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Voltage Sag Effect on Three Phase Five Leg Transformers

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***Abstract*—**The behavior of three phase five leg transformer under voltage sag is studied in this paper. This paper proposes a simple, practical model of a three phase-five leg, saturated transformer with accurate performance. Transformer saturation is produced when the voltage sag is recovered and it causes inrush current in transformer. Effects of voltage sag depth, duration and initial point on wave have been analyzed in this paper. Initial point on wave can produce maximum inrush current in five leg transformers while comparing with three leg transformers. The magnetic circuit symmetry of five leg transformer produces the more symmetrical shape of inrush current curves versus initial point on wave and sag duration than three leg transformer. The simulations show that current peak has a periodical dependence on sag duration and linear dependence on sag depth. Inrush current that is produced in three phase five leg transformer is higher than three phase three leg transformer.

***Keywords*—**Inrush current, three phase five leg transformer, saturation, voltage sag.

I. INTRODUCTION

SINCE 1960’s efforts have been devoted to develop computer model for transformers. In recent years, a number of detailed three phase transformer models appropriate for the analysis of transformers have been proposed. Most models are based on magnetic circuit analysis of the core and represented the transformer as a set of couple inductances. An initial effort for developing a model is described in [1] where inductances' matrix was derived for a three phase five leg transformer with constant leakage inductances. More general condition of core and leakage inductance saturation was derived with modeling L inverse matrix in [2]. One model for three phase three leg transformer in PSPICE was introduced in [3]. The transformer was modeled with variable characterization of its nonlinear magnetic behavior. Each leg was viewed as a separate magnetic circuit. A function is proposed to present core nonlinear behavior as a functional relationship between the magnetic potential in the leg and the flux through it. Behavior of three phase’s three leg transformers depends on different depth, duration; initial point on wave of symmetrical voltage sag was implemented in [4].

Modeling of three phase three leg transformer operating under different types of voltage sag in PSPICE is implemented in [3]. Unsymmetrical voltage sag effect on three phase three leg transformer and current peak relation with type of voltage sags, duration and depth were implemented [5]. In this paper behavior of a three-phase five-leg transformer under symmetrical and unsymmetrical voltage sags is investigated. For simulation purposes, a model is developed for 3-phase five-leg transformer in MATLAB/SIMULINK environment. The model is based on the Pspice model implemented for simulation of three phase three leg transformer [3]. Effects of symmetrical and unsymmetrical voltage sags are studied.

II. VOLTAGE SAG CLASSIFICATION

Depending on magnitude and phase angle, voltage sags are defined in seven types, denoted as A, B, C, D, E, F and G [6]. To clear the faults, circuit breakers usually act at zero crossing point of current. Number of steps for clearing the fault type special voltage recovery is considered for each type of voltage sags. The number of sequences for voltage recovery depends on the fault type and produces 14 subgroups [7]. To clearly show the voltage sag dependence on depth (h), duration $(\Delta t = t_i - t_f)$ and initial point on wave (ψ_i), the voltage sag and inrush current will be represented by $v(h, \Delta t, \psi_i)$ and $i(h, \Delta t, \psi_i)$ respectively, where t_i is the instant when the voltage drops, t_f is the instant when the sag ends and $(\psi_i = wt_i + \alpha)$.

III. VOLTAGE SAG SIMULATIONS

In order to produce different types of voltage sag a block is created in Matlab which takes the voltage sag parameters related to the different voltage sags (Fig. 1). All type of voltage sags are produced with changing voltage sag characteristics (sag duration, sag depth and initial point on wave).

IV. THREE PHASE FIVE LEG TRANSFORMER MODELING

The proposed three phase three leg transformer model [3] is re-simulated in MATLAB/SIMULINK environment. A 60kVA-380/220V-WyeG-WyeG three phase three leg transformer is used for simulation purposes. In the next step this model is developed to three phase five leg transformer.

