A Novel Method for Modeling Magnetic Saturation in the Main Flux of Induction Machine

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Abstract: - The phenomenon of saturation of electric machines constitutes an important subject of investigation in electrical engineering. This paper presents a new modeling technique for saturation in the case of induction machines. Necessary calculations to introduce this technique in the linear flux model are presented. Computed results and experimental tests on the transients of the self-excited induction generator are clearly compared. These experimental and computed results agree closely, validating the proposed technique as well as the developed model.

Key-Words: - Induction machine, Generator, Modeling, Saturation, Experimental investigation.

1 Introduction

The induction machine has traditionally been modeled with the assumption of linear magnetics in steady-state and most transient analysis. However, it is well known that the induction machines are usually designed to operate in saturated range. In fact, for proper utilization of the magnetic material, the machine operating region has to extend above the knee point of the magnetic characteristics. That technically forces the machine into saturation. Furthermore, in many variable torque applications, it is desirable to operate with the main flux path in magnetic saturation, allowing an induction machine to produce higher torque. To improve the machine modeling and to enable a more accurate prediction of the performance, it is, thus, necessary to consider the magnetic saturation [1]-[8]. Conventional models generally represent this phenomenon by the technique of saturation factors or by adjusting the magnetizing reactance [8]. These models are often inaccurate and do not give enough precision, particularly during transient conditions [8].

In this work, we present a new technique of modeling of saturation in the case of the induction machine, as well as calculations necessary to the introduction of this technique in the linear flux model. This technique is based primarily on a function called “Saturation Degree Function” (SDF).

2 Induction Machine Flux Model

The induction machine voltage equations in the q-d axis arbitrary reference frame may be written as [9]

$$v_{qs} = r_s i_{qs} + \omega \varphi_{ds} + p \varphi_{qs} \tag{1}$$

$$v_{ds} = r_s i_{ds} - \omega \varphi_{qs} + p \varphi_{ds} \tag{2}$$

$$v'_{qr} = r'_r i'_{qr} + (\omega - \omega_r) \varphi'_{dr} + p \varphi'_{qr} \tag{3}$$

$$v'_{dr} = r'_r i'_{dr} - (\omega - \omega_r) \varphi'_{qr} + p \varphi'_{dr} \tag{4}$$

All rotor quantities and parameters are referred to the stator.

$p = d/dt$, denotes the differential operator with respect to time t.

ω and ω_r are the angular speeds of reference frame and rotor respectively.

v_{qs}, v_{ds}, v'_{qr} and v'_{dr} denote the q-d axis components of the stator, and rotor voltages referred to the stator respectively.

i_{qs}, i_{ds}, i'_{qr} and i'_{dr}, represent the q-d axis components of the stator, and rotor currents referred to the stator respectively.

φ_{qs} , φ_{ds} , φ'_{qr} and φ'_{dr} represent the q-d axis components of the stator, and rotor fluxes referred to the stator respectively.

r_s and r'_r denote stator and rotor resistances referred to the stator.

The stator and rotor currents, in terms of q-d axis fluxes can be written

$$i_{qs} = \frac{\varphi_{qs} - \varphi_{mq}}{l_s} \quad (5)$$

$$i_{ds} = \frac{\varphi_{ds} - \varphi_{md}}{l_s} \quad (6)$$

$$i'_{qr} = \frac{\varphi'_{qr} - \varphi_{mq}}{l'_r} \quad (7)$$

$$i'_{dr} = \frac{\varphi'_{dr} - \varphi_{md}}{l'_r} \quad (8)$$

where

l_s and l'_r denote stator and rotor leakage inductances referred to the stator.

φ_{mq} and φ_{md}, which are useful quantities when representing saturation, denote the q- and d-axis components of the magnetizing flux. φ_{mq} and φ_{md} are defined by

$$\varphi_{mq} = M(i_{qs} + i'_{qr}) \quad (9)$$

$$\varphi_{md} = M(i_{ds} + i'_{dr}) \quad (10)$$

where

$$M = \frac{3}{2} L_{ms} \quad (11)$$

In which L_{ms} represents the stator magnetizing inductance.

