Application of Direct Torque Control Method to an Electric Vehicle

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Abstract

The purpose of this paper is to report the application of direct torque control (DTC) method to motor drive of an electric vehicle (EV). The EV, named NEV-II, is a converted one which originally had a gasoline engine (550cc) and manually-shifted transmission. The drive motor of the EV is a three phase induction motor, and its stator winding is altered to increase the practical rated output (4.5kW). DTC method can achieve a quick response to torque command. Besides, a motor drive system using DTC method is easy to realize without a position sensor. Several kinds of performances of the EV are shown in this paper. According to these experimental and calculated data, it is proved that the EV has satisfied characteristics as a car, in spite of such a small output motor. In addition, applying field-weakening control method to the motor drive system, the EV can speed up to 90km/h.

Keywords

electric vehicle, direct torque control (DTC) method, induction motor, PWM inverter, field-weakening control

1. INTRODUCTION

In these years, topics of electric vehicle (EV) have been increased amazingly, and many kinds of EVs are commercially available in Japan [Sato et al., 2002]. Moreover, there are several interesting EVs driven by wheel-in-motors [Shimizu, 1992], [Nasu et al., 1996], [Shimizu, 1999], [Onishi et al., 2003]. In particular, hybrid EVs made by some car-makers have become to popularize gradually, then they will surely contribute to the future traffic system and problem of the environment of the earth.

Regarding the drive motor, there are many discussions [Hori et al., 2003], and almost all the EVs use AC motors that are generally driven by using field-oriented control method [Takahashi et al., 1999]. On the other hand, one of the authors developed a high quality control method for induction motors, namely "Direct Torque Control (DTC) method", and its performances proved in detail [Takahashi et al., 1986].

The main purpose of this paper is to introduce a converted pure EV, named NEV-II, controlled by DTC method. Meanwhile, an ordinary induction motor was altered to suit the total system of the EV. Then, some experimental and calculated characteristics from several viewpoints are obtained. Evaluating these data, it is cleared that NEV-II has proper performances as a car.

2. BASIC STRUCTURE OF NEV-II

2.1 Remodeling of a Conventional Car

Figure 1 shows a picture of NEV-II which is a converted pure EV. The original car is "Leeza-Turbo" made by Daihatsu Co.,Ltd. It had a gasoline engine (550cc), i.e., the car is classified into the light-sized car of Japanese standards.

Fig. 1 Picture of NEV- II

The specifications of the EV are shown in Table 1. Because of the putting space of batteries, a backseat is removed and the seating capacity changes to two persons. As a power supply, 20 lead-acid maintenance free batteries (24Ah) are connected in series, then the total voltage is 240V.

Table 1 Specifications of NEV-II

Seating capacity	2 persons
Size	3195 (L), 1395 (W), 1335 (H) mm
Weight	720kg (including battery weight: 180kg)
Power source	Maintenance free battery (lead-acid battery) 240V/24Ah (12V×20pieces)
Transmission	FF, 5-speed manually-shifted transmission
Brake system	Mechanical & regenerative brake
Motor	3 phase squirrel-cage type induction motor Ratings: 4.5kW, 150V, 24A 2900rpm, 50Hz, 2poles
Drive system	Voltage source PWM inverter (Applying DTC method)
Maximum speed	90km/h

The EV utilizes the transmission and the mechanical brake of the original car, but there is an additional brake, i. e., the regenerative function of the drive motor. Then the EV has 5-speed and manually-shifted transmission. Figure 2 illustrates the layout of main components of the EV, where the original ones are the transmission, two front seats, and a sub-battery for the electric devices of the car.

Concerning about the induction motor (IM), its drive system, some original-made equipments are described later in detail.

Figure 3 shows the inner engine room. Figure 3 (a) is the original one and Figure 3 (b) is the condition after remodeling. There is a drive motor which is coupled with the clutch and the transmission. A vacuum pump for assist of the mechanical brake is placed at left side of the sub-battery. The drive and control circuit of the motor is put in the black aluminum box which is seen in front of the transmission.

