ON THE DETERMINATION OF THE NEUTRAL LINE AT D.C. MACHINES

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Abstract: *The neutral line of the D.C. machines is given by those position of the brushes (as a matter of fact the position of the brush rocker) that determines a maximum induced voltage at no-load operation as generator. Two types of methods are usually used for determination of neutral line: with blocked rotor and with running rotor respectively. In the paper the authors comment two well-known methods and then present a new method. This method can be applied to D.C. machines with auxiliary poles. It consists in the feeding of the armature winding which is series connected with the auxiliary pole windings with a low D.C. voltage. For the series D.C. motors which are usually present in electric traction, this method can be easily employed by short-circuit connection of the brushes. The main idea is to fix the brush rocker in the position that determines an immobile rotor.*

1. INTRODUCTION

Generally, the D.C. machines with auxiliary poles have the brushes placed in the neutral axis in order to have a good commutation. However there are situations when the brushes are shifted in space with a certain angle in order to develop performance for a specific purpose. The magnitude and the shifting sense depend also on duty-type (motor or generator). The D.C. motors used in electric traction have the brushes placed on neutral axis since they use two units on each driving bogie. Thus the characteristics of both machines are identical which represents a very important factor for a good exploitation [1 – 5]. Placement of the brushes on the neutral line is the responsibility of the producer (case of the new units) or of the user (maintenance operations).

In practice, some methods are usually used for the positioning of the brushes on neutral line: the method of operation as generator at no-load and the method of operation as motor at no-load and in both directions. These two methods have an important drawback: the determination of the proper position corresponds to a duty with a reduced current in the commutator-brush contact. As consequence, it is possible to appear important errors due to imperfect contacts. In this paper a new method is proposed that takes into consideration close conditions to the real ones.

2. THE METHOD OF MAXIMUM INDUCED VOLTAGE AS GENERATOR

This method is based on the neutral line definition itself. The machine is excited with constant D.C. current (I_e=ct), the rotor is driven to the rated speed (n=ct), and one measures the armature induced voltage. One modifies the position of the brush rocker till the measured voltage becomes maximal. This position represents the position of neutral line where should be positioned the brush rocker [2], [6]. As follows a theoretical approach is given. Let us assume an excited bipolar D.C. machine (Fig. 1a). One calculates the dependence of induced voltage with brush shifting angle, α_0, corresponding to no-load generator operation. The radial or normal component of air-gap flux density can be expressed as a function of the angle between radial or normal axis and horizontal axis (Fig. 1b), denoted with OX:

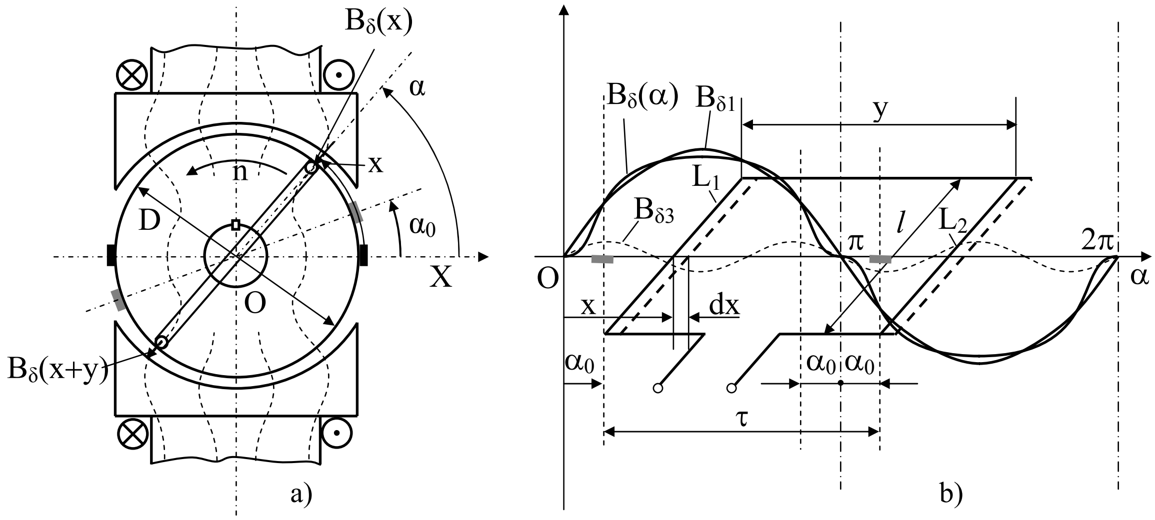

Fig. 1

$$B_\delta(x) = B_{\delta 1m} \sin\alpha + B_{\delta 3m} \sin 3\alpha + B_{\delta 5m} \sin 5\alpha + ... \tag{1}$$