The use of (5)-(8) helps to eliminate the currents in (9) and (10) as well as in the voltage equations given by (1)-(4), and if the resulting voltage equations are solved for the q-d axis fluxes, the following state equations can be obtained

$$p\varphi_{qs} = v_{qs} - \omega\varphi_{ds} + \frac{r_s}{l_s}(\varphi_{mq} - \varphi_{qs}) \quad (12)$$

$$p\varphi_{ds} = v_{ds} - \omega\varphi_{qs} + \frac{r_s}{l_s}(\varphi_{md} - \varphi_{ds}) \quad (13)$$

$$p\varphi'_{qr} = v'_{qr} - (\omega - \omega_r)\varphi'_{dr} + \frac{r'_r}{l'_r}(\varphi_{mq} - \varphi'_{qr}) \quad (14)$$

$$p\varphi'_{dr} = v'_{dr} - (\omega - \omega_r)\varphi'_{qr} + \frac{r'_r}{l'_r}(\varphi_{md} - \varphi'_{dr}) \quad (15)$$

The transient selected for verification of the proposed saturation modeling technique and the developed model is the self-excitation of the induction generator, where coherent results in the simulation are only achieved if saturation is taken into account by the model.

In this operating mode, the reactive power is provided by a three-phase capacitor bank. The voltage-current equations of the excitation capacitor are expressed in the arbitrary reference frame as [10]

$$p\,v_{qs} = \frac{1}{C_e} i_{qs} - \omega\, v_{ds} \quad (16)$$

$$p\,v_{ds} = \frac{1}{C_e} i_{ds} - \omega\, v_{qs} \quad (17)$$

C_e denotes the excitation capacitor.

If the saturation effect is not accounted for (the induction generator is assumed to be magnetically linear), the flux model, in the arbitrary reference frame, may be obtained by the use of the magnetizing flux expressions (9), (10), the set of conventional state equations (12)-(15) and the self-excitation equations (16)-(17).

However, the modeling of the self-excited induction generator under the assumption of magnetic linearity leads to unrealistic results. Figure 1 shows the influence of neglecting the saturation effect in the simulation and particularly in the computed stator voltage during the self-excitation process. It can be seen that the voltage reaches thousands of volts in less then half a second. This computed result cannot be obtained experimentally, because the generator output voltage is limited by the magnetic saturation phenomenon. The following section presents the technique proposed in this paper, which take into account the saturation effect in the modelling of induction machine.

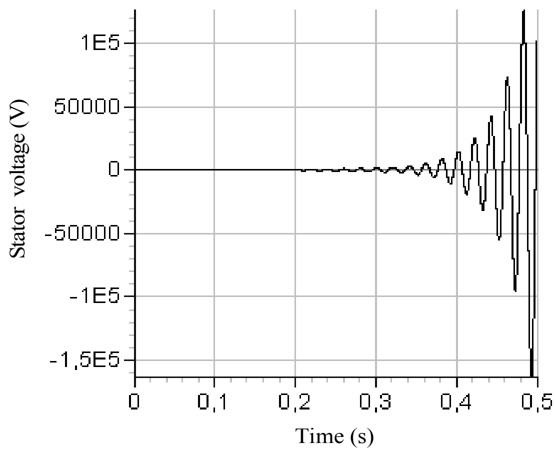

Fig. 1. Computed stator voltage during the self-excitation process when the saturation effect is neglected.

3 Saturation Model

The saturation effect in the main flux path of the induction machine is accounted for by use of the Saturation Degree Technique. As mentioned already, the principle of this accurate technique is mainly based on a function called "Saturation Degree Function" (SDF). Calculations involved for the elaboration and use of this technique into the flux model of the induction machine are set forth in this section.

3.1 Construction of the SDF

The construction of the SDF is carried out in the following way:
First, we perform the necessary measurements for the determination of the studied induction machine magnetizing curve.

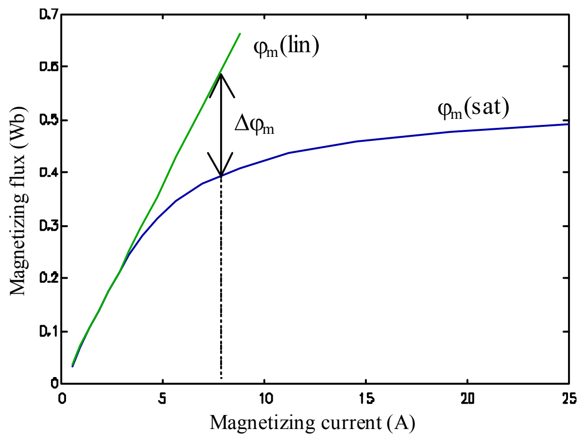

Fig. 2. Magnetization curve of the studied induction machine.