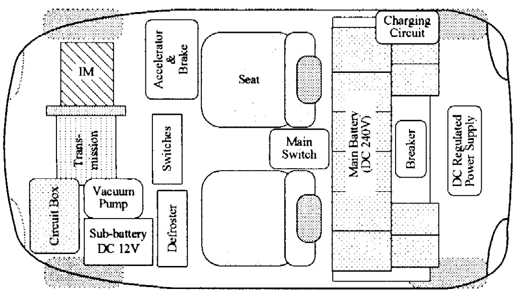
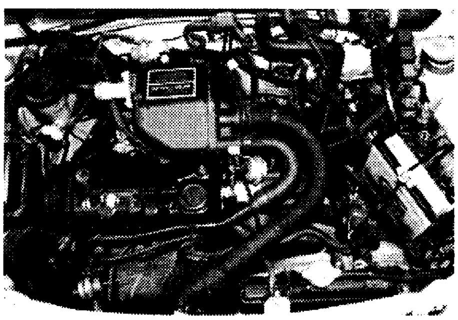
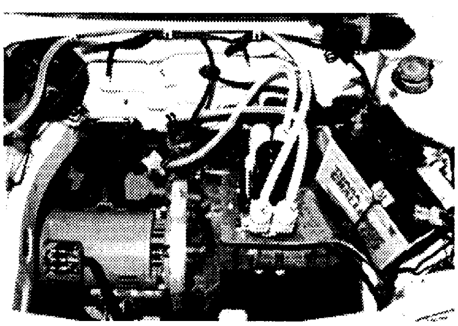


Fig. 2 Layout of main components



(a) Original condition



(b) After remodeling

Fig. 3 Picture of inner engine room

2.2 Drive Motor

NEV-II is driven by an three phase squirrel-cage type induction motor. To improve the characteristics of the motor, the winding of an ordinary induction motor have re-wound. The basic aim is to increase line current and output of the motor, so the thickness of wires and the number of turns of the winding have changed as shown in Table 2. Owing to these conditions, the insulation type also has converted into high class.

Table 2 Specifications of the induction motor

Items \ Condition	Original	Altered
Number of poles	2	
Slot pitch	11	
Rated output [kW]	3.7	4.5
Rated current [A]	14	24
Rated voltage [V]	200	150
No-load current [A]	7	12
Sectional area of wire [mm^2]	0.95	1.1, 1.2
Number of turns	42	28
Connection method	Double star	
Insulation type (JIS)	Type E (120℃)	Type F (155℃)

After alternation of the induction motor, an experiment of the steady-state characteristics was carried out. Figure 4 and Figure 5 show the experimental results, using the same data. According to the characteristics, practical rated current and rated output are evaluated 24A and 4.5kW respectively, taking account of efficiency, power factor, and slip.

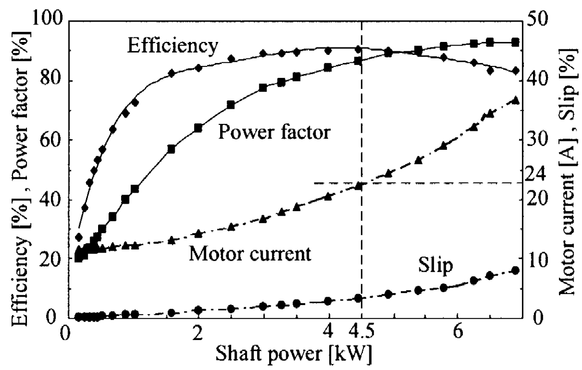


Fig. 4 Steady-state characteristics

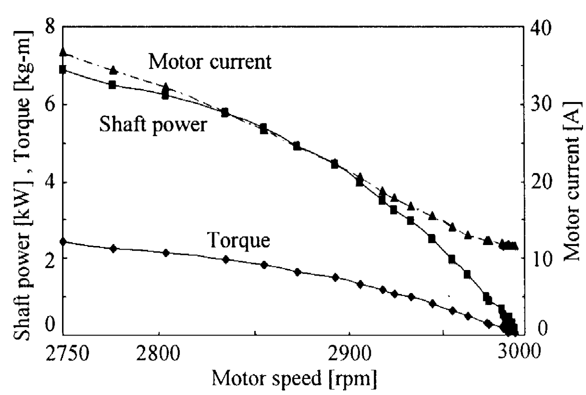


Fig. 5 Load characteristics vs. motor speed

2.3 Other Equipments

There are some special equipments for NEV-II, for example, a vacuum pump assisting the brake function instead of an original-equipped brake booster, and a defroster device which is altered a hairdryer, because they are worked by help of the gasoline engine. Besides the accelerator and the brake mechanisms are attached potentio-meters at the side of each pedal to detect these signals.

