Comparative Study of 3D Simulation and Experiment on Stator MPPUA of Generator under FWISC Faults with Different Degrees

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Abstract:In order to study the impacts of the stator magnetic pull per unit area (MPPUA) characteristics under different field winding inter-turn short-circuit (FWISC) degrees in generator, comparative study of 3D numerical simulations and experiments are respectively taken to calculate the quantitative data of stator MPPUA by finite-element method (FEM) in this paper. Firstly, the nature exciting force of stator vibration, which is called MPPUA, is carried out. Then simulations data on MPPUA under normal condition and different short-circuit degrees are obtained. Finally, the variation rules of MPPUA characteristics by experiments under different conditions are studied. The results show that in normal condition the main harmonic components of MPPUA consist of only 6th-harmonic component. However, the occurrence of FWISC will bring in extra 1st, 2nd, 3rd, 4th and 5th-harmonic components to MPPUA. Meanwhile, with the increasing of the rotor short circuit degrees, the amplitudes of 1st, 2nd, 3rd, 4th and 5th-harmonic components will present an increasing trend. However, the amplitudes of 6th-harmonic component will present a decrease trend.

Keywords:Magnetic pull per unit area (MPPUA); field winding inter-turn short-circuit (FWISC); different short-circuit degrees; finite-element method (FEM)

1. Introduction

FWISC is a common electrical fault. When FWISC develops seriously, intensive consequences such as field current increment, reactive power output decrease, and generator-set vibration aggravation, etc., will be caused[1]. Due to the connection between the stator and the foundation, the stability of stator is relatively strong. However, Stator windings are embedded in the stator slots. Stator vibration will cause the vibration of the stator windings, which will lead to aggravate the insulation wears of the windings[2]. Therefore, it is important to study the mechanical properties on stator and find the mechanical origin of stator vibration.

So far, a lot of research work about FWISC has been carried out. Typically, the detection coil method was proposed to detect FWISC, which can judge whether there is a rotor winding inter-turn short-circuit fault, and show the location of the faulty slot by analyzing the distortion degrees of the induced potential waveform on the detection coil[3]. The formulas of the magneto motive force (MMF) and MFD are analyzed under normal condition and fault. The rules are revealed that FWISC mainly affects MMF but has a very little impact on the permeance per unit area (PPUA)[4]. In addition, the harmonic components of the parallel branch circuit on stator windings and air gap differential coil induction potential are analyzed[5]. FWISC will cause the excitation current to increase, but the reactive power is relatively reduced or unchanged, and a method to identify the rotor winding fault is found by using the relative change rate of the excitation current before and after fault. Thus a criterion for on-line identification of FWISC is established[6].

Currently, for the vibration characteristics of stator under FWISC, the method of stator vibration characteristic identification among single and composite faults composed of faults air-gap eccentricity and rotor inter-turn short-circuit is revealed[7]. The stator will induce the vibration at f, 2f, 3f, and 4f under FWISC[8]. The vibration characteristics of stator under compound fault are studied. And the variation rules of vibration characteristics under different fault degrees are analyzed by experiment[9]. Therefore, comparably, the influence of stator vibration on the normal operation of generator is also very huge, though most scholars have paid their primary attention to the rotor vibrations but not the stator vibration characteristics[10]. The above references could lay a solid foundation for the study of this paper.

As an improvement, for the generator (p=3), previous studies often use 2D models for simulation, while the simulation environment of 3D models is closer to the real operation of generator. Therefore, theoretical derivation based on Ref[11], this paper investigates the impacts of stator MPPUA characteristics under different FWISC degrees in generator by comparative study of 3D simulation and experiment. The results in this paper are an argument and supplement to the existing technology.

2. Exciting characteristics of MPPUA

Generator stator is made up of the stator core, the windings, the frame, the end covers, etc. Stator vibrations are primarily produced by the magnetic forces acting on the stator core. This kind of magnetic force is actually a unit magnetic pull performing on the whole inner surface of the stator core, and usually called magnetic pull per unit area (MPPUA), as shown in **Figure 1.**

MPPUA mainly acts on the stator core surface, and the composite magnetic pulls can be obtained by integrating MPPUA. Because the stator core is a shell structure that made up of silicon steel sheets, the radial rigidity is small and the composite magnetic pull is zero (shown in Figure.1 (a) and (c)). However, under the periodic MPPUA, the stator core also can generate the radial vibration, such as the periodic expansion contraction. Therefore, MPPUA is the nature exciting force of stator vibration.

