DTC Technique for Induction Machine based Integrated Starter-Generator of an Automobile

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Abstract

This paper mainly concentrates on the application of the direct torque control (DTC) technique for the induction machine based integrated starter-generator (ISG) for automobile applications. It also discusses in brief about the higher DC bus voltage requirements in the automobiles i.e. present 14V system vs. 42V system to meet the power requirements, modes of operation of ISG, electric machine and the drive selection for the ISG, description of DTC technique, simulation and experimental results, and implementation.

1 Introduction

The architecture of the electric power system in conventional present day automobiles is: 14V DC bus with 12V battery, 12V starter (DC series motor) for starting the engine, 14V alternator (PM type) for generating, and power grid. The demand for electric power in the passenger cars has been growing steadily as the vehicle performance is improved and more and more features are added to enhance comfort, convenience, and safety. The practical limit on the load current in light vehicle electric systems is 200A, beyond which the current carrying conductors are bulky. 200Amps represent about 3kW for the 14V-bus (12V battery) system. It is clear that if the emerging higher power loads are to be served, then higher voltage is a desirable option. The 42V (with 36V battery) has been internationally agreed upon, as the maximum safe voltage used in a conventional unprotected vehicle system. By using 42Volts system, a maximum power of about 9kW can be achieved without exceeding the limit of 200A.

The electrical architecture of proposed 42V system is shown in fig (1). In the proposed system, instead of separate alternator and starter motor as used in conventional engines, a single machine is used to perform both the functions. Such a system

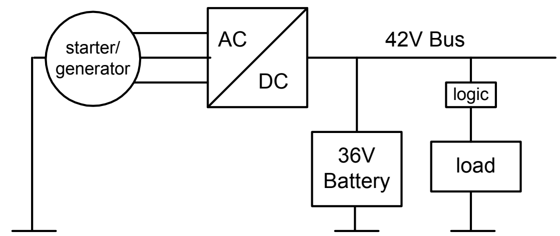


Fig (1) 42V architecture of an automobile.

is named Integrated Starter Generator (ISG).

Powered with the 36V battery through an inverter, the ISG acts as either starter motor or generator. The switching between the functions occurs according to the driving condition. With the power availability from 36V (9KW max) one can achieve the following with ISG.

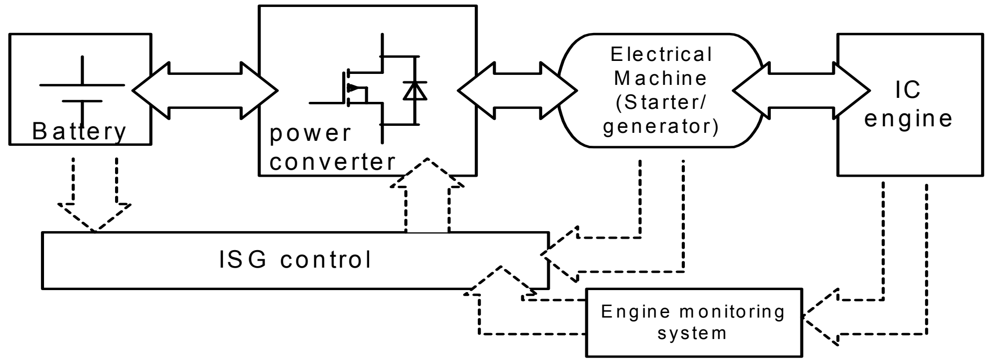
- Start the engine within 200ms.
- Charge battery (optimally) during engine operation.
- Recover the brake energy during deceleration and braking.
- Give power boost during overload on engine.

In addition, fast starting, regenerative braking and power boost reduce the emissions, and improve the fuel economy.

2 Description of ISG

The basic block diagram for the ISG is shown in fig (2). The system consists of

1) Battery pack
2) Electrical machine (Motor-generator)
3) Power converter
4) ISG control system



_____ bold line represent power flow ------ dashed line represent control signals

Fig (2) Basic block diagram of ISG

Battery pack: The electrical bus voltage is fixed to 42(14*3) and corresponding battery voltage is 36V (12*3). The lead acid type of the battery is used and its power rating (40AH, 60AH and 90AH) depends on the size of the vehicle.

Starter/alternator or motor generator (MG): Induction machine is best choice to work as starter motor cum generator for the ISG operation.

