Considerations regarding the Induction Generator's Compound Excitation

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Abstract: - The paper presents considerations regarding the problematic of induction generator's (IG) excitation. There are presented theoretical considerations and experiments that confirm the efficiency of the capacitive excited induction generator compounding regarding the load voltage variation compensation. There is presented the determination of the compounding condenser's capacity by using the graph-analytical method and respectively the calculation of the compound condenser excited induction generator characteristics. The present paper shows only the peculiarities which occur in the use of induction generator in energy power stations and some solutions for solving of the stated problems.

Key-Words: - induction generator, compound excitation, graph-analytical method, excitation condenser determination

1 Introduction

In the present, the domain of energetic has to solve important issues such as: the reduction of the industry's negative impact over the environment; to deliver the electrical energy safely and optimally; etc. The above problems may be solved only by increasing the exploitation efficiency of energy resources by new means, methods and techniques. The above mentioned issues can be solved by using modern energy conversion systems, such as the case of wind energy power systems based on the usage of the induction generator.
There are taken into consideration energetically groups at variable controlled rotation equipped with induction generators (double feed induction machine, induction machine cascades, special construction machine types).
The above mentioned possibilities of using the induction generator as well as many other positive characteristics prove its considerable importance for unconventional energetic domain. The system integrator will need to embed these components, incorporating the applicable criteria to be followed.
The operation of induction machine as a generator, parallel with a constant frequency and voltage grid, is generally known, being considered in the electric machines handbooks, side by side with the operation as motor, with the same mathematics models, the same equivalent circuit, the same circular diagram, etc., the difference residing only in the slip values, positive for motor and negative for generator functioning regime. This functioning regime and its characteristics being well known, the present paper shows only the peculiarities which can be noticed in such use, and some solutions for solving the problems occurred by the use of induction generators.[1][2][10]

2 Compound Excited Induction Generators - Considerations

The theoretical considerations checked by the experiments presented in [1], confirm the efficiency of capacitive excited induction generator compounding regarding the load voltage variation compensation.
The induction generator compounding, by analogy of d.c. generator compounding, consists of using some serial condensers C_S (depicted in fig.11) complementary to shunt exciting condensers C_d.
The phase-modifying effect of the serial condensers is explained by the fact that the load voltage is equal to vector sum of the generator voltage U_G and of the compounding condensers voltage $(U)_{C_s}$.

$$\overline{U}_S = \overline{U}_G - (\overline{U})_{C_s} \qquad (1)$$

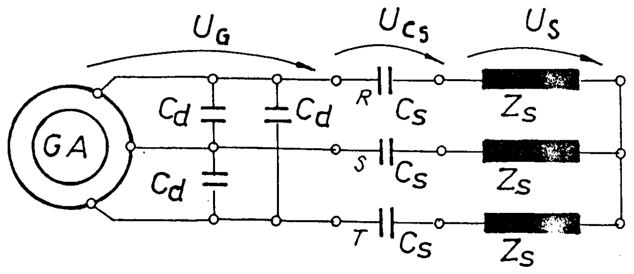

Fig. 1 Schematic diagram of compound induction generator power circuit.

where U_G decreases with the load and $(U)_{C_s}$ increases with the load, and choosing adequately the capacity of condensers Cs, there can be obtained a load voltage

$\overline{U}_S = \overline{U}_G - (\overline{U})_{C_s}$ (presented in fig. 2 and fig.3) almost constant on module.[8]

3 Determination of the Compounding Condenser Capacity by using the Graph-Analytical Method

There is used the external characteristic family $\underline{U} = f_k(\underline{I})$ represented in relative units $\frac{U}{U_0} = f_k\left(\frac{I}{I_N}\right)$, for different values of the power factor (cos φ)$_k$ = constant, considered as parameter, analytically calculated or experimentally determined. In Fig. 2 there are reproduced the characteristics of an case study induction generator, given in [7], U_f =143 V, I_N = 2.48 A, at C_d = 78 μF and different values of the power factor (cos φ)$_k$ = const.