Therefore, due to the specific structure of the stator core, the essential exciting force for the stator vibration is MPPUA, which can be deduced based on Eq. (1) and Eq. (2).

$$B(\alpha_m, t) = f(\alpha_m, t)\Lambda(\alpha_m, t) \tag{1}$$

$$q(\alpha_m, t) = \frac{B^2(\alpha_m, t)}{2\mu_0} = \frac{1}{2\mu_0}\Lambda^2(\alpha_m, t)f^2(\alpha_m, t) \tag{2}$$

(a) Structure of stator core   (b) model of stator core   (c) MPPUA on stator core
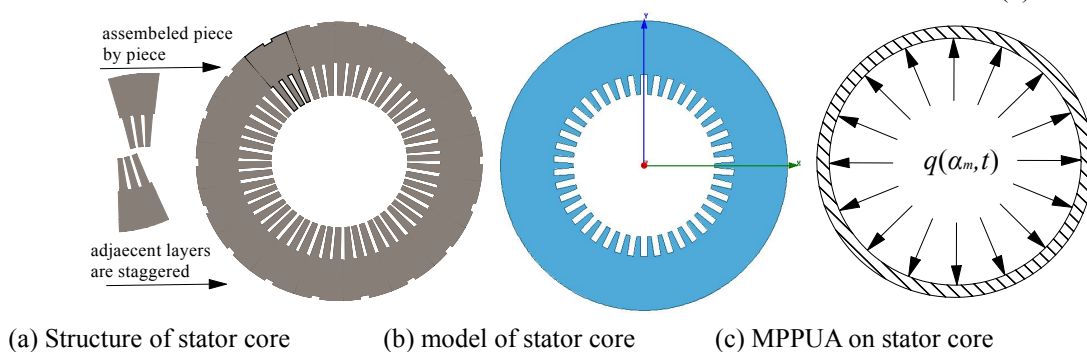
Figure 1. Structure and magnetic force of stator core.

3. 3D numerical simulation

3.1 Object and method

3D numerical simulation is taken for a MJF-30-6 type generator under normal condition and different FWISC degrees in ANSOFT. The primary parameters are indicated in Tab 1.

Parameter	Value
Rated capacity	30KVA
Rated speed	1000rpm
Number of stator slots	54
Number of rotor slots	30
Number of turns in per stator slot	72 turns
Number of turns in per rotor slot	88 turns
radial length of air gap	0.85mm

Table 1. Primary parameters of MJF-30-6 type generator

In this paper, the excitation winding at short-circuit parts is divided into two parts: short-circuit winding and residual winding. The turns of the short-circuit winding and residual winding are equal to the turns of the original winding. When No. 2 rotor winding shorts 88 turns and No. 3 rotor winding shorts 44 turns, different short-circuit degrees can be achieved by changing No. 1 rotor winding, such as short-circuit 0 turns, 44 turns and 88 turns. In other words, different short-circuit degrees respectively are 10%, 13.3%, 16.7%, as indicated in **Figure 2**.