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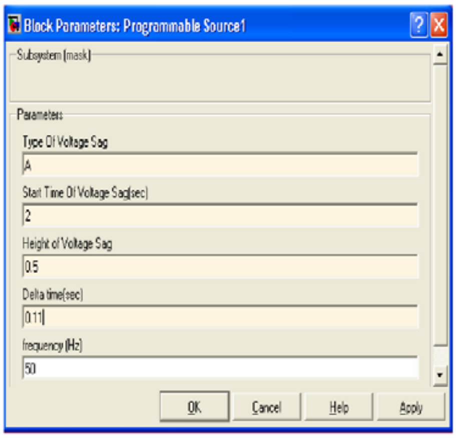

Block Parameters: Programmable Source1

Subsystem (mask)

Parameters

Type Of Voltage Sag: A

Start Time Of Voltage Sag(sec): 2

Height of Voltage Sag: 0.5

Delta time(sec): 0.11

frequency (Hz): 50

Fig. 1 MATLAB/SIMULINK block for simulation of different types of voltage sag

A. Electrical Circuit Model

The electrical relations of the transformer windings are:

$$\begin{aligned} u_{pk} &= (R_p + L_{dp}\frac{d}{dt})i_{pk} + e_{pk} \\ e_{pk} &= \frac{d\lambda_{pk}}{dt} = N_p\frac{d\phi_k}{dt} \\ u_{sk} &= (R_s + L_{ds}\frac{d}{dt})i_{sk} + e_{sk} \\ e_{sk} &= \frac{d\lambda_{sk}}{dt} = N_s\frac{d\phi_k}{dt} \\ (k &= a,b,c) \end{aligned} \tag{1}$$

where $i_{sk}, i_{pk}, u_{sk}, u_{pk}$ are the current and voltages of primary/secondary windings, ϕ_k is the core magnetic flux across the winding legs, $\lambda_{sk} = N_s\phi_k$ and $\lambda_{pk} = N_p\phi_k$ are the core magnetic flux linked by the primary/secondary windings. e_{pk} and e_{sk} are the induced primary/secondary voltage due to the core magnetic fluxes across the winding legs. L_{ds}, L_{dp}, R_s, R_p are constant leakage inductances and the winding resistances. N_p and N_s are the winding turns.

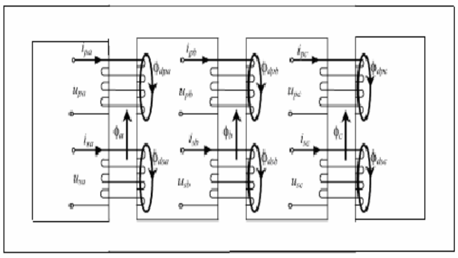


Fig. 2 Simulated Three Phase Five Leg Transformer

B. Magnetic Circuit Model

Fig. 3 shows the proposed magnetic equivalent circuit of the five-leg iron core of Fig. 2. This circuit provides the magnetic flux and current relations.

$$\begin{aligned} u_{pk} &= (R_p + L_{dp}\frac{d}{dt})i_{pk} + e_{pk} \\ e_{pk} &= \frac{d\lambda_{pk}}{dt} = N_p\frac{d\phi_k}{dt} \\ u_{sk} &= (R_s + L_{ds}\frac{d}{dt})i_{sk} + e_{sk} \\ e_{sk} &= \frac{d\lambda_{sk}}{dt} = N_s\frac{d\phi_k}{dt} \\ (k &= a,b,c) \end{aligned} \tag{2}$$

The primary magnetomotive force depends on the current $i_{epk} = i_{pk} - i_{pRk}$, where i_{pRk} is the current of the core-losses resistances, $f_k = \Re_k(f_k)$ is the magnetic potential across the k-legged branch. $\Re_k(f_k)$ is the nonlinear reluctances of the branch k, which depends on its own magnetic potential (f_k). $f_r = \Re_r\phi_r$ is the magnetic potential across the air branch and outer legs. Outer yokes nonlinear reluctances (R_1 and R_2) are added to air linear reluctance (R_3). Added yoke branch (R_r) is considered as: $\frac{1}{R_r} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$.

