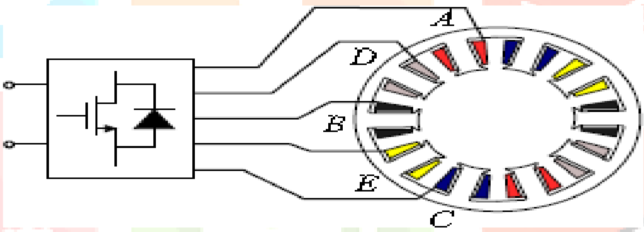

Fig.2 Scheme of the five–phase motor drive.

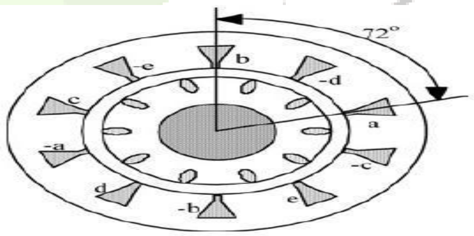

Fig. 3 five-phase concentrated winding induction machine

It is not practically possible to directly implement the five phase stator winding into standard three phase machine stator slots. Five phase machine requires custom laminations for the machine stator and custom inverter to supply the five phase motor. The standard squirrel cage rotor of three f machine can be used. The advantage of using squirrel cage rotor is that, it can adjust to any number of phases which is not possible in case if wound rotor. A five phase induction machine may have five phase distributed winding or fractional slot concentrated winding.

Characteristics of Multiphase Induction Machines

To achieve a motor drive with high fault tolerance, it is important to choose the motor exhibiting an intrinsic fault–tolerant capability. Fractional slot winding motors with non– overlapped coils are suitable for fault–tolerant applications . They allow a physical separation among the phases, limiting the propagation of the fault. They are also characterized by a high self- inductance, necessary to limit the short circuit current. In addition, a suitable combination of slots and poles yields a very low mutual coupling between phases. For better performance of the machine, the mutual coupling between the phases should be less, so that when fault occurs on one phase of a machine it is not carried to the other phase mutually.

The stator excitation in multiphase machine produces a field with lower harmonic content, so the efficiency of the machine is increased than that with three phase machine. Multiphase machine have greater fault tolerance than their three phase counterparts. If one phase of the three phase machine becomes open-circuited the machine becomes single phase. It may continue to run but requires some external means for starting, and must be massively de-rated. But in case of multi-phase machine if one phase is open circuited, it will self-start and will run with minimal de-rating. Multiphase machines are less susceptible than their three phase counterparts to time harmonic components in the excitation waveform. Such excitation components produce pulsating torques at even multiple of fundamental excitation frequency. All the above aspects are elaborated in detail in.

Over the years, many advantages of multiphase machines have been recognized, including higher machine torque density, reduced torque ripples, reduced harmonic currents, better transient and steady-state performance, and more robust control offered by current harmonic injection.

Concerning the five phase motor drive advantages and drawbacks are as follow:

The main advantages of using a five phase motor drive are found in its reliability to operate properly also in faulty conditions. It can operate with one or two open circuited

C. MATHEMATICAL MODEL OFFIVE-PHASE INDUCTIONMOTOR

The parameter equations such as voltage and torque that describe the dynamic behavior of an induction motor are time-varying in nature. Such equations involve complexity while solving as differential equations. A change of variables from time varying to time invariant can be used to minimize the complexity from the voltage equations of motor due to relative motion of electric circuit. By this technique, a multi-phase winding can be reduced to a set of two phase winding (d-q) which are in quadrature to each other. In other words, the stator and rotor variables (voltage, current and flux linkages) of an induction motor are transferred to arbitrary reference frame.

The steady state model and equivalent circuit of induction motor are useful for studying the performance of the machine in steady state. Fig.4 shows a q-d-0 equivalent circuit of an Induction motor. The circuit comprises of various time varying inductances which are to be simulated to analyze the dynamic behavior of five-phase Induction motor.

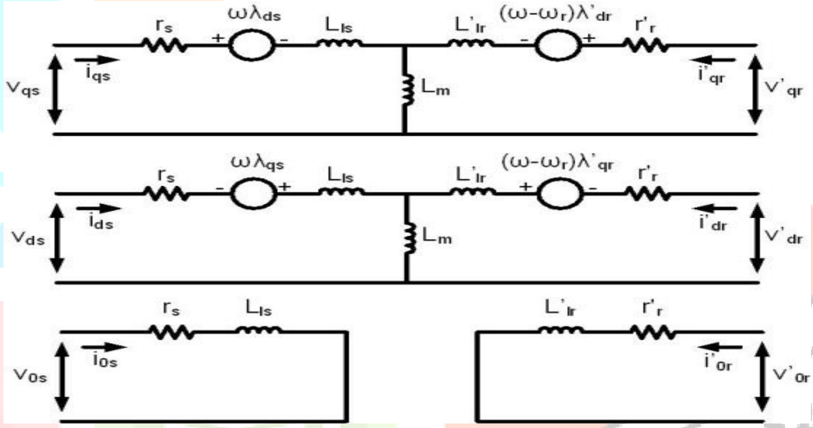

Fig.4 A d-q-0 axis equivalent circuit of five phase Induction machine in arbitrary reference frame

Five phase stator voltage of induction motor under balanced condition is expressed as follows.