The e.m.f. induced in a single-turn or a section with w_s series-connected turns is:

$$e_s = w_s \frac{d\varphi}{dt} \quad v = \frac{dx}{dt} \text{ or } dt = \frac{dx}{v} \tag{2}$$

where v is the speed of the conductors.

Let us consider the move of the turn with linear coordinate dx as equivalent two consecutive steps. In the first step the L_1 turn-side moves with dx and the flux variation due to the decrease of the surface is:

$$d\varphi_1 = B_\delta(x) \cdot dS = B_\delta(x) \cdot l \cdot dx \tag{3}$$

In the second step the L_2 turn-side moves with dx and the flux variation due to the increase of the surface is:

$$d\varphi_2 = B_\delta(x+y)(-dS) = -B_\delta(x+y) \cdot l\, dx \tag{4}$$

The total flux variation through the entire turn results as a superposing of the two steps:

$$d\varphi = d\varphi_1 + d\varphi_2 = l\, dx\left[B_\delta(x) - B_\delta(x+y)\right] \tag{5}$$

If the turn has diametrical pitch then $B_\delta(x) = -B_\delta(x+y)$ and the expression (5) becomes:

$$d\varphi = 2B_\delta(x) \cdot l \cdot dx \tag{5'}$$

From (2) results for the considered section:

$$e_s(x) = 2B_\delta(x) \cdot l \cdot v \cdot w_s \tag{6}$$

If the brushes position correspond to neutral line the total e.m.f. can be obtained by summation from x=0 to x=πD/2 in expression (6). If we refer to angular coordinate α the summation is from α=0 to α=π (Fig. 2a).

$$E_0 = \sum_{i=1}^{k} e_s(x_i) = 2w_s \cdot l \cdot v \sum_{i=1}^{k} B_\delta(x_i) = 2w_s \cdot l \cdot v \cdot B_{\delta med} \cdot k \tag{7}$$

where: k - number series-connected sections on a current path; $B_{\delta med}$ - polar-pitch flux density; $2w_s k = N/2a$ - number of turns on a current path; N – number of armature active conductors; $v = \pi D n/60 = 2p\tau n/60$. One obtains:

$$E_0 = \frac{p}{a} N \frac{n}{60} \Phi_0 ; \qquad \Phi_0 = B_{\delta med} \cdot l \cdot \tau \tag{8}$$

Flux density can be calculated with:

$$B_{\delta med} = \frac{1}{\pi}\int_0^{\pi} B_\delta(\alpha) d\alpha = \frac{1}{\pi}\left|\int_0^{\pi} B_{\delta 1} \sin\alpha \, d\alpha\right| = \frac{2}{\pi} B_{\delta 1m} \tag{9}$$

If the brushes are shifted in space with the angle α_0 in comparison with neutral line then:

$$E_0 = w_s \cdot l \cdot v \cdot 2\sum_{i=1}^{k} B_\delta(x_i, \alpha_0) \tag{10}$$

where the sum is taken into consideration on α intervals from α_0 to $\alpha_0 + \pi$.

The mean value of this sum can be determined with expression (11):

$$\begin{aligned} B_{\delta med\alpha} &= \frac{1}{\pi}\int_{\alpha_0}^{\alpha_0+\pi} B_\delta(\alpha)\, d\alpha = \frac{1}{\pi}\int_{\alpha_0}^{\pi-\alpha_0} B_\delta(\alpha)\, d\alpha + \frac{1}{\pi}\int_{\pi-\alpha_0}^{\alpha_0+\pi} B_\delta(\alpha)\, d\alpha = \\ &= \frac{1}{\pi}\int_{\alpha_0}^{\pi-\alpha_0} \left(B_{\delta 1m}\sin\alpha + B_{\delta 3m}\sin 3\alpha + \ldots\right) d\alpha \end{aligned} \tag{11}$$

since there is a symmetry of flux density wave relatively to $\alpha = \pi$.