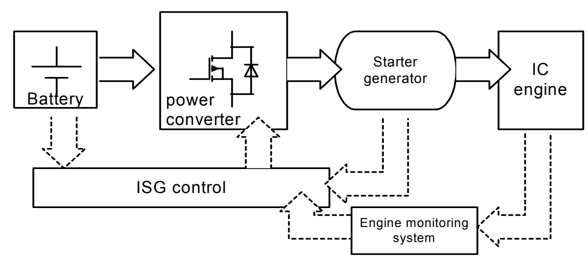
Power converter: The power converter employed should be designed to meet the high starting current requirements and capable of switching at high speed.

ISG control system: ISG controls four modes of operation as explained in next section.

2.1 Modes of Operation of ISG

As mentioned ISG control system has totally four modes of operation. The switching between the modes is possible but it can operate in only one mode at a time.

Engine cranking mode: When the ignition switch is in the start position, ISG enters in to this mode. Engine cranking mode is in effect when the engine speed is in between 0-150 rpm. During this mode ISG will provide sufficient torque to the drive the engine. Once engine is fired, control transfers to one of the other modes.



Fig(2)a Power flow in cranking and power boost mode

Running power generation mode: Once the engine has taken control over the system, ISG enters power generation and extracts power from the crankshaft and maintains the bus voltage at 42V, irrespective of the load on the bus.

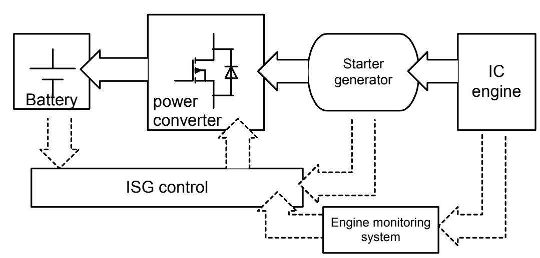


Fig (2)b Power flow in generation and power braking mode

Braking power generation mode: When the engine brake is on, the ISG will check the battery voltage, such that if it is below 58Volts the ISG will operate in the braking power generation mode. In this mode, the ISG will deliver power to the battery and thus provide a retarding force on the crankshaft. When the engine brake is on and the average voltage is above 58Volts, ISG will operate in braking with power dissipation mode. In this mode power will be diverted to power grid array to dissipate the energy.

Power boost mode: When the engine is running at low speeds (from 600-1000RPM) and there is high acceleration demand (when the acceleration pedal is greater than 75%) and the battery capacity is greater than 50% of the rated capacity, the ISG will operate in the power boost mode. In this mode ISG will provide the torque to the crankshaft to assist in accelerating the engine.

2.Selection of electrical machine

Dc machines have many drawbacks when compared with ac machines, such as low power to weight ratio, high speed limitation, high maintenance etc. So ac machines are preferred. Permanent magnet machines even though it is most efficient, is very expensive for this application and sensitive to high temperatures. Switched reluctance motor has various interesting features, but it is very sensitive to torque ripple, noise and vibration. It also needs high resolution encoder and its control techniques are still evolving. The induction machine, in contrast, is an established technology, with higher efficiency and smoother torque with additional advantages such as ruggedness, low maintenance, high reliability etc. Therefore for this application, ISG based on induction machine is proposed.

3.Selection of the control technique

In the automobile ISG application, very fast torque response is required, but speed accuracy is not a very important constraint. Vector control and direct torque control (DTC) are the two contending technologies for this scheme. Vector control reestablishes the advantages of the dc drive through implementation of direct control of flux. The vector control technique has a few disadvantages; firstly torque is indirectly controlled rather than directly controlled and secondly, inclusion of PWM modulator creates a signal delay between the input references and resulting stator voltage vector produced. These last two factors limit the ultimate ability of the flux vector to achieve very rapid flux and torque control. Likewise, DTC also reestablishes both direct flux control and direct torque control. But as both flux and torque controllers are hysteresis comparators, the delays associated with the PWM modulator stage are removed, as it is been replaced with optimal switching logic. In addition, DTC offers simplicity, sensor less operation, excellent dynamics and is less sensitive to parameters variations etc. Considering all these features DTC is chosen for this application.