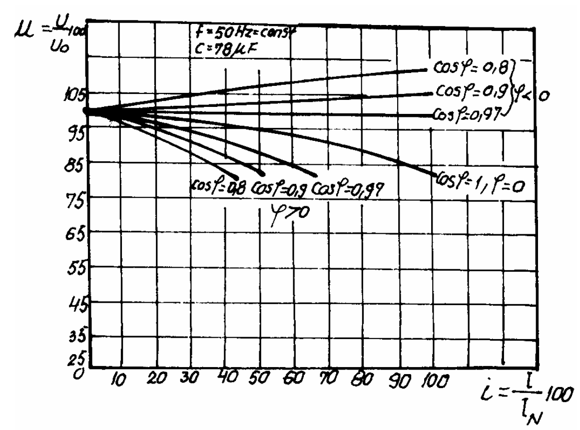

Fig. 2 External characteristic family for the induction generator.

For a given current I = const. and different values of the power factor (cos φ), from the external characteristics family C = const., there can be determined the voltage values. By means of voltage values at different cos φ there can be represented the hodographs $\overline{U}_G = f(\cos\varphi)$, as shown for $\underline{I}$ = 50% in fig.3.

In fig. 3 there are represented the hodographs of the generator considered in [7] for $\underline{I}$ = 0%, 25%, 50%, 75%, 100%.

The calculation method of the condenser C_S consists in searching the vector $(U)_{C_s}$ beginning from a vector $\overline{U}_S$ (load supply voltage-module and phase related to the load current), for example $U_S = U_N$, cos φ = 0.9, φ > 0, in such way do exist a voltage vector $\overline{U}_G$ with the extremity on the hodograph $\overline{U}_G$, $\underline{I} = 100\%$ (the current for which is calculated the condenser which fully compensate the voltage loose in the generator).[9]

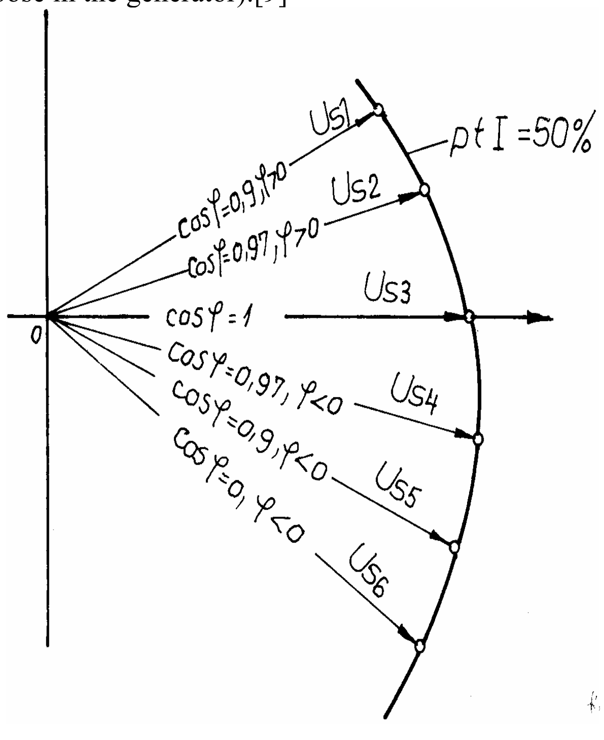

Fig. 3. Hodograph (geometric place of a vector extremity) $\overline{U}$ = f (cos φ), $\underline{I}$ = 50%.

$$\overline{U}_G = \overline{U}_S + (\overline{U})_{C_S} \qquad (2)$$

Corresponding to the above agreement, we proceed as follows:

1. There is built the wished voltage phasor $\overline{U}_S$ at the imposed current and power factor (cos φ) (Fig.5a)

2. There is built the vector $(\overline{U})_{C_S}$ direction and sense knowing that it is in advance with 90º, related to the current phasor $\overline{I}$ (Fig. 5b).
3. Knowing that the phasor $(\overline{U}_G)$, according to relation (2), has the extremity of phasor $(\overline{U})_{C_S}$ and, at the same time, the extremity of $(\overline{U}_G)$ is on the hodograph $\overline{U}_G = f(\cos\varphi_G)$, results that the extremity of $(\overline{U}_G)$ shall be at the intersection of phasor $(\overline{U})_{C_S}$ direction with the hodograph, the point of intersection being the only one for which the above mentioned conditions are respected (Fig. 5c). Knowing the voltage $(U)_{C_S}$ on the condenser Cs and the current $(I)_{C_S} = I_C = I_S$, corresponding to the considered operating condition, for which the compensation condenser capacity is determined, there can be calculated the sought capacity value.

$$C_S = \frac{I}{\omega \cdot (U)_{C_S}} \tag{3}$$

In the examined case in [I$_1$] the C_S voltage has resulted

$$(U)_{C_S} = a_0 a_4 = 53.5\% U_f = 53.5\% U_S = 0.535 \cdot 143 = 76.5V \tag{4}$$

In the considered operating condition, the current being I = I_N = 2.48 A, according to (3) it has resulted C_S = 103μF . It can be noted that $C_S > C_d$.