Accordingly, the excitation windings in the external circuit are divided into two parts: Field_SC and Field_Leftover. Field_SC is the short-circuit winding and Field_Leftover is the residual winding. At the same time, the values of R168 and R299 are changed. R168 is the residual resistance and R299 is the short circuit resistance. R5 is the contact resistance produced by short circuit, as shown in **Figure 3**.
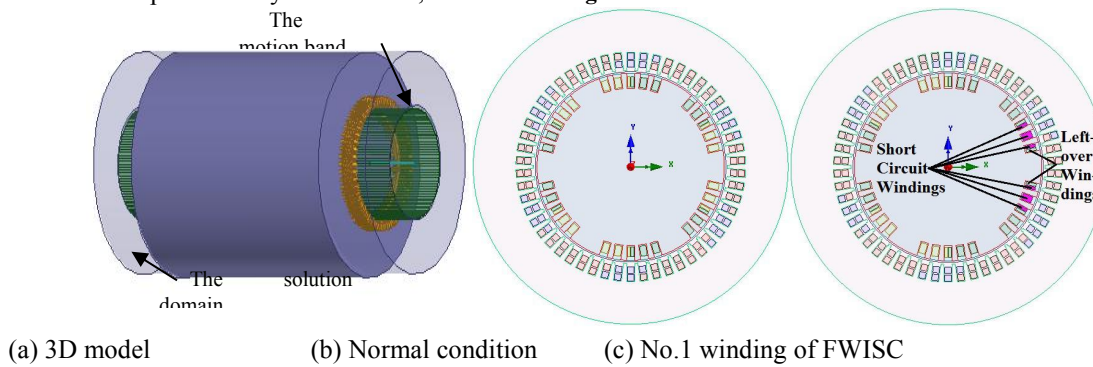

(a) 3D model　　　　　(b) Normal condition　　　　(c) No.1 winding of FWISC

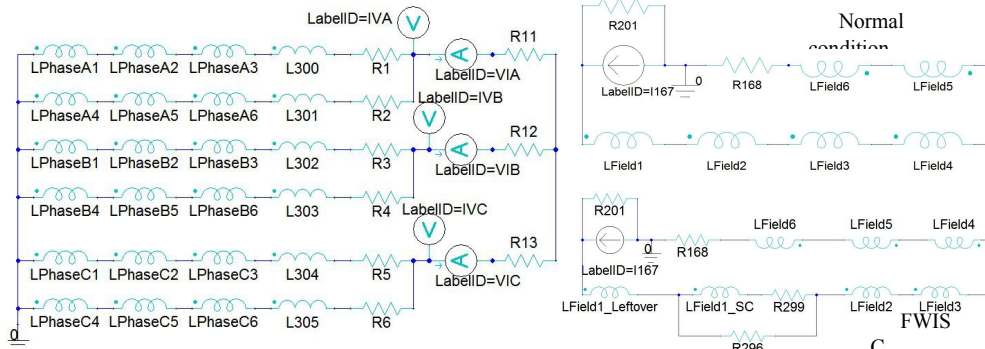**Figure 2.** 3D simulation model of the generator under different conditions.

Figure 3. Coupling circuit set of the armature winding and the excitation winding.

3.2 Results and discussion

In order to study the variation rules of stator MPPUA, time domain waveforms of stator MPPUA as well as the spectra obtained from the 3D numerical simulation for normal condition and different short-circuit degrees are demonstrated in Figure.4.

(a) Stator MPPUA waveforms and spectra under normal condition

Name	X	Y
m6	100.0000	15000.9562

(b) Stator MPPUA waveforms and spectra under FWISC (shorted 10%)

Name	X	Y
m1	16.6667	99.3062
m2	33.3333	64.7487
m3	50.0000	21.5153
m4	66.6667	128.3664
m5	83.3333	80.3982
m6	100.0000	13326.6105

(c) Stator MPPUA waveforms and spectra under FWISC (shorted 13.3%)

Name	X	Y
m1	16.6667	248.5434
m2	33.3333	185.4635
m3	50.0000	47.7691
m4	66.6667	258.4614
m5	83.3333	161.2430
m6	100.0000	12422.0768

(d) Stator MPPUA waveforms and spectra under FWISC (shorted 16.7%)