4.Brief description of DTC technique

Fig (3) shows the basic functional blocks used to implement the core of the DTC scheme.

Estimator: The function of this block is to calculate the developed torque, as well as magnitude and position of the stator flux in the air gap. Inputs for his block are two line currents, DC bus voltage and the switching signals.

Controllers: Flux controller and torque controller are hysteresis comparators. Speed controller is a PI controller.
Flux controller is a two level hysteresis comparator as the flux in ISG is always to rotate in the single direction. But the torque controller uses three level hysteresis comparator to accelerate the flux in either direction. The flux and torque comparators are shown in fig (5).

Switching table: Switching table is the optimized table which contains information of switching status for switches for particular input combinations of torque controller output, flux controller output and sector location. The switching table is evolved seeking that there will be minimum switching between sampling intervals. The switching table used for the implementation is shown in fig(4).
The detailed description about DTC technique and implementation is available in reference[1].

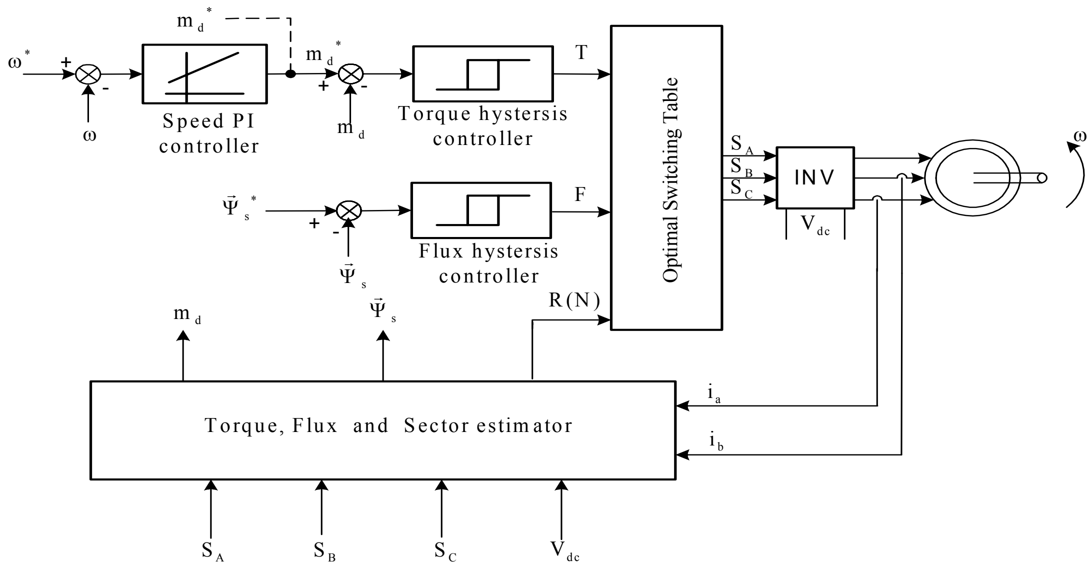


Fig (3) Block diagram of DTC

F	T	θ(1)	θ(2)	θ(3)	θ(4)	θ(5)	θ(6)
1	1	110	010	011	001	101	100
1	0	111	000	111	000	111	000
1	-1	101	100	110	010	011	001
0	1	010	011	001	101	100	110
0	0	000	111	000	111	000	111
0	-1	001	101	100	110	010	011

Fig (4) Optimum switching table

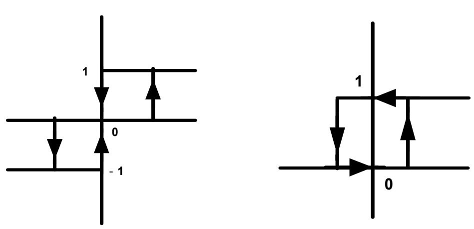


Fig (5) Two and three level hysteresis comparators

5. Implementation

Controller: In order to achieve all the desirable functions of ISG, it is necessary to employ a versatile controller. Therefore in the implementation TMS320F240 DSP controller is used.

Power converter MOSFET based three phase 2KVA power converter was developed.

Battery Power source was 60AH (36V) lead acid battery.

Induction machine specification: 3-phase, 26V, 90A, 3KW, 960rpm.

Software implementation: Total control loop needs to be executed every sampling period. Sampling time of 57 microseconds was used. The flowchart of the implementation is given in fig (6).