Figure 6 illustrates the connection between main circuits and the equipments. Using a voltage-doubler circuit, the main battery set (DC240V) is charged from commercial AC100V power source. DC240V battery and a DC regulated power supply connect directly when SW1 select the drive mode, and the power supply charges the sub-battery (DC12V) if SW2 is ON condition.

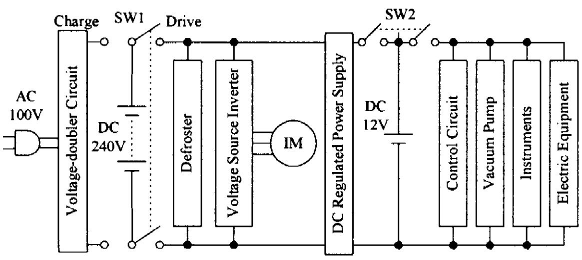


Fig. 6 Connection between main circuits & equipments

3. DRIVE SYSTEM OF NEV-II

The induction motor is driven by a voltage source PWM inverter, and DTC circuit controls the inverter. Figure 7 demonstrates the block diagram of DTC system of NEV-II. Here, it is significant to review the feature and the principle of DTC method briefly.

The method can achieve quick response and high efficiency control of an induction motor [Takahashi et al., 1986]. In general, field-oriented control method has been employed, including the case of EVs, to attain the excellent performance of AC motor drive.

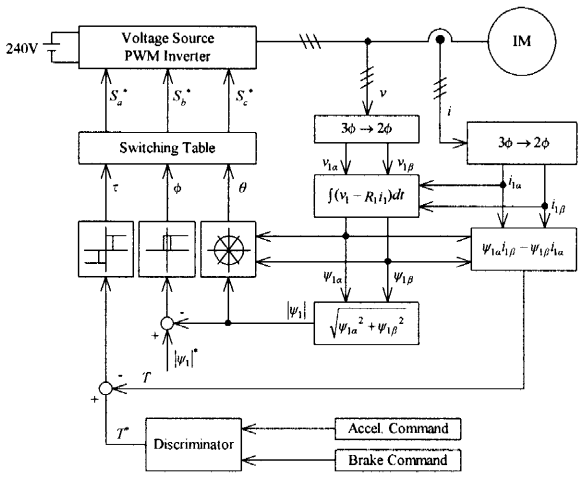


Fig. 7 Block diagram of DTC system

The points of DTC method are as follows: it has equivalent characteristics of field-oriented control, and it doesn't need a position sensor attached on a induction motor, so the system can compose easily and at low cost.

To describe the principle of DTC, firstly, a schematic diagram of PWM inverter shows in Figure 8. The line-to-neutral voltages v_{1a}, v_{1b}, and v_{1c} are determined only by the inverter switching modes. Considering the combinations of status of switches S_a, S_b, and S_c, the inverter has eight conduction modes. These switching functions have values of 1 or 0, and the primary voltage vector is presented as v_1 (S_a, S_b, S_c). Therefore, v_1 has eight kinds of vectors: zero voltage vectors (0, 0, 0), (1, 1, 1), and non-zero voltage vectors (0, 0, 1), -----, (1, 1, 0), as shown in Figure 9.

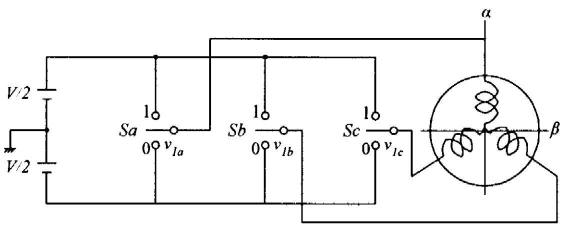


Fig. 8 Diagram of PWM inverter

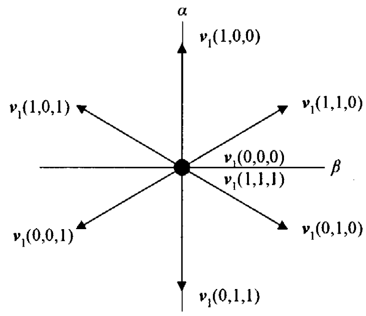


Fig. 9 Instantaneous primary voltage vector of inverter

Figure 10 shows 1/4 circular locus of magnetic flux, where open symbols mean the zero vectors. Since the primary linkage flux Ψ_1 is calculated from v_1, the mag-