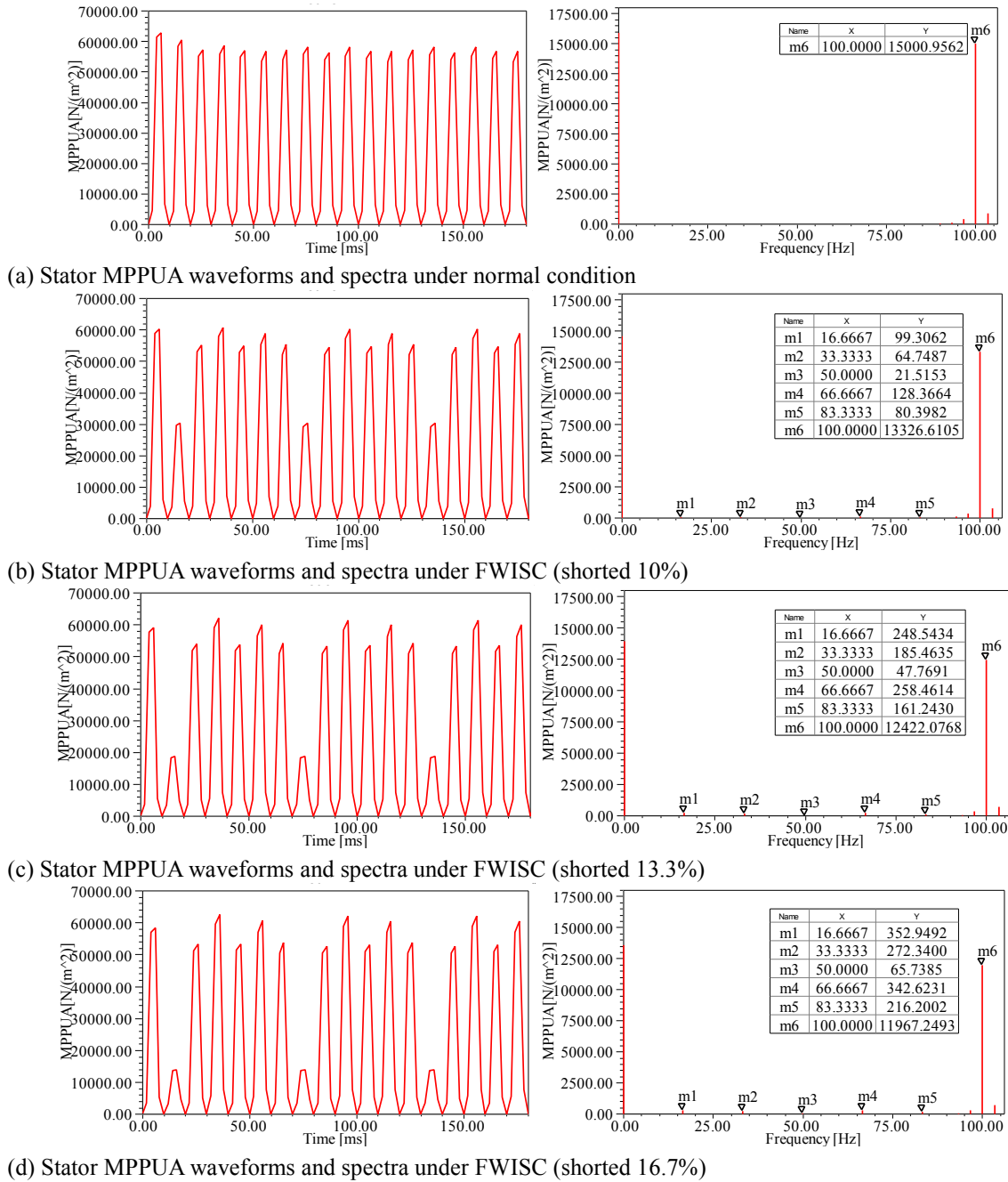| Name	X	Y
m1	16.6667	352.9492
m2	33.3333	272.3400
m3	50.0000	65.7385
m4	66.6667	342.6231
m5	83.3333	216.2002
m6	100.0000	11967.2493

Figure 4. Stator MPPUA waveforms and spectra under different running conditions.

The main component of stator MPPUA is 6th-harmonic component under normal condition. The occurrence of FWISC will bring in 1st, 2nd, 3rd, 4th and 5th-harmonic components to MPPUA, as shown in **Figure 4** (a) and (b). In other words, the main harmonic components of stator MPPUA under FWISC are 1st, 2nd, 3rd, 4th, 5th and 6th-harmonic components. Meanwhile, with the increasing of the short circuit degrees, the amplitudes of 1st, 2nd, 3rd, 4th and 5th-harmonic components will present an increasing trend. However, the amplitudes of 6th-harmonic component will present a decrease trend, as shown in **Figure 4** (a), (b), (c) and (d).