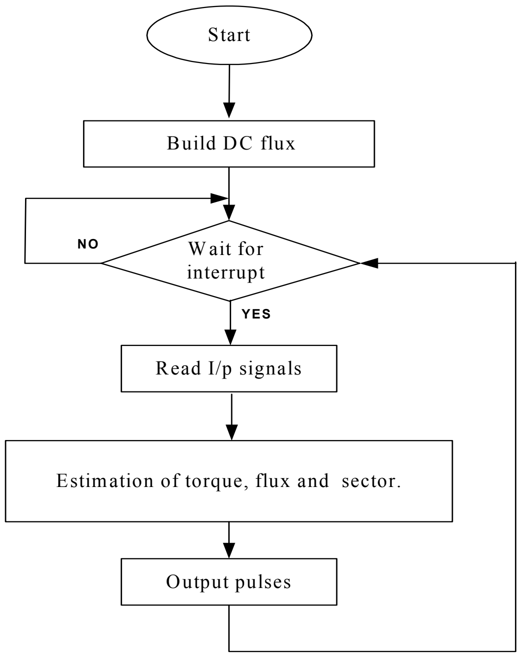


Fig (6). Flowchart for Program Implementation

6. Simulation and experimental results

Simulation was initially done to verify the proposed model. It was carried out using matlab simulink.
Simulated results at cranking mode are shown in fig (7). Fig 7(a) shows the speed response when there is a step input command of torque reference command. Fig 7(b) shows the torque controller response. Initially estimated torque tracks torque reference as the speed is increasing, but finally it will settle down to its rated load torque as speed reaches it final value. Line currents are shown in fig 7(b). Magnitude of the current is seen to be proportional to the torque estimate. Similarly battery current waveform is shown in fig 7(d). Its magnitude is proportional to line current.

Corresponding experimental results at cranking mode are shown in fig (8). The waveforms of speed response, torque response, line current and battery current match with the simulated results.

Simulated results at power generation mode are shown in fig (10). Fig 10(a) shows the different speeds of the prime mover (engine) at which generation mode was simulated. Fig 10(b) shows the torque response at different speeds. Torque estimated is tracking the torque estimated at all speeds. Fig 10(c) shows the line currents during generation. Fig 10(d) shows the battery current. It is negative implying generation. It is seen to be decreasing as the speed is increased, because in the constant power region torque reference generated decreases inversely proportional to speed (base speed is chosen as the speed where the control transfers from motoring to generation).

Corresponding experimental results at power generation mode are shown in fig (11). The waveforms of torque response, line current and battery current match with the simulated results.

Finally fig (9) shows the waveform at power boost mode. ISG enters this mode when there is increase in load demand during generation, which leads to decrease in speed. In this mode the induction machine will acts as motor and assist the engine to supply the load demand to maintain constant speed. Fig 9(a), fig 9(b), fig9(c) and fig 9(d) shows the waveforms of speed, torque, line current and battery current at this mode.

7. Conclusion

In the present work, induction machine based integrated starter generator with DTC technique was simulated and experimented in the laboratory setup. It works satisfactorily in all the modes of operation.

Fig 7 Simulated results at cranking mode

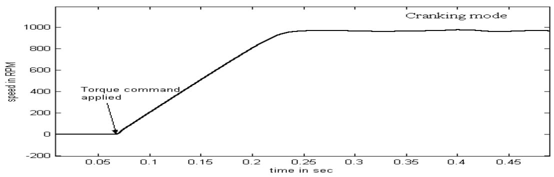


Fig7(a)Speed response(200rpm/div,0.05sec/div)

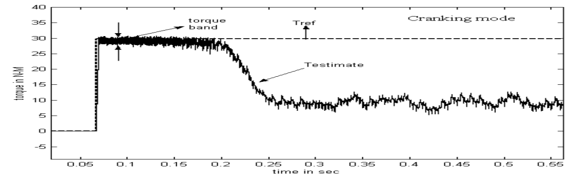


Fig7(b)Torque response(10Nm/div,0.05msec/div)