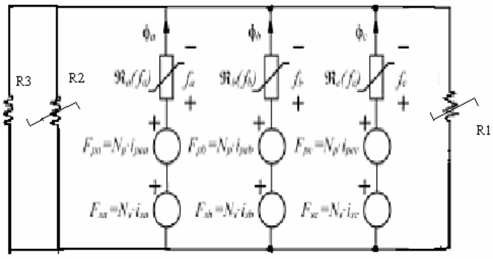


Fig. 3 Magnetic Equivalent of Three Phase Five Leg Transformer

Reluctance of the air path (R_3) has been considered constant. Five leg transformers have smaller reluctances value than three leg transformers. Fig. 3 shows that the air and outer leg reluctances have been added to magnetic equivalent circuit.

V. VOLTAGE SAG EFFECTS ON TRANSFORMER

Transformer is simulated under symmetrical voltage sag first. Effects of voltage sag duration, voltage sag depth and initial point on wave on transformer has been investigated where the transformer load is 0.8 p.u.

VI. VOLTAGE SAG TYPE A

Fig. 4 (a) shows three and five leg transformer's current in a voltage sag with following characteristics: $v(h = 0.4, \Delta t = 125T, \psi_i = 0)$. In these cases no peak current is occurred in all type of transformers when $\Delta t = nT$ and (n=1, 2, 3…).

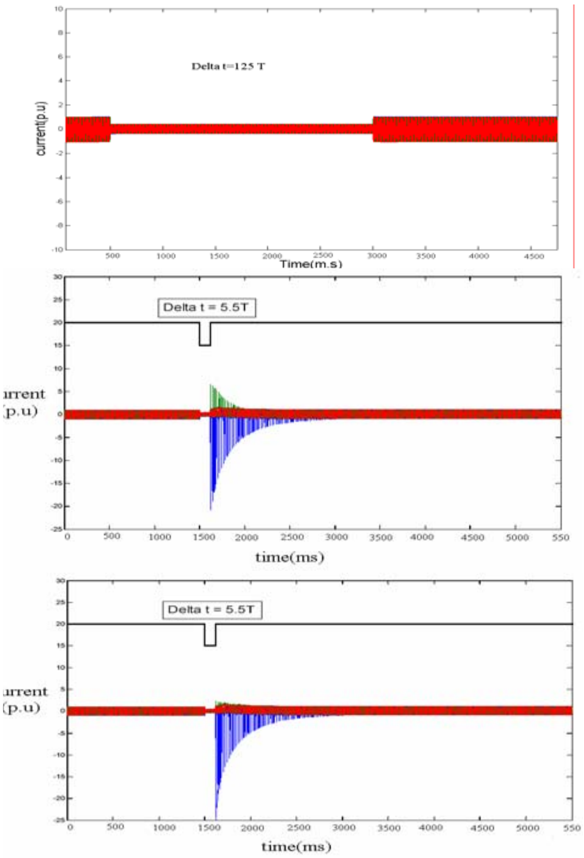


Fig. 4 (a) Three and Five Leg Transformer current for a sag type $v(h = 0.4, \Delta t = 100T, \psi_i = 0)$.(b) Three leg and (c) Five leg Transformer inrush current for a sag type $v(h = 0.4, \Delta t = 5.5T, \psi_i = 0)$

Fig. 4 (b) & (c) show three leg and five leg transformer inrush current in a voltage sag with the following characteristics respectively with $v(h = 0.4, \Delta t = 5.5T, \psi_i = 0)$. This figure shows that maximum transformer saturation is occurred when $\Delta t = nT + T/2$ and (n = 1, 2, 3,...). Moreover, inrush current magnitude in five leg transformer is higher than three leg one. Fig. 5 (a) and (b) show three leg and five leg transformer inrush current that is occurred in long term voltage sag with characteristics $v(h = 0.4, \Delta t = 150.5T, \psi_i = 0)$ respectively. This figure shows that the current peak has a periodical dependence on sag duration in symmetrical voltage sags when three and five legs are simulated. It means that $i_{peak}(h, \Delta t, \psi_i) = i_{peak}(h, \Delta t + nT, \psi_i)$. Simulation results also show that the magnitude of transformer inrush current in five leg transformers is higher than three leg transformers.