Then, we define for any value of the magnetizing current (I_m) the variation $\Delta\varphi_m$ as

$$\Delta\varphi_m = \varphi_m(lin) - \varphi_m(sat) \tag{18}$$

where:
φ_m *(sat)* represents the actual value (saturated) of magnetizing flux,
φ_m *(lin)* represents the value of the magnetizing flux under the assumption of the linearity (Fig. 2),
$\Delta\varphi_m$ represents the attenuation of the magnetizing flux with regard to the value that it would have under the assumption of linearity (i.e., by supposing that the machine does not saturate whatever the value of the magnetizing current is).
The quantities φ_m *(sat)*, φ_m *(lin)* and $\Delta\varphi_m$ as functions of the magnetizing current (I_m) are represented on figure 2.
Last, the saturation degree function, noted *F*, is defined as follows

$$F(\varphi_m(lin)) \equiv \frac{\Delta\varphi_m}{\varphi_m(lin)} \tag{19}$$

Fig. 3, shows the SDF curve of the test machine.

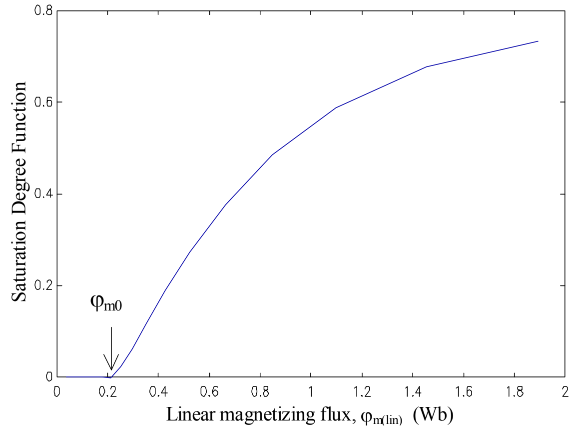

Fig. 3. Variation of the SDF as a function of the linear magnetizing flux.

3.2 Modeling of the SDF

The measured points on the curve of the SDF are then used to generate a continuous curve by use of an analytical model.

In order to maximize accuracy, a combination of two exponential functions is used in this model. A least-square optimization method is applied for the determination of the model coefficients.

This model writes as follows:

$$F = \begin{cases} F_0 = 0 & \text{if } \varphi_m \le \varphi_{m0} \\ F_1 \ne 0 & \text{if } \varphi_m > \varphi_{m0} \end{cases} \tag{20}$$

with

$$\begin{aligned} F_1 = {} & C_1[1 - \exp(-\lambda_1(\varphi_m(lin) - \varphi_m 0))] \\ & + C_2[\exp(\lambda_2(\varphi_m(lin) - \varphi_m 0) / (\varphi_m(lin) + \varphi_m 1)) - 1] \end{aligned} \tag{21}$$

3.3 Modified Expressions of the Magnetizing Fluxes

In the linear model of the induction machine appear two very significant quantities as for the modeling of saturation, namely, the components of axes q and d of the magnetizing flux, φ_{mq} and φ_{md}. The introduction of saturation into the dynamic model of the induction machine is essentially based on the knowledge of these two components in each operating point. These components are expressed in q-d variables by

$$\varphi_{mq}(sat) = \varphi_{mq}(lin) - \Delta\varphi_{mq} \tag{22}$$

$$\varphi_{md}(sat) = \varphi_{md}(lin) - \Delta\varphi_{md} \tag{23}$$

The resulting magnetizing flux $\varphi_m(lin)$ is related to its components $\varphi_{mq}(lin)$ and $\varphi_{md}(lin)$ by

$$\varphi_m(lin) = \sqrt{\varphi_{mq}(lin)^2 - \varphi_{md}(lin)^2} \qquad (24)$$