$V_a = 2V_{rms} \sin \omega t$

$V_b = 2V_{rms} \sin (\omega t - 2\pi\ 5)$

$V_c = 2V_{rms} \sin (\omega t - 4\pi\ 5)$

$V_d = 2V_{rms} \sin (\omega t + 4\pi\ 5)$

$V_e = 2V_{rms} \sin (\omega t + 2\pi\ 5)$

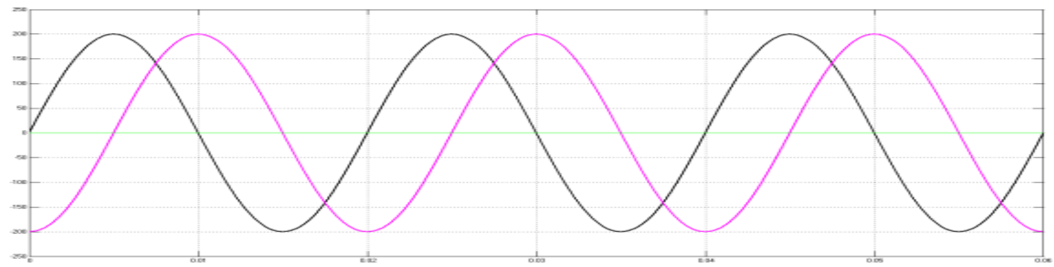

Fig 5 q- and d- axis stator voltages

As stator to rotor coupling takes place in only d-q equations, rotational transformation is applied to these two pairs of equation. The nature of this equation is identical to the three phase machine equations. Assuming that the machine equations are transformed into arbitrary frame of references rotating at angular speed,ωa.

As stator to rotor coupling takes place in only d-q equations, rotational transformation is applied to these two pairs of equation. The nature of this equation is identical to the three phase machine equations. Assuming that the machine equations are transformed into arbitrary frame of references rotating at angular speed,ωa, the model of five phase induction machine with Stator side voltage equations in d- and q- reference frame are given as follows

$V_{ds} = R_s i_{ds} - \omega_a \varphi_{qs} + \rho\varphi_{ds}$
$V_{qs} = R_s i_{qs} + \omega_a \varphi_{ds} + \rho\varphi_{qs}$
$V_{xs} = R_s i_{xs} + \rho\varphi_{xs}$
$V_{ys} = R_s i_{ys} + \rho\varphi_{ys}$
$V_{0s} = R_s i_{0s} + \rho\varphi_{0s}$

Rotor side voltage equations in d- and q- reference frame are given as,
$V_{dr} = R_r i_{dr} - \omega a - \omega\ \varphi_{qr} + \rho\varphi_{dr}$
$V_{qr} = R_r i_{qr} + \omega a - \omega\ \varphi_{dr} + \rho\varphi_{qr}$
$V_{xr} = R_r i_{xr} + \rho\varphi_{xr}$
$V_{yr} = R_r i_{yr} + \rho\varphi_{yr}$
$V_{0r} = R_r i_{0r} + \rho\varphi_{0r}$

Flux equation of stator side of five phase induction motor is given as,
$\varphi qs = L_{ls} + L_m\ i_{ds} + L_m i_{dr}$
$\varphi_{ds} = L_{ls} + L_m\ iqs + L_m i_{qr}$
$\varphi_{xs} = L_{ls} ixs$
$\varphi_{ys} = L_{ls} iys$
$\varphi_{0s} = L_{ls} i0s$

Flux equation of rotor side of five phase induction motor is given as,
$\varphi_{qr} = L_{lr} + L_m\ i_{dr} + L_m i_{ds}$
$\varphi_{dr} = L_{ls} + L_m\ i_{qr} + L_m i_{qs}$
$\varphi_{xr} = L_{lr} i_{xr}$
$\varphi_{yr} = L_{lr} i_{yr}$
$\varphi_{0r} = L_{lr} i_{0r}$
Where, L_m = (n /)2* M and M is the maximum value of the stator to rotor mutual inductances in the phase-variable model.