If we keep only the first term of the flux density, the fundamental, then the expression (11) becomes:

$$B_{\delta med\alpha} = \frac{1}{\pi}\left|\int_{\alpha_0}^{\pi-\alpha_0} B_{\delta 1m}\sin\alpha \, d\alpha\right| = \frac{2}{\pi} B_{\delta 1m}\cos\alpha_0 = B_{\delta med} \cdot \cos\alpha_0 \tag{12}$$

We can estimate that the polar mean value of the flux density is $(\cos\alpha_0)$ times smaller when the brushes are shifted with an α_0 angle from neutral line (Fig. 2b).

The expression of induced voltage at no-load operation is:

$$E(\alpha_0) = \frac{p}{a} N \cdot \frac{n}{60} \cdot l \cdot \tau \cdot B_{\delta med} \cdot \cos\alpha_0 = E_0 \cos\alpha_0 \tag{13}$$

If the brushes are shifted with an α_0 then the voltmeter indicates a value given by the following approximate relation:

$$U_0 = U_{m0} \cos \alpha_0 \tag{13'}$$

where: U_{m0} – the maximum value of the voltage corresponding to a placement of the brushes on the neutral line.

The relative sensitivity:

$$\frac{\Delta U_0}{\Delta \alpha_0} = U_{m0} \sin \alpha \tag{14}$$

goes to zero when the α_0 goes to zero. As consequence, this method can be considered as a low precision one. In other words, it is quite difficult to establish when the value of voltage is maximal in order to obtain the ideal position of the neutral line.

Other cases that can diminish the precision of the method are: changes in commutator-brush path; speed fluctuations of the rotor during test; the influence of the turns that commute, a.s.o..

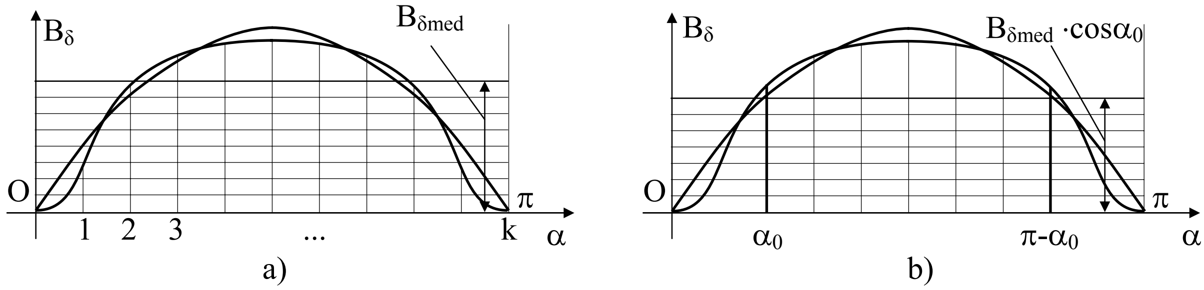

Fig. 2

3. THE SIMILAR SPEEDS AS MOTOR OPERATION METHOD

A separately excited machine is connected to a constant voltage source that can ensure a no-load speed very close to the rated value [2], [6]. One modifies the position of the brush rocker till the value of the speed becomes maximum (gross positioning). The speed of the motor depends on main flux, auxiliary pole flux, armature reaction and the influence of short-circuited sections. Since the motor has to develop an electromagnetic torque greater then the torque corresponding to no-load losses results from the expression (15) a minimum value of the current I_{AO} (we assumed only the presence of the main flux - an ideal situation).

$$T = k_m \cdot I_{A0} \cdot \Phi_0 \cdot \cos \alpha_0 = T_{r0} \tag{15}$$

In conclusion, an approximate position of the brushes on the neutral line results when the I_{AO} = minim. For a more precise positioning one has to change the polarity of the voltage. The newly opposite speed must be the same value previously (also the current). After some successive tests one can establish as acceptable position the one that determines both equal speeds and currents. The sensitivity of the method can be increased if the excitation currents have low values. Of major importance is also to have symmetrical brushes for both senses of rotation.