4. Experimental verification

4.1 Object and method

Experimental verification is taken for MJF-30-6 fault simulation generator in the State Key Lab of New Energy and Electric Power System, P.R. China, as presented in **Figure 5** (a) and Tab.1. During the experiment, MJF-30-6 fault

simulation generator is paralleling operation. P=4.08kW, Q=0.83kvar, I_f=2.85A, U=400V, I=6.4A. In the experiment, the rated value of excitation current under each operation condition is 1A. The two short-circuit taps of C1 and C2 are selected for fault test. Taking into account the safety of the experiment, a slide-wire rheostat is connected in series between C1 and C2. (see **Figure 5** (b)-(c)). The different short-circuit degrees are simulated by adjusting the resistance of the slide-wire rheostat.

The vertical vibration of generator stator core is measured by CD-21C type vibration speed sensor, and its sensitivity is 30mV/mm/s. (see **Figure 5** (d)). The output end of the vibration speed sensor is connected to the U60116 type acquisition instrument, and the sampling frequency is 5KHz. The signal collected by the acquisition instrument is accordingly processed. In order to reduce the influence of faults on the transient process of generator, the excitation current is reduced at first and then the conductors are directly shorted, finally the excitation current is increased. The signal collected by the collector will be processed by experimental test system, as shown in **Figure 5** (e).
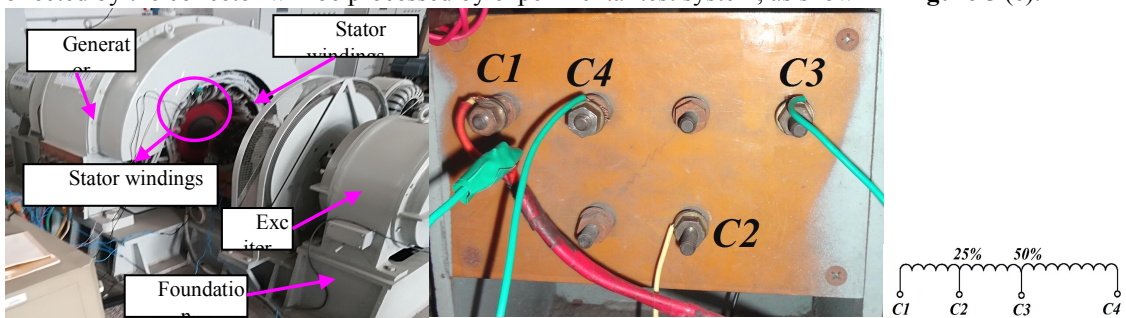
(a) MJF-30-6 fault simulation generator (b) Method to set rotor FWISC (c) Method to set rotor short-circuit taps
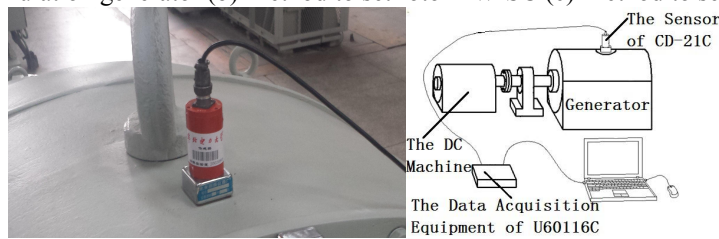

(d) Installation method of vibration velocity sensor (e) Experimental test system