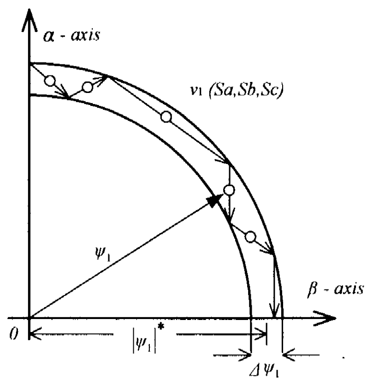


Fig. 10 Circular locus of magnetic flux

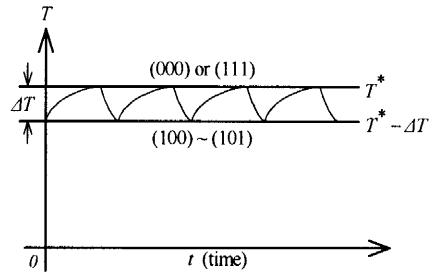


Fig. 11 Control of instantaneous torque

netic flux rotates by selecting proper v_l vector. As shown in this figure, by inserting zero vectors, the rotary speed of Ψ_1 can be changed. Figure 11 shows that the motor torque T is controlled so as to keep between the reference value T^* and $(T^* - \Delta T)$.

In the case of NEV-II, the torque command is applied as the acceleration or the brake signal, as shown in Figure 7. When both signals exist at once, the brake signal precedes the acceleration one, employing a discriminator. In this figure, τ and ϕ mean digitalized errors from T^* and $|\psi_1|^*$ respectively, and θ means region of the circle of the rotating magnetic flux. Judging these parameters, the optimum switching of the inverter is determined by a switching table.

Figure 12 shows an experimental primary linkage flux vector locus when $|\psi_1|^*$=0.39Wb. Two kinds of thin solid lines mean the regulated maximum and minimum

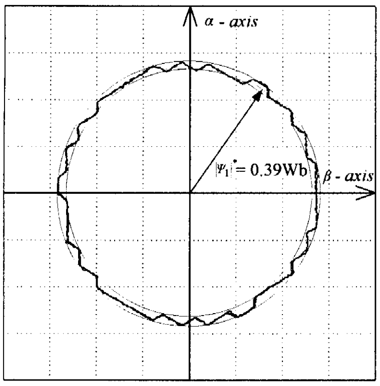


Fig. 12 Primary linkage flux vector locus

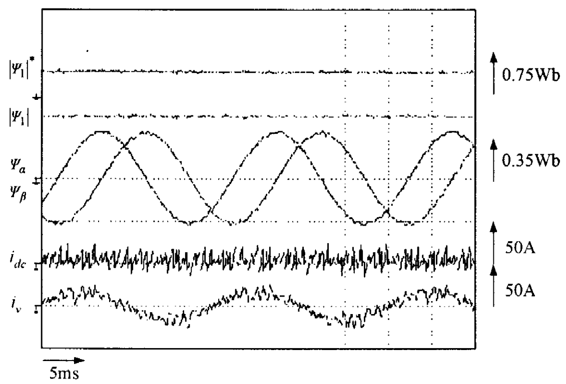


Fig. 13 Experimental data when $|\psi_1|^*$ is constant

range. Figure 13 shows the experimental data of $|\psi_1|^*$, $|\psi_1|$, ψ_α, ψ_β, i_{dc}, and i_v. The result of Figure 12 is obtained by these ψ_α and ψ_β.

4. EVALUATION OF NEV-II

For the sake of the evaluation of NEV-II as a car, some kinds of experiments were carried out.

Firstly, Figure 14 shows a result of a running test. The accelerator command, the brake command, the torque command, and the battery current were observed simultaneously during 50 seconds under the following conditions. The EV ran on a flat and straight-line road. The transmission was shifted from the 1st gear to the 4th gear, and finally the brake was performed. The maximum vehicle speed was about 50km/h.