Symbols R and L stand for resistance and inductance, v, iand φ denote voltage, current and flux linkage, while indices s, r identify stator/rotor variables/parameters. Index l identifies leakage inductances.
From the above equations the Torque and rotor speed can be determined as,

$$T = \frac{5}{2}(^{P}/_{2}) * \frac{1}{\omega b}(\varphi ds\ iqs - \ \varphi qsids) \quad (35)$$

$$\omega_r = \int \frac{P}{J2}(T_e - T_l) \quad (36)$$

Where, P is the number of poles; J moment of inertia; TL Load Torque; Te electromechanical torque; ωr Rotor Speed.

Mathematical model equations for d-q components and the torque equation are identical as for a three-phase induction machine. The only difference between five phase machine model and corresponding three phase machine model is the presence of x-y components in voltage and flux equations. Rotor x-y components are fully decoupled from d-q components and one from other. Since rotor winding is short circuited, x-y components does not appear in the rotor winding. Zero sequence component equations for both stator and rotor can be omitted from further consideration due to short-circuited rotor winding and star connection of stator winding. Finally, since stator x-y components are fully decoupled from d-q components and one from the other, the equations for x-y components can be omitted from further consideration as well. This means that the model of five phase induction motor in arbitrary reference frame is identical to the model of three phase induction machine and the same control schemes can be apply to multiphase induction machines as for three-phase machines. However, existence of xy equations means that utilization of a voltage source that creates stator voltage x-y components will lead to a flow of potentially large stator x-y current components, since these are restricted only by stator leakage impedance. These x-y components correspond to certain voltage and current harmonics, the order of which depends on the machine's number of stator phases. Hence the inverter, used to supply a multiphase induction machine, must not create low-order voltage harmonics that will excite stator current low-order harmonic flow in x-y circuits.

D. MATALB/SIMULINK IMPLIMENTATION

The voltage, flux, torque equations and transformation matrices are used to implement the model of five phase induction motor in MATLAB/Simulink as shown in Fig. 6. The input to the motor is the five phase sinusoidal voltage supply. The five phase to two phase conversion block transfers the five phase stator voltages to d- and q- axis voltages. This block gives stator current, rotor currents and fluxes in direct and quadrature axis. Current-flux to torque- speed block gives the rotor speed and torque using above equations. The simulation of the internal structure of five phases induction motor is run assuming different load condition.The stator and rotor currents in d and q references frame are transferred to machine variable as i_{as} , i_{bs} , i_{cs} , i_{ds} and i_{es} using inverse transformation matrices to analyze the nature of the stator and rotor currents.