4. ARMATURE AND AUXILIARY POLE FEEDING METHOD

This method was developed at Electrical Machine laboratory of "Gh.Asachi" T.U. of Iaşi and can be applied successfully only for D.C. machines provided with auxiliary poles (especially to series motors used in electrical traction). The method consists in feeding of the series-connected armature winding and auxiliary pole winding (Fig. 3). As supply source a variable D.C. current source is needed (for example a D.C. welding generator). The motor must not be mechanically coupled with another machine.

One increases the current close to the rated value. If the brushes are not on the neutral line then the rotor runs due to the transversal component created by the auxiliary poles that acts with the armature current and creates a torque. In this case it is necessary to rotate the brush rocker till the motor stops and consequently the brushes occupy the neutral position.

The theoretical explanation is: the resultant torque of a D.C. machine with shifted brushes results from general theory of electric machines [5]:

$$T = p \cdot L_{De} \cdot I_e \cdot I_A \cdot cos\alpha' - p \cdot \frac{L_d - L_q}{2} \cdot I_A^2 \cdot sin\, 2\alpha' = T_{ex} + T_{er} \tag{16}$$

where: p – number of pole pairs; L_{De} – longitudinal axis mutual inductance between armature winding and exciting winding; L_d, L_q – longitudinal and transversal inductances of the armature winding; I_A – armature current; I_e – excitation current. From Fig. 3 one can calculate the torque under the condition $\alpha' = \pi/2 - \alpha$, that is:

$$T = p \cdot L_{Ae} \cdot I_A^2 \cdot sin\alpha_0 \tag{17}$$

where, L_{Ae} is the mutual inductance between armature winding and auxiliary pole winding. The expression (17) kept only the excitation torque component created by the auxiliary pole flux.

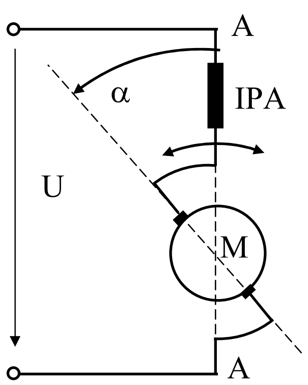

Fig. 3

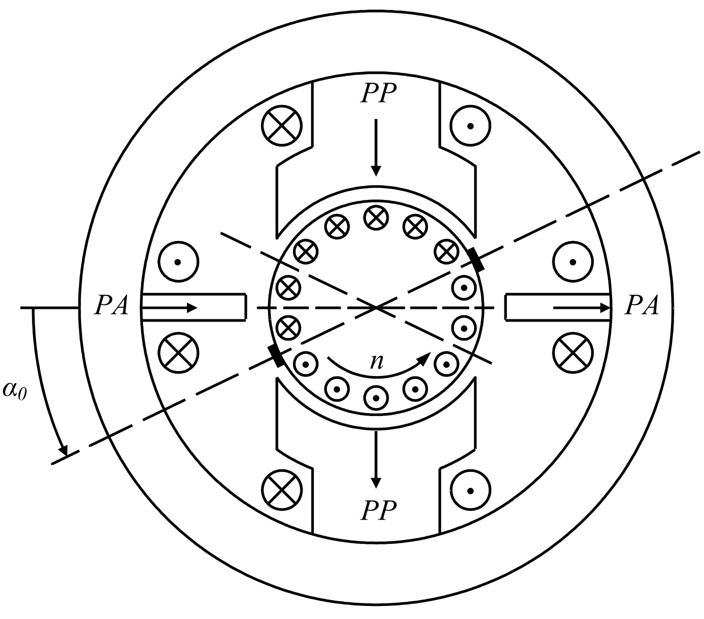

Fig. 4

In conclusion, a shifting of the brushes with an angle α determines a torque which is proportional with $sin\alpha$ and has the same direction as the shifting itself. Consequently, if the rotor is running, the brush rocker has to be rotated in the opposite direction till the rotor stops. This represents the correct position of the brushes on neutral line.

The tests made by the members of our collective on traction motors pointed out better results then for the other methods including the method with variable current. The advantage of the method consists in the possibility of making tests directly on the place where the motor operates. However the motor must be not connected to the load machine and a variable D.C. voltage source is necessary. For this purpose a controlled current source can be used.