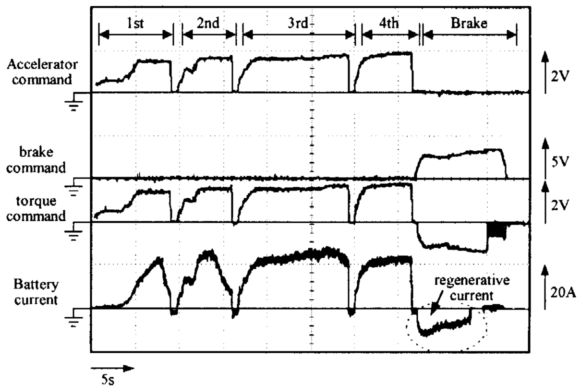


Fig. 14 Running test of NEV-II

The torque command is derived from the commands of the accelerator (plus value) or the brake (minus value). For these commands, the battery current reacts quickly. The regenerative current is measured when the brake command applies. The mechanical and the regenerative brake work together on this condition.

Figure 15 proves this phenomenon. When the vehicle speed was 90km/h, the brake pedal was pressed down. Then the vehicle speed decreased to 20km/h quickly, and after this point the speed decreased slowly. The curve indicates that the mechanical and the regenerative brake work simultaneously between 90km/h and 20km/h.

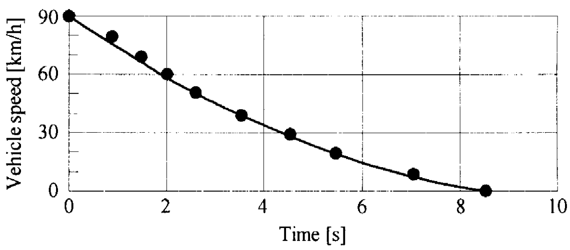


Fig. 15 Deceleration test

Secondly, Figure 16 shows a result of a running test with the field-weakening control method for the motor drive system. The conditions of the running test were basi-

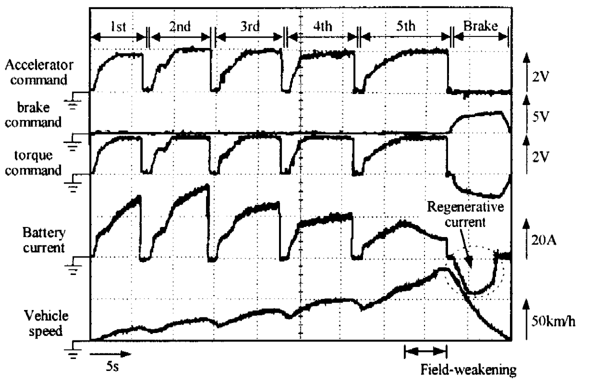


Fig. 16 Running test of NEV-II (with field-weakening control)

cally the same as the case of Figure 14. The field-weakening control was applied when the transmission gear was 5th and the vehicle speed was about 60km/h, then the maximum speed reached at 90km/h. Besides, comparing with the case of Fig.14, much regenerative current (about two times) occurs.

Figure 14 and Figure 16 show that the battery current changes with the accelerator and the brake command at the moment. It means the drive motor responds quickly. Lastly, Figure 17 shows the vehicle covering performance curve of NEV-II calculated by the results of Fig.4 and Figure 5. The solid lines mean the motive forces and the dashed lines mean the running resistances expressed as the slope angle. Figure 17 indicates the EV can run 63km/h on a flat road, and the capability for climbing slope angle is about 12deg.