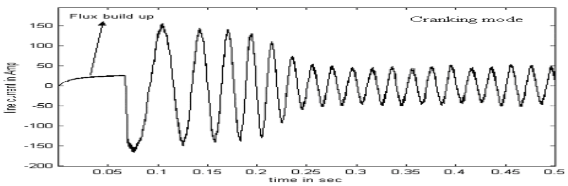


Fig7(c)Line current(50amps/div,0.05sec/div)

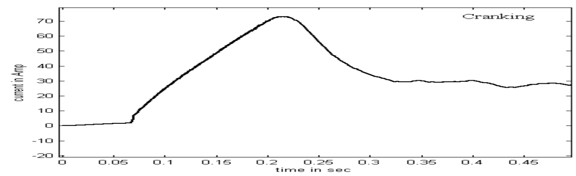


Fig7(d)Battery current(10amps/div,0.05sec/div)

Fig 8 Experimental results at cranking mode

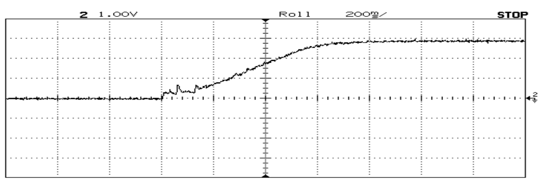


Fig8(a)Speed response(340rpm/div,0.2sec/div)

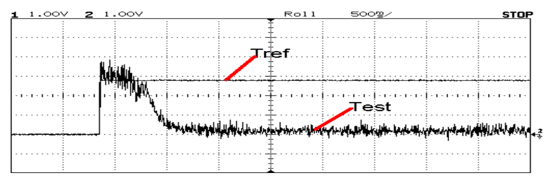


Fig8(b)Torque response(10Nm/div,0.5sec/div)

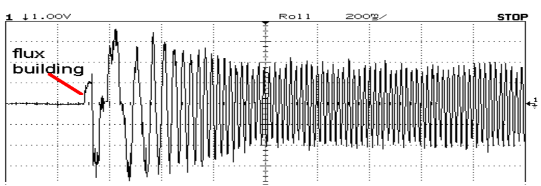


Fig8(c)Line current(40amps/div,0.2sec/div)

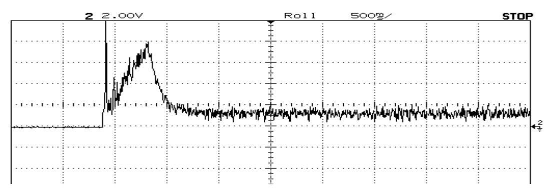


Fig8(d)Battery current(20amps/div,0.5sec/div)

Fig 9 Experimental results at power boost mode

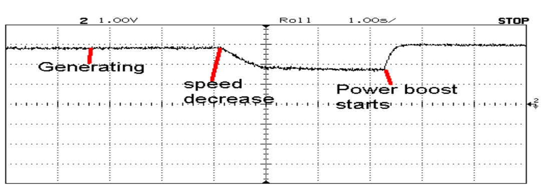


Fig9(a)Speed Response(340rpm/div,1sec/div)

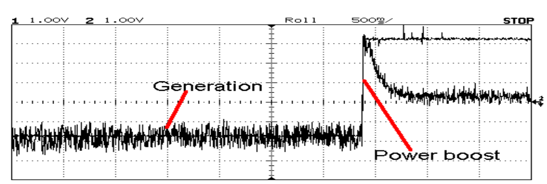


Fig9(b)Torque Response(10Nm/div,0.5sec/div)

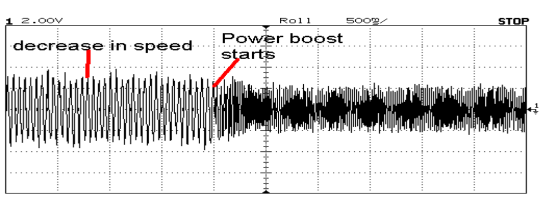


Fig9(c)Line current (80amps/div,0.5sec/div)

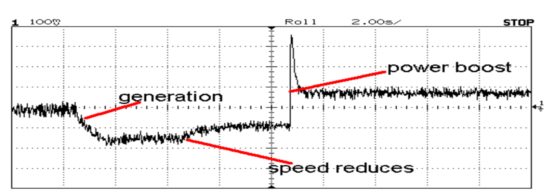


Fig9(d)DC bus current (20amps/div,2sec/div)