Fig. 4 illustrates the principle that produces the torque in the same direction as shifted brushes. Is it well known that the operation as a motor involves such a polarity of the auxiliary pole winding so that the auxiliary pole and the main pole behind him have the same polarity. When the brushes are shifted with an α_0 angle then in front of the auxiliary pole there are armature turns under load. These currents and the auxiliary polar flux create a torque that rotates the rotor.

In conclusion one can formulates the following rule available for motor operation: for a shifting of the brushes with a certain angle which determines the rotor running the exactly position of the neutral line can be achieved by moving the brush rocker backwards.

A theoretical demonstration of this method requires an analysis of the machine operation when the brushes are shifted from neutral line. For this purpose the estimation of the electromagnetic torque corresponding to motor duty and shifted brushes is necessary.

In order to calculate the torque expression one starts with magnetic energy from two coupled circuits: an armature section (a) and the exciting winding (e) – Fig 5.

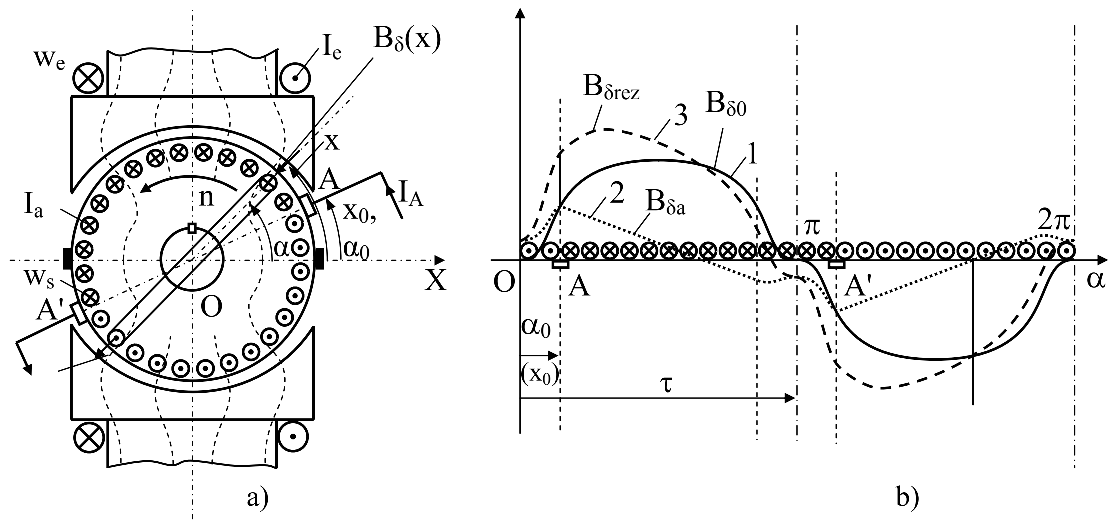

Fig. 5

The electromagnetic torque that act upon the section (x) is:

$$T(x) = \frac{dW_m(x)}{d\alpha} = \frac{d}{d\alpha}\left(\frac{1}{2}L_a I_a^2 + \frac{1}{2}L_e I_e^2 + M_{ae} I_a I_e\right) = \frac{d\left(M_{ae} I_a I_e\right)}{d\alpha} \tag{18}$$

where M_{ae} is the mutual inductance of armature section with w_s turns and excited winding with w_e turns. It results:

$$M_{ae} = w_s \cdot w_e \cdot \lambda_{se}(x) \tag{19}$$

where $\lambda_{se}(x)$ is the permeance of the flux through the section. Its value varies with the position of the section relatively to main flux. Hence:

$$\begin{aligned} T(x) &= w_a I_a \frac{d[w_e I_e \lambda_{se}(x)]}{d\alpha} = w_s I_a \frac{d[\Phi(x)]}{d\alpha} = w_s I_a \frac{d[\Phi(x)]}{dx} \cdot R = \\ &= w_s I_a \cdot \frac{D}{2} \cdot 2B_\delta(x) l = \frac{2p}{\pi} \cdot w_s I_a \cdot \tau l \cdot B_\delta(x) \end{aligned} \tag{20}$$