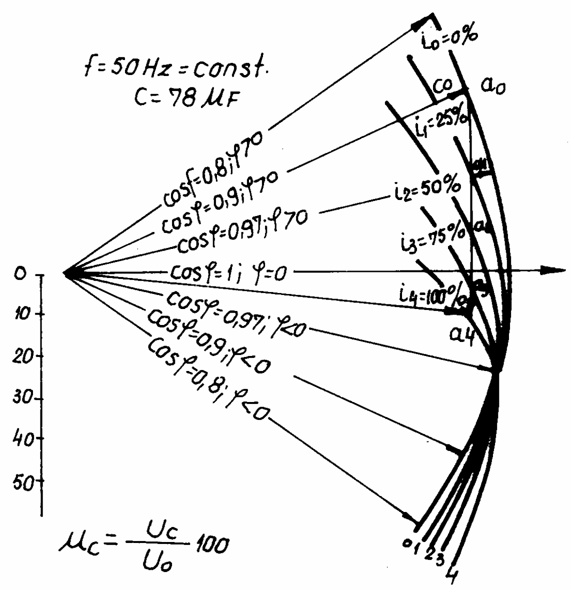

Fig. 4 Hodograph $\overline{U} = f_k(\cos\varphi)$ for different values of the current $\underline{I}_k = const.$

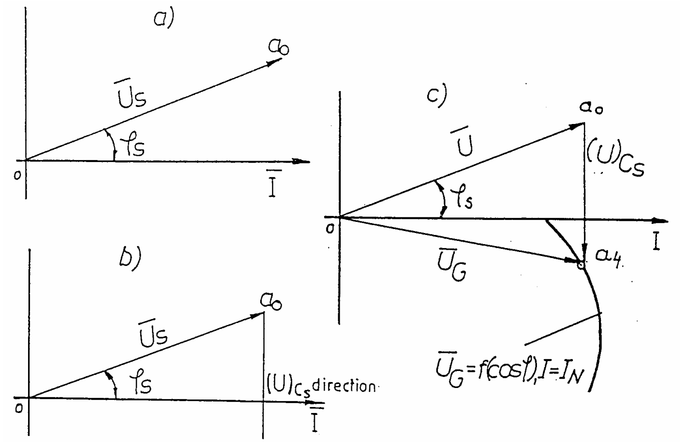

Fig. 5 Graphical determination of the phasor $(\overline{U})_{C_S}$ on the condenser required for the compensation of voltage lose in the generator.

The calculus method of the load voltage U_S, for different values of the load current, consists, according to relation

$$\overline{U}_S = \overline{U}_G - (\overline{U})_{C_S}, \tag{5}$$

in seeking a phasor $\overline{U}_S$ which satisfies the relation (5) and, thus, the construction from Fig.6, in which $(\overline{U})_{C_S} = \frac{I_K}{\omega C_S}$ (can be calculated proportionally with the ratio between I and I_N for which was calculated C_S), the phasor $\overline{U}_S$ direction is known (imposed by the considered cos φ_S) and the extremity of $\overline{U}_S$ coincides with the extremity of $(\overline{U}_G)$ and thus it must be on its hodograph for the considered I_k value of the current. The construction is shown in fig. 6.
By means of the shown proceeding, in [7] there were determined the values of voltages U_S , U_G , $(U)_{C_S}$ corresponding to different values of the current, for a small power induction generator. With the resulted data there had been possible to built the characteristics U, U_G $(U)_{C_S}$ = f (I), represented in fig. 7. There can be noted that the compounding performed by means of static condensers is an efficient proceeding of compensation. There is mentioned [I$_1$] the proceeding efficiency even in case of sudden variations of inductive loads. Examining the influence of the load power factor, there is mentioned [I$_1$] that in case of cos φ < 1, the compounding is more efficient than in case of active load. Thus, in case of generator considered in [I$_1$], for a load with cos φ_S = 0,9 there can be noted (fig. 7) an error up to 2%, while for

pure resistive load (cos φ_S =1) there result compensating errors up to 7% (fig. 8). In [I$_1$], in order to reduce the compounding condenser capacity and, correspondingly their costs and dimensions, there is also discussed the possibility of compounding condenser connection by means of some step-down current transformers as shown in fig. 9.