Fig 10 Simulated results at power generation mode

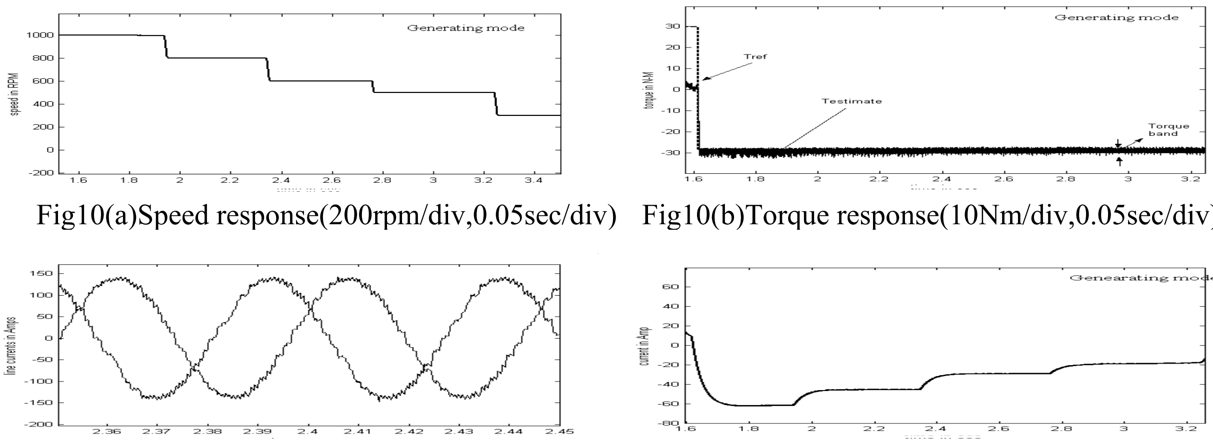


Fig10(a)Speed response(200rpm/div,0.05sec/div)   Fig10(b)Torque response(10Nm/div,0.05sec/div)

Fig10(c)Line current(50amps/div,0.05sec/div)   Fig10(d)Battery current(50amps/div,0.05sec/div)

Fig 11 Experimental results at power generation mode

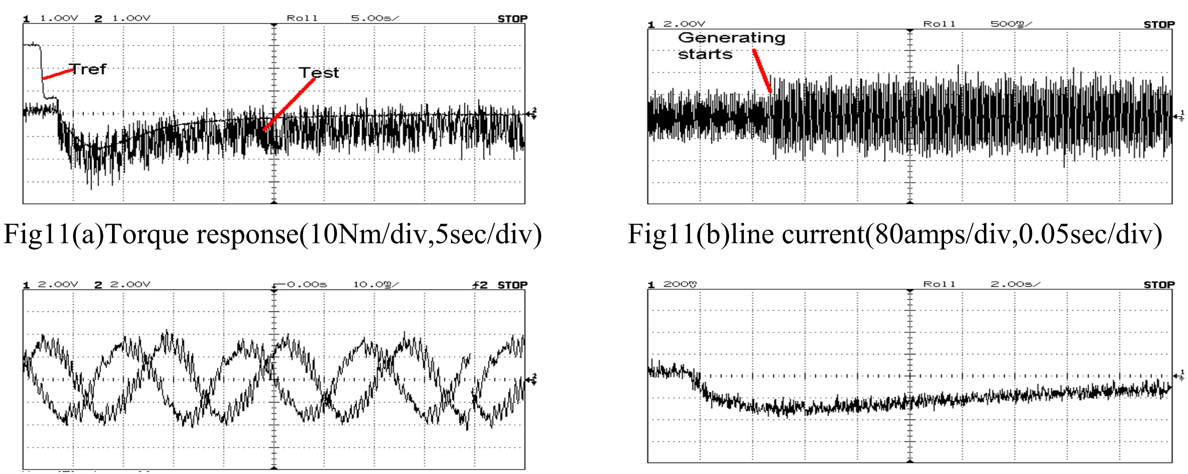


Fig11(a)Torque response(10Nm/div,5sec/div)   Fig11(b)line current(80amps/div,0.05sec/div)

Fig11(c)line current(80amps/div,0.01sec/div)   Fig11(d)DC bus current(30amps/div,2sec/div)

References

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