If the brushes are placed on the neutral line then the resultant torque can be calculate as follows:

$$\begin{aligned} T &= \sum_{i=1}^{k} T(x_i) = \frac{2p}{\pi} w_s I_a \cdot \tau l \cdot \sum_{i=1}^{k} B_\delta(x_i) = \frac{2p}{\pi} w_s I_a \cdot \tau \cdot l \cdot B_{\delta med} \cdot k = \\ &= \frac{2p}{\pi} \cdot \frac{N}{4a} \cdot \frac{I_A}{2a} \cdot 2a \cdot (\dot{\tau}\, l\, B_{\delta med}) = \frac{p}{a} \cdot \frac{N}{2\pi} \cdot I_A \cdot (\Phi_P) = K_m I_A \cdot \Phi_P \end{aligned} \tag{21}$$

where: $2a$ – current paths number; $I_A = I_a \cdot 2a$ - total armature current; N – total number of armature conductors.

The parameter Φ_P is called polar flux and can be considered identical with the parameter Φ_0 from expression (8) if the armature is neglected, that is $I_A = 0$.

At under-load operation the polar flux represents the sum of elementary fluxes, that is:

$$\Phi_P = \tau \cdot l \cdot \sum_{i=1}^{k} B_\delta(x_i) \tag{22}$$

The values of flux density, $B_\delta(x_i)$, can be obtained by superposing the no-load flux density $B_{\delta 0}(x)$ and armature reaction flux density $B_{\delta a}(x)$ respectively.

If the magnetic circuit is not saturated then the resultant polar flux density (mean value) is $B_{\delta med}$, similar to those at no-load operation. Practically, at under-load operation, can be noticed a diminish of mean polar flux density in comparison with the no-load operation.

For an α_0 shifting angle, in the same sense as armature rotation, one can obtain the polar flux through a mathematical integration of flux density $B_{\delta rez}(\alpha)$ between α_0 and $\alpha_0 + \pi$ limits (Fig. 5b). There is a zone with positive flux densities followed by another zone with negative values. As consequence the resultant value decreases in comparison with the situation when $\alpha_0 = 0$. For an analytical approach one can create a function destined to approximate $B_{\delta rez}(\alpha)$. Then this function is analysed with Fourier expansion and only the first two or three terms are taken into account. If the angle α_0 has a low value then for one obtains the following variation when the brush rocker is moved:

$$\Phi'_P = \frac{d\Phi_P}{d\alpha_0} \approx 0 \tag{23}$$

As concerns the torque variation we have:

$$\frac{dT}{d\alpha_0} = k_M I_A \frac{d\Phi_P}{d\alpha_0} \approx k_M I_A \Phi'_P \approx 0 \tag{24}$$

The precision of the method by moving the brush rocker when the machine operates as a motor is quiet low. The precision can be increased if the current I_A increases.

The machines with auxiliary poles have a smaller variation of the flux (and also the torque) with α_0 since the auxiliary pole flux diminishes the resultant flux on neutral line. This observation and the superposing of the armature and auxiliary pole fluxes on neutral line at non-excited machine justify the following method for establishing of neutral line. To be more precisely, when one feeds the series-connected armature and auxiliary pole winding circuits (in condition of a non-excited machine) the polar flux is compose by armature reaction flux and auxiliary pole flux, $\Phi_{rp}= \Phi_a+\Phi_{pa}$. The resultant value of this flux is zero if $\alpha_0 = 0$. If one modifies the shifting angle then the resultant flux Φ_{rp} increases from zero to a certain value and its component Φ_{pa} acts like an excitation one. The interaction between this flux and armature current I_A creates a torque that rotates the rotor in the same sense as the shifting of the brushes. In expression (24), instead Φ_p appears the new value of polar flux. Its variation with the shifting angle α_0 is not zero anymore, that is:

$$\frac{dT'}{d\alpha_0} = k_M I_A \frac{d\Phi_{rp}}{d\alpha_0} \approx k_M I_A \frac{d\Phi_{pa}}{d\alpha_0} \neq 0 \qquad (25)$$

5. CONCLUSIONS

In the paper one presents three methods for evaluation of neutral line of D.C. machines. The first two methods are well known in scientific literature.

For the last method, developed by the authors and tested successfully on series motors used in urban traction, the theoretical approach and its advantages are presented. The proposed method has as main advantage the determination of the neutral axis under conditions that are very close to rated operation. The commutator-brush contact supports a current value similar to the rated one. Moreover, the method can be applied anywhere; it is not necessary a special test bench.

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