The variations $\Delta\varphi_{mq}$ and $\Delta\varphi_{md}$ are given by

$$\Delta\varphi_{mq} = \frac{\varphi_{mq}(lin)}{\varphi_m(lin)}\Delta\varphi_m \qquad (25)$$

$$\Delta\varphi_{md} = \frac{\varphi_{md}(lin)}{\varphi_m(lin)}\Delta\varphi_m \qquad (26)$$

According to the definition of the SDF, these expressions of $\Delta\varphi_{mq}$ and $\Delta\varphi_{md}$ can be written as:

$$\Delta\varphi_{mq} = \varphi_{mq}(lin)F(\varphi_m(lin)) \qquad (27)$$

$$\Delta\varphi_{md} = \varphi_{md}(lin)F(\varphi_m(lin)) \qquad (28)$$

Therefore, for given value of $\varphi_{mq}(lin)$ and $\varphi_{md}(lin)$ it is possible to determine $\Delta\varphi_{mq}$ and $\Delta\varphi_{md}$ from (24), (27) and (28).

The two components of the saturated magnetizing flux are obtained from (22–(24), (27) and (28), and can be written as

$$\varphi_{mq}(sat) = \varphi_{mq}(lin)[1 - F(\varphi_m(lin))] \qquad (29)$$

$$\varphi_{md}(sat) = \varphi_{md}(lin)[1 - F(\varphi_m(lin))] \qquad (30)$$

To determine the linear and saturated components of the magnetizing flux, we write their expressions in terms of q-d axis currents as:

$$\varphi_{mq}(lin) = M(i_{qs} + i'_{qr}) \qquad (31)$$

$$\varphi_{md}(lin) = M(i_{ds} + i'_{dr}) \qquad (32)$$

The expressions of the q-d axis currents in terms of saturated fluxes are written as follows

$$i_{qs} = \frac{\varphi_{qs}(sat) - \varphi_{mq}(sat)}{l_s} \qquad (33)$$

$$i_{ds} = \frac{\varphi_{ds}(sat) - \varphi_{md}(sat)}{l_s} \qquad (34)$$

$$i'_{qr} = \frac{\varphi'_{qr}(sat) - \varphi_{mq}(sat)}{l'_r} \qquad (35)$$

$$i'_{dr} = \frac{\varphi'_{dr}(sat) - \varphi_{md}(sat)}{l'_r} \qquad (36)$$

By substituting these equations for currents (33)-(36) in the expressions of the linear components of magnetizing fluxes (31) and (32), we obtain

$$\frac{\varphi_{mq}(lin)}{M} + \varphi_{mq}(sat)\left(\frac{1}{l_s} + \frac{1}{l_{r'}}\right) = \left(\frac{\varphi_{qs}(sat)}{l_s} + \frac{\varphi_{q'r}(sat)}{l_{r'}}\right) \qquad (37)$$

Eliminating $\varphi_{mq}(sat)$ in (20), by using of (5) and (6), we arrive at

$$\varphi_{mq}(lin) = L_q\left(\Delta\varphi_{mq}\left(\frac{1}{l_s} + \frac{1}{l_{r'}}\right) + \left(\frac{\varphi_{qs}}{l_s} + \frac{\varphi'_{qr}}{l_{r'}}\right)\right) \qquad (38)$$

In a similar manner as for $\varphi_{mq}(lin)$, the expression of $\varphi_{md}(lin)$ can be written as follows

$$\varphi_{md}(lin) = L_d\left(\Delta\varphi_{md}\left(\frac{1}{l_s} + \frac{1}{l'_r}\right) + \left(\frac{\varphi_{ds}}{l_s} + \frac{\varphi'_{qr}}{l'_r}\right)\right) \qquad (39)$$

where

$$L_q = L_d = \left(\frac{1}{M} + \frac{1}{l_s} + \frac{1}{l_{r'}}\right)^{-1} \qquad (40)$$

To deduce the expression of $\varphi_{mq}(sat)$, we use again (22) ((23) in the case of $\varphi_{md}(sat)$)

$$\varphi_{mq}(sat) = \Delta\varphi_{mq}\left(L_q\left(\frac{1}{l_s} + \frac{1}{l'_r}\right) - 1\right) + L_q\left(\frac{\varphi_{qs}}{l_s} + \frac{\varphi'_{qr}}{l'_r}\right) \qquad (41)$$