**Figure 5.** MJF-30-6 type fault simulating generator and method to test the stator vibration.

4.2 Results and discussion

In order to study the variation rules of stator MPPUA, time domain waveforms of stator MPPUA as well as the spectra obtained from the experimental verification for normal condition and different short-circuit degrees are demonstrated in **Figure 6.**
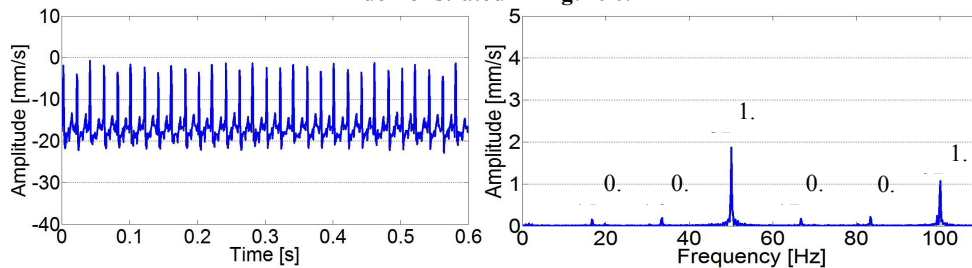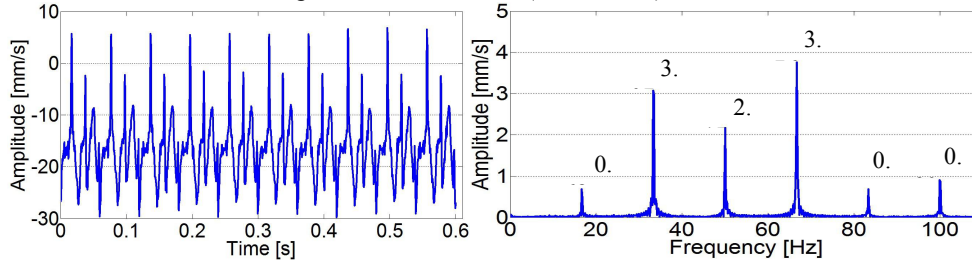

(a) Stator vibration waveforms and spectra under normal condition
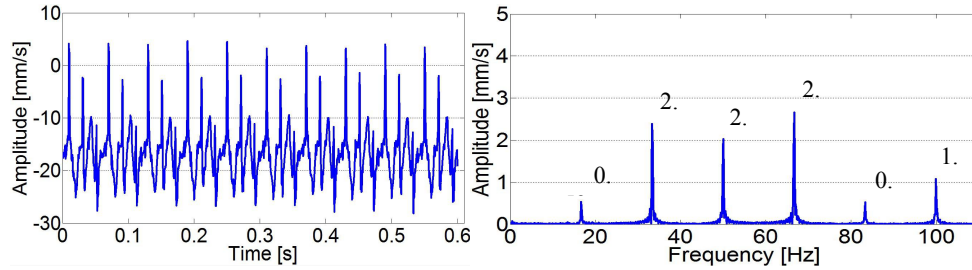
(b) Stator vibration waveforms and spectra under FWISC (shorted 2%)

(c) Stator vibration waveforms and spectra under FWISC (shorted 5%)

Figure 6. Stator vibration waveforms and spectra under different running conditions.

The experimental results are consistent with the results of numerical simulation. The main component of stator MPPUA is 6th-harmonic component under normal condition. The occurrence of FWISC will bring in 1st, 2nd, 3rd, 4th and 5th-harmonic components to MPPUA, as presented in **Figure 6** (a) and (b). Meanwhile, with the increasing of the short-circuit degrees, the amplitudes of 1st, 2nd, 3rd, 4th and 5th-harmonic components will present an increasing trend. However, the amplitudes of 6th-harmonic component will present a decrease trend, as shown in **Figure 6** (a), (b) and (c).

5. Conclusion

The variation rules of stator MPPUA characteristics under normal condition and different short-circuit degrees by the comparative study of 3D simulation and experiment. The results can be as follow:

(1) Normal condition, the main component of stator MPPUA is 6th-harmonic component.

(2) The occurrence of FWISC will bring in 1st, 2nd, 3rd, 4th and 5th-harmonic components to the stator MPPUA. In other words, the main harmonic components of MPPUA under FWISC are 1st, 2nd, 3rd, 4th, 5th and 6th-harmonic components. Specifically, with the increasing of the short circuit degrees, the amplitudes of 1st, 2nd, 3rd, 4th and 5th-harmonic components will present an increasing trend. However, the amplitudes of 6th-harmonic component will present a decrease trend.

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