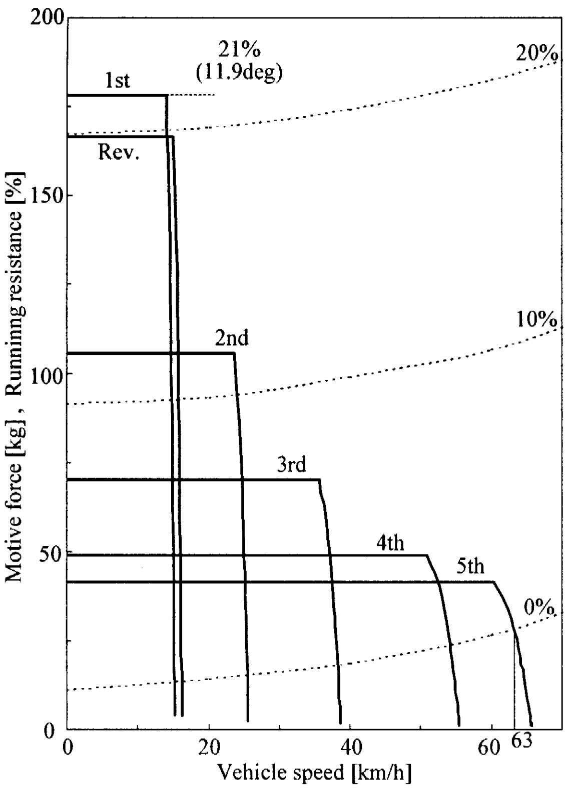


Fig. 17 Vehicle covering performance curve of NEV-II

It is evaluated that NEV-II satisfies for any conditions as a car, in spite of such a small output of the motor.

5. CONCLUSION

The converted pure EV named NEV-II has satisfied performances as a car.

Firstly, the drive motor was altered to increase the line current and output. Then, applying DTC method to the voltage source PWM inverter, the motor responds smoothly to the acceleration and the brake commands. Moreover, the maximum vehicle speed reaches at 90km/h using field-weakening control method.

As a result, the authors think that the concept of the drive and control system shown in this paper would contribute to the design of EVs. Naturally, the DTC control method is also applicable to any other types of vehicles using an induction motor.

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References

Abe, M., *Vehicle Dynamics and Control*, Sankaido, 1992.

Badrul, H. B. M., K. Saito, and I. Takahashi, et al., Characteristics of an Electric Vehicle "NEV-II", *Proceedings of the Niigata Branch Conference of the IEEJ*, V-6, 121-122, 1997.

Hori, Y., T. Teratani, R. Masaki, *Motor Technology for Cars*, Nikkan Kogyo Shinbun, 2003.

Kisanuki, T., K. Saito, and I. Takahashi, et al., Motor Control of an Electric Vehicle "NEV-II" (Application of Direct Torque Control Method), *Proceedings of the 1997 Joint Conference of Hokuriku Chapters of Electrical Societies*, A-31, 31, 1997.

Kisanuki, T., K. Saito, and I. Takahashi, Manufacture and Evaluation of a Converted EV "NEV-II", *Proceedings of the Fourth Conference of Society of Electric Vehicle (SEV)*, 1998.

Nasu, H., and H. Higasa, et al., Study on Motion Control of an Experimental Electric Vehicle, *Transactions of the Japan Society of Mechanical Engineers*, Vol. 62, No. 595, C, 166-172, 1996.

Takahashi, I. and T. Noguchi, A New Quick-Response and High-Efficiency Control Strategy of an Induction Motor, *IEEE Transactions on Industry Applications*, Vol. IA-22, No. 5, 820-827, 1986.

Takahashi, I., and T. Noguchi, Quick Response Torque Control of an Induction Motor by Using Instantaneous Slip Frequency Control, *Transactions of the IEEJ*, Vol. 106, No. 1, B, 9-16, 1986.

Takahashi, I., et al., *The Latest Technology of Electric Vehicles*, Ohmsha, 1999.

Takehana, Y., *The Introduction to Car Engineering*, Rikogakusha, 1995.

Sato, K., and Y. Kou, *Electric Vehicle*, Sankaido, 2002.

Shimizu, H., *All About Electric Vehicles* (the 2nd edition), Nikkan Kogyo Shinbun, 1992.

Shimizu, H., *High Performance Electric Vehicle Named Luciole*, Nikkan Kogyo Shinbun, 1999.

Omar, B. S. A., K. Saito, and I. Takahashi, et al., Basic Structure of an Electric Vehicle "NEV-II", *Proceedings of the Niigata Branch Conference of the IEEJ*, V-5, 119-120, 1997.

Onishi, M., T. Nakamura, and H. Shimizu, A New Suspension Technology Optimized for Electric Vehicles (Verifying Performance of 8 Wheel Tandem Wheel Suspension System with KAZ), *Journal of Asian Electric Vehicles*, Vol. 1, No. 1, 2003.

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