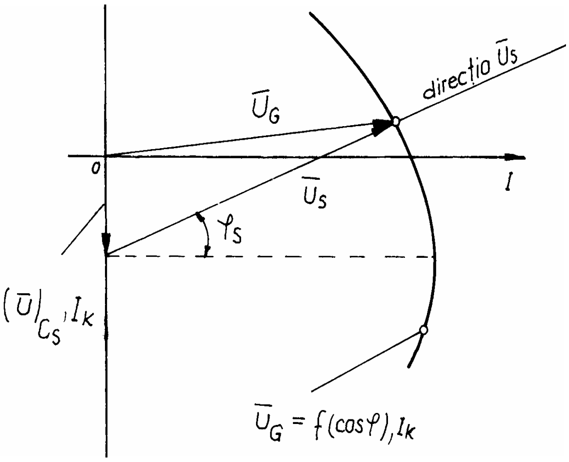

Fig. 6 $\overline{U}_S$ phasor construction for given values of C_d , C_S , and I.

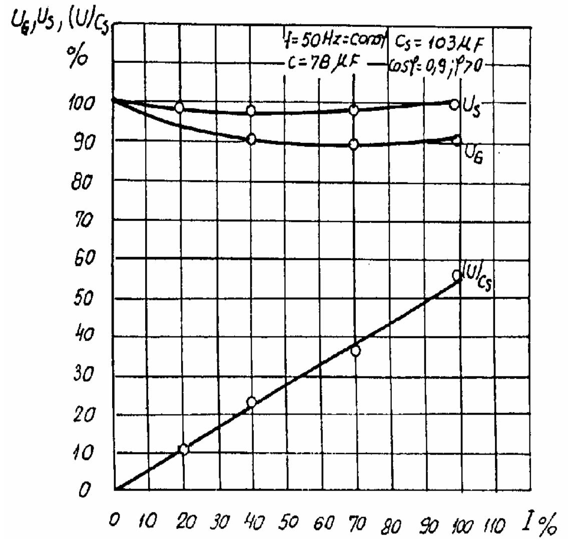

Fig. 7 Voltage U_S, U_G , $(U)_{C_S}$ characteristics of compounded induction generator at inductive character load with power factor cos φ_S =0,9

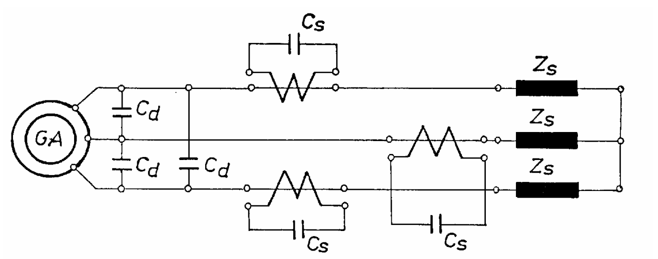

Fig. 8 Schematic diagram of condenser excited induction generator compounded with condensers C_S separated from the load circuit by current transformers.

4 Three-phase Short-Circuit of the Compound Condenser Excited Induction Generator

There is presented in fig. 8, the case of no-load three-phase short-circuit at the load terminals, the condensers C_S represent a star connection (the neutral being the point of three-phase short-circuit) connected to generator terminals, parallel with the derivation exciting condensers C_d. The situation is equivalent with the no-load operation and increasing derivation-exciting capacity.

$$(C_d)_{eqyivalent} = C_d + C_s \tag{6}$$

The increasing of derivation-exciting capacity conducts to the increase of no-load voltage at a value, which can be determined, as was shown at no-load operation of the parallel condenser excited generator. The voltage increase determines important increase of the generator current (of approx. 2 times) concomitantly with form deformation of the currents and voltages. The voltage and current oscillograms indicate (at short-circuit removing) a quick return (2-3 periods) of the generator to normal operation.[3][4]

5 Compound Condenser Excited Induction Generator Characteristics' Calculation in the case Cd, Cs, n = const.

The grapho-analytical above exposed method of the compound induction generator characteristics is very laborious. The variation of induction generator parameters x_1, x'_2, x_m, r_m are due to the frequency variation with the load or the rotation speed and / or the parameters x_m, r_m [5][7][11]

Operation characteristics determination.