Using the definition of L_q as in (40), it can be seen that

$$L_q\left(\frac{1}{l_s} + \frac{1}{l_{r'}}\right) - 1 = L_q\left(\frac{1}{l_s} + \frac{1}{l_{r'}} - \frac{1}{L_q}\right) = -\frac{L_q}{M} \qquad (42)$$

Hence, (41) becomes

$$\varphi_{mq}(sat) = L_q\left(\frac{\varphi_{qs}}{l_s} + \frac{\varphi'_{qr}}{l_{r'}}\right) - \frac{L_q}{M}\Delta\varphi_{mq} \qquad (43)$$

In a similar manner as for $\varphi_{mq}(sat)$, the expression of $\varphi_{md}(sat)$ can be written as

$$\varphi_{md}(sat) = L_d\left(\frac{\varphi_{ds}}{l_s} + \frac{\varphi'_{dr}}{l_{r'}}\right) - \frac{L_d}{M}\Delta\varphi_{md} \qquad (44)$$

3.4 Equations of the Saturated Model

Finally, the flux model of saturated induction machine in the arbitrary reference frame is obtained by use of the expressions of linear and saturated components of magnetizing fluxes (38), (39), (43), (44) jointly with the set of conventional state equations (12)-(15) given above.

For self excited induction generator operating mode, used in the present paper for the verification of the developed model, the voltage-current equations of the excitation capacitor (16) and (17) must also be added to the developed model.

4 Experimental Verification

The experimental and computed results presented in this section (Fig. 4-9) describe the dynamic responses of the induction machine during the self-excitation process.

The machine used for the tests is a wound-rotor induction machine rated: 3.5kW, 220/380V, 14/8A, 50Hz, 4 poles.

The self-excited induction generator operating mode is obtained by driving the machine at synchronous speed, and then a three-phase capacitor bank is switched onto the stator terminals of the machine. The three-phase capacitor bank used in tests is 90µF.

Figures 4 and 5 illustrate the computed and measured stator voltage during the self-excitation process, the machine being driven at 1500 rpm. The computed and measured stator current are presented on figures 6 and 7. Figures 8 and 9 show the transient of the rotor current during the self-excitation process.

The comparison of these results shows a very good agreement between the experimentation and simulation.

The coherence between computed and measured results is very good, as well for dynamic conditions as for steady state. The amplitudes of the signals, their shapes as well as their duration present practically the same values for both simulation and experimentation.

The examination of all these results shows a very good agreement between the experimentation and simulation and thus confirms the validity of the developed model.

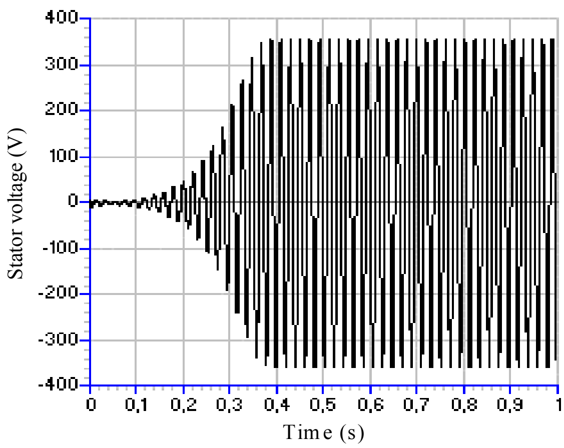

Fig. 4. Computed stator voltage during the self-excitation process at 1500 rpm and 90µF.

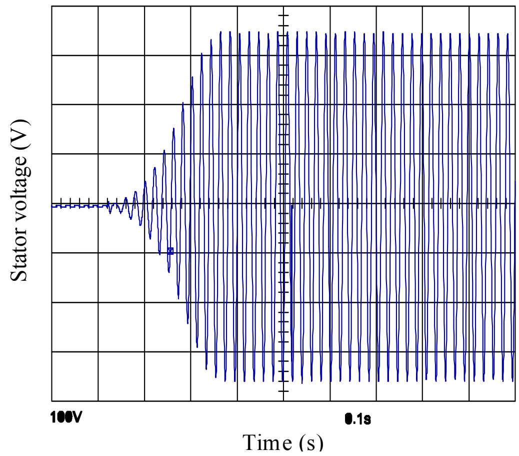

Fig. 5. Measured stator voltage during the self-excitation process at 1500 rpm and 90µF.