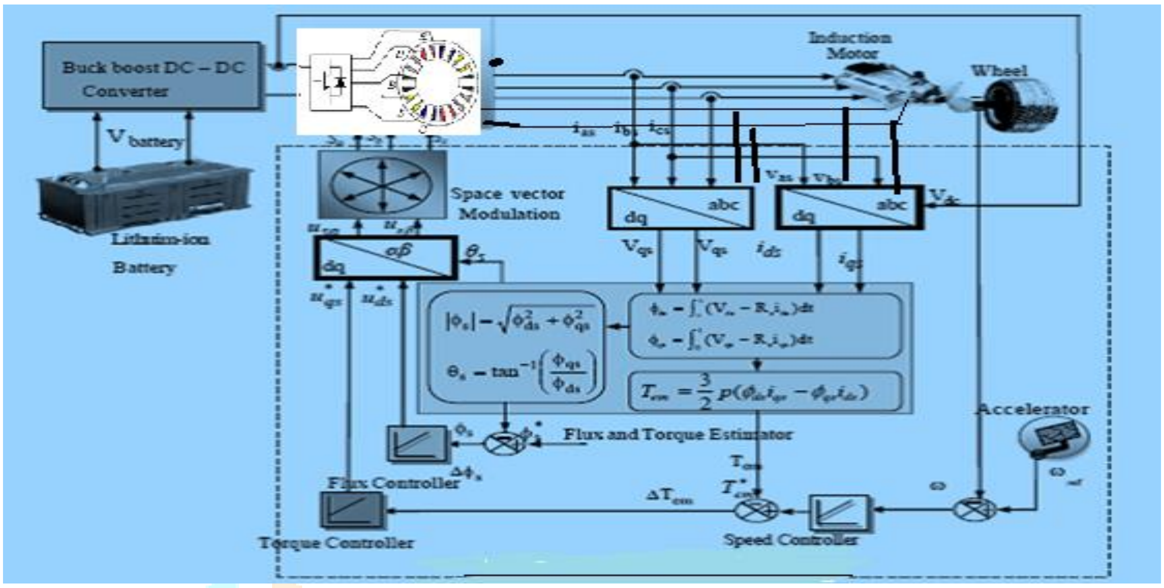

Fig 6. Implementation of Electric Vehicle with Five phase Induction Motor

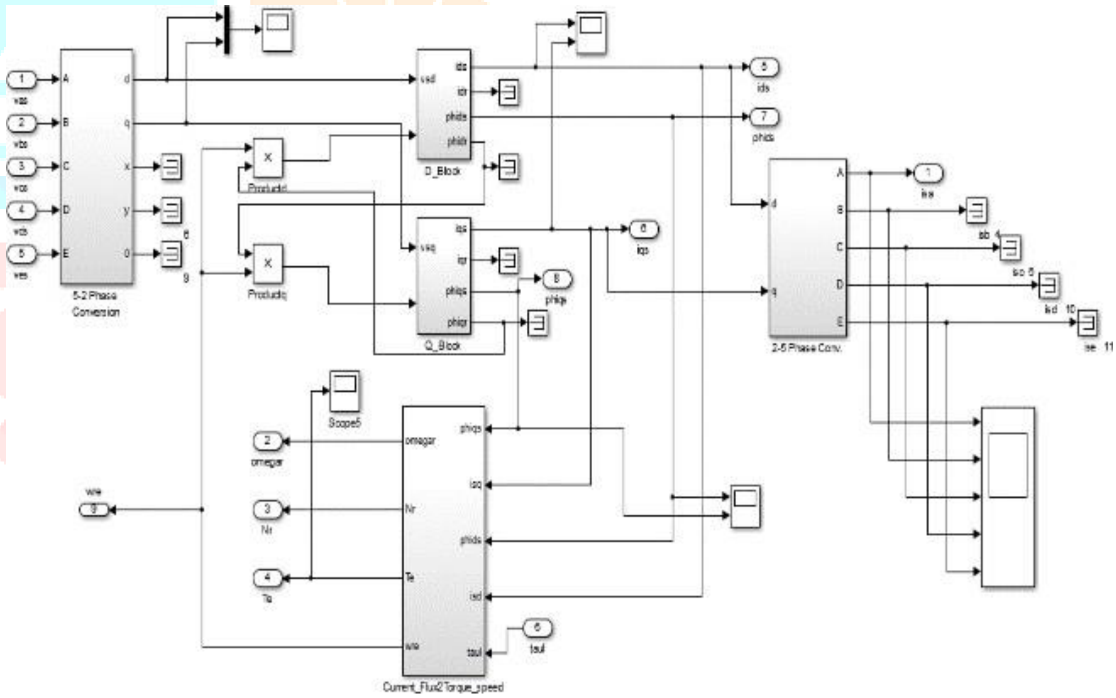

Fig7. Mathematical Model of Five phase Induction Motor

SIMULATION RESULTS:

For electric drive the following paths are chosen path 1 corresponds to straight road, Path 2 corresponds Right curve , Path 3 corresponds to straight road and path 4 corresponds to left curve. Simulation of novel electric vehicle using five phase induction motor is modeled and simulated in Matlab. It is observed that the torque and current ripples for five phase induction motor is reduced and at the same time, time response is improved. Following are the results compared with the conventional three phase induction motor to the proposed five phase induction motor

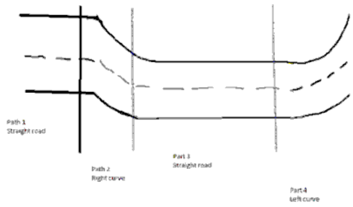

Fig 8. Road path for the Electric Drive

Path	Time (sec)	Road Topology
1	0<t<0.5	Straight road
2	0.5<t<1.5	Right curve
3	1.5<t<2.5	Straight road
4	2.5<t<3	Left curve

Table.1 For Road path

A) Five phase Induction Motor(2- level Inverter)

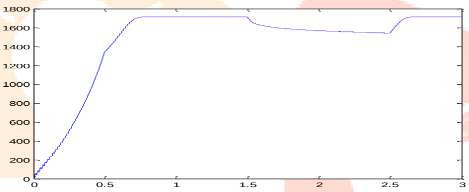

Fig 9.Speed curve for right tire

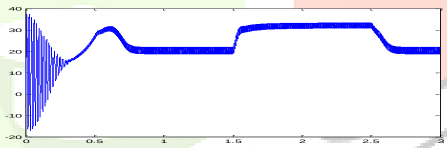

Fig 10.Torque for right tire

Table 2. Comparison of 3phase and 5 phase of two Level Inverter

S.no		Conventional 3 Phase (2level Inverter)	Proposed 5 Phase (2-level Inverter)
1	Torque (Fund)	26 N-m	29 N-m
2	Current (Fund)	7 A	8.5 A
3	Torque ripple	10.8(%)	7.23(%)
4	Current ripple	18.9(%)	15.23(%)

Table 3. Transient Response

Transient response	**Rising time (sec)**
Proposed 5phase(2-level Inverter)	.54
Conventional 3 phase(2- Level Inverter)	.752

Rated phase voltage (V)	250
Rated Power (Hp)	5
Rated Phase current (A)	10
Rated frequency (Hz)	50
Number of Poles	2
Rated Speed (rpm)	1440

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