For a given load S power factor, that is for a constant ratio R_S / X_S will be considered N values of the active and reactive resistances of the load

$$R_S = (N - k + 1)(R_S)_N \tag{7}$$

$$(X_S)_{f_N} = (N - k + 1)\left[(X_S)_N\right]_{f_N} \tag{8}$$

where

$$k=1,2,...,N \tag{9}$$

For each regime, that is for each value of the parameter k, the unknowns s (slip) and U (voltage) will be found as solutions of currents' equilibrium equations

$$ABS(I_{aG}) = ABS(I_a)_{C_s,S} \quad (10)$$

$$ABS(\bar{I}_{rG}) = ABS\left((\bar{I}_r)_{C_s,S} + \bar{I}_{Cd}\right) \quad (11)$$

and $(I_r)_G$ will be expressed considering the equivalent scheme. For $\overline{I_c}$ results:

$$\bar{I}_c = -j \cdot 2\pi f_N \cdot U \cdot C_d /(1-s) \quad (12)$$

The active and reactive components of the current $(\bar{I})_{C_s,S}$ will be calculated as follows

$$Z_{C_s,S} = R_s + j(X_S - 1/\omega C_s) \quad (13)$$

$$\bar{I}_{C_s,S} = U / Z_{C_s,S} = \frac{U[R_S - j(X_S - 1/\omega C_S)]}{R_S^2 + (X_S - 1/\omega C_S)^2} \quad (14)$$

$$(I_a)_{C_s,S} = UR_S / \left(R_S^2 + (X_S - 1/\omega C_S)^2\right) = = UR_S / \left(R_S^2 + ((X_S)_{f_N} /(1-s) - (1-s)/2\pi \cdot f_N \cdot C_S)^2\right) \quad (15)$$

$$(I_r)_{C_s,S} = -jU\left(X_S - 1/\omega \cdot C_S\right) / \left(R_S^2 + (X_S - 1/\omega \cdot C_S)^2\right) = = \frac{-jU\left((X_S)_{f_N} /(1-s) - (1-s)/2\pi \cdot f_N \cdot C_S\right)}{\left(R_S^2 + \left((X_S)_{f_N} /(1-s) - (1-s)/2\pi \cdot f_N \cdot C_S\right)^2\right)} \quad (16)$$

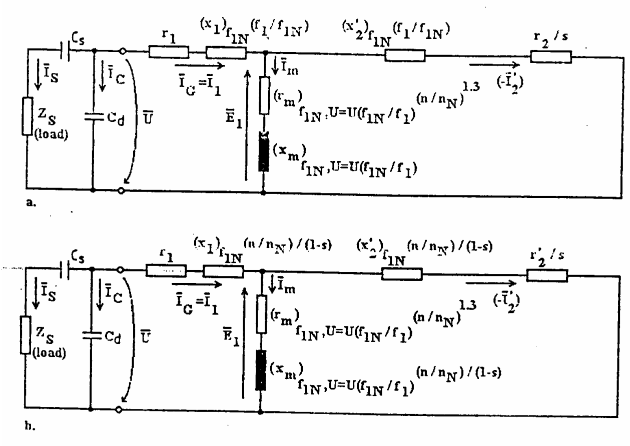

Fig. 9 Compound condenser-excited induction generator

Considering (12), (15), (16) the equations (10), (11) will have the expressions

$$ABS\bar{I}_{aG} = ABS \frac{UR_S}{R_S^2 + \left(\dfrac{(X_S)_{f_N}}{1-s} - \dfrac{1-s}{2\pi \cdot f_N \cdot C_S}\right)^2} \quad (17)$$