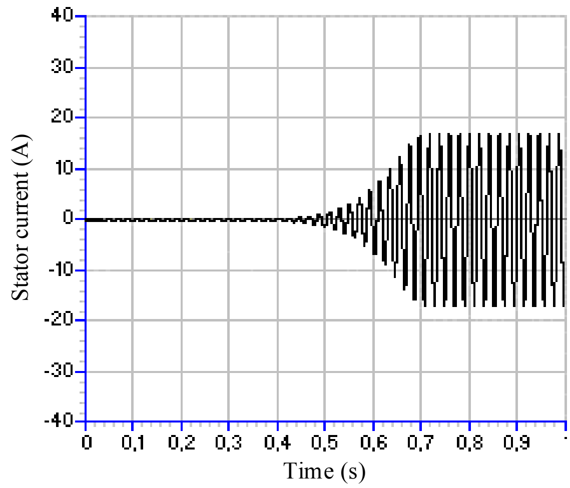

Fig. 6. Computed stator current during self excitation process at 1500 rpm and 90µF.

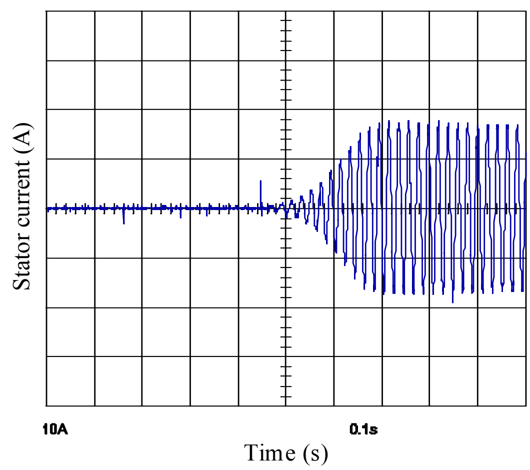

Fig. 7. Measured stator current during self excitation process at 1500 rpm and 90µF.

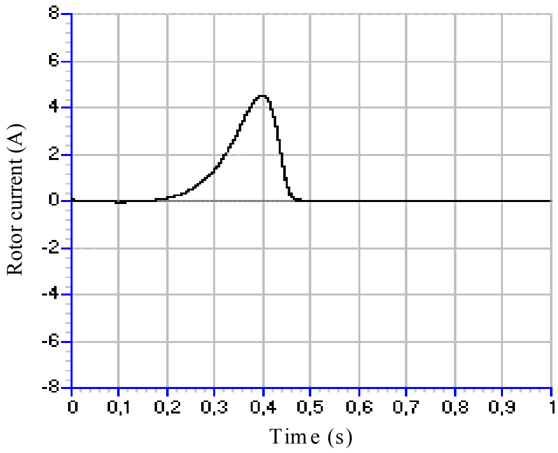

Fig. 8. Computed rotor current during self excitation process at 1500 rpm and 90μF.

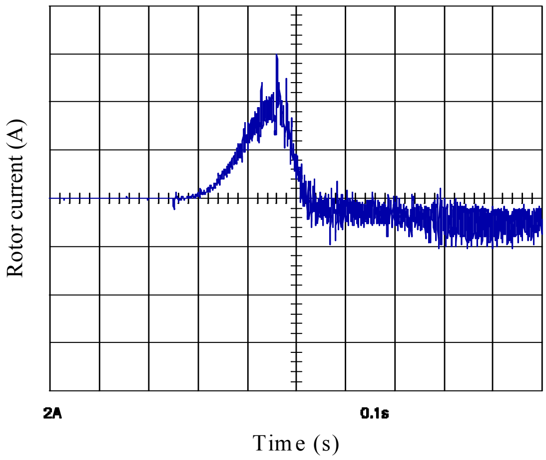

Fig. 9. Measured rotor current during self excitation process at 1500 rpm and 90μF.

5 Conclusion

The SDF technique for the modeling of saturation and the necessary calculations for its introduction in the induction machine dynamic model are presented.

Experimental and computed results that describe the transients of the voltage buildup process of the self excited induction generator are also presented.

The very good agreement between the experimental and computed results shows the precision that the SDF technique provides and thus confirms the validity of the developed saturated model.

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