or , by adopting the notations

$$(X_S)_{f_N} / (1-s) - (1-s)/2\pi \cdot f_N \cdot C_S = A \quad (18)$$

$$2\pi \cdot f_N \cdot U \cdot C_d / (1-s) = B \quad (19)$$

the equations (16), (17) will be

$$ABS\bar{I}_{aG} = ABS \frac{UR_S}{R_S^2 + A^2} \quad (20)$$

$$ABS\bar{I}_{rG} = ABS\left(\frac{UA}{R_S^2 + A^2} + B\right) \quad (21)$$

Solving the equations (20), (21), for each pair of R_S and $(X_S)_{f_N}$ values, will be found the corresponding operating slip s and voltage U and, correspondingly, the operating values of f_1 ,I_a, P_{aG}, P_{rG}, $\cos\varphi_G$, $I_{C_s,S}, U_{C_S}, U_S$.

The calculated values will permit to depict the needed induction generator characteristics to be used in the control process. The search of solutions s and U will be made iteratively in an estimated domain

$s = [s_{min}=0,\ s_{max}]$ (22)

$U = [U_{min},\ U_{max}]$, (23)

beginning with

$s = s_{max} / 2$ (24)

$U = (U_{min} + U_{max}) / 2$ (25)

and verifying the equations (10) and (11) .

If the equation (10) is not verified for the considered s, other values of s will be considered for the same value of U. In accordance with the divided interval method, each time the previous value of s divides the previous interval into two parts. At the next step will be considered and divided the part

a) of smaller values of s, in the case when $I_{aG} > I_{aS}$, that is $s = (s_k + s_{min}) / 2$,

b) of greater values of s, in the case when $I_{aG} < I_{aS}$, that is $s = (s_k + s_{max}) / 2$.

For the slip for which equation (12) is satisfied, the solution search will continue at other value of the voltage. In accordance with the divided interval method, each time the previous value of the voltage divides the previous interval into two parts. At the next step will be considered and divided the part

a) of smaller values of U, in case when $I_{rG} < (I_r)_{C,S}$, that is $U = (U_k + U_{min}) / 2$

b) of greater values of U, in the case when $I_{rG} > (I_r)_{C,S}$, that is $U = (U_k + U_{max}) / 2$.

The calculation diagram based on above exposed algorithm.

Excitation condenser capacitance C_d determination.

Estimating an admissible variation of the frequency from the standard at unload operation the frequency value, may be accepted

$$f = f_N \pm \Delta f \quad (26)$$

The rotation speed that may assure at unload operation this frequency will be

$$n = f_0 / p = (f_N + \Delta f) / p \quad (27)$$

Considering the equivalent scheme at nonload operation, that is at s = 0, we'll have

$$I_C = (I_G)_0 \quad (28)$$

where

$$I_c = U_0 / X_c = U_0 \cdot \omega \cdot C = U_0 \cdot 2\pi \cdot f_0 \cdot C \quad (29)$$

and

$$(I_G)_0 = U_0 / \sqrt{(r_1 + r_m)^2 + (x_1 + x_m)^2} \cong U_0 /(x_1 + x_m) \quad (30)$$

Having in view the above relations, we'll obtain

$$U_0 \cdot 2\pi \cdot f_0 \cdot C = U_0 /(x_1 + x_m)$$

where from

$$C = 1 / 2\pi \cdot f_0 \cdot (x_1 + x_m) =$$

$$... = f_N / 2\pi \cdot (f_N + \Delta f)^2 \cdot (x_{1N} + x_{mN}) \quad (31)$$

Series condenser capacitance C_S determination.

The condenser capacitance C_S may be found considering successively different values of it and calculating each time the external characteristics U_S = f(s). The needed value of C_S will be that which assures an acceptable external characteristic. [7][6]

6 Conclusions

There already exist the technical - economic premises to a wider introduction of induction generators in micro hydro power plants connected to the grid, wind energy conversion systems and mixed systems.

The theoretical and experimental studies allowed the establishment of technical conditions necessary for a normal operation of an IG in power energy stations.

There is presented a graph-analytical method for the determination of the compounding condenser's capacity and respectively the calculation of the compound condenser excited induction generator characteristics. There can be drawn the conclusion that the theoretical considerations and experiments confirm the efficiency of the capacitive excited induction generator compounding regarding the issue of load voltage variation compensation.

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