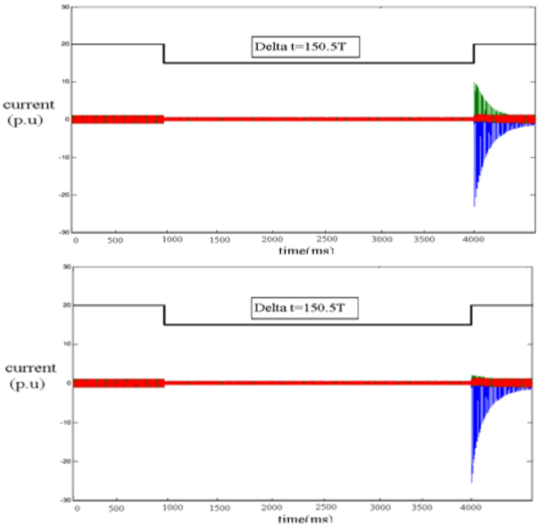


Fig. 5 (a) Three leg and (b) Five leg Transformer current for a sag type $v(h = 0.4, \Delta t = 5.5T, \psi_i = 0)$

A. Voltage Sag Duration Effect

Four series of voltage sags with different initial point on wave ($\psi_i = 0 \_ \psi_i = 270$) and voltage sag duration influence on transformer is considered here. Each series has constant initial point on wave and voltage sag depth and different voltage sag duration as:

$$\begin{cases} v_1(h = 0.4, \Delta t, \psi_i = wt_i = 0^\circ), \Delta t \in [5T...6T] \\ v_2(h = 0.4, \Delta t, \psi_i = 90^\circ), \Delta t \in [5T....6T] \\ v_3(h = 0.4, \Delta t, \psi_i = 180^\circ), \Delta t \in [5T...6T] \\ v_4(h = 0.4, \Delta t, \psi i = 270^\circ), \Delta t \in \left[5T....6T\right] \end{cases}$$

Fig. 6 shows clearly that maximum inrush current is occured when $\psi_i = 0^\circ$ or $\psi_i = 180^\circ$ and $(\Delta t = nT + 1/2)$ when n=1, 2, 3 etc. Inrush current curve versus sag duration in five leg transformer is more symmetrical than three leg one because of five leg transformer symmetry. Also inrush current's magnitude in five leg transformer is higher than three leg one.

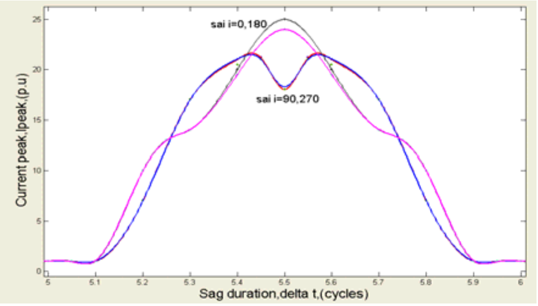


Fig. 6 Maximum inrush current versus different voltage sag duration in voltage sag type A with h=0.4

B. Voltage Sag Depth Effect

Influence of voltage sag depth is considered here with the following characteristics:

$$\begin{cases} v_1(h, \Delta t = 5.5T, \psi_i = 0^\circ), h \in [0...0.9] \\ v_2(h, \Delta t = 5.4T, \psi_i = 0^\circ), h \in [0...0.9] \\ v_3(h, \Delta t = 5.3T, \psi_i = 0^\circ), h \in [0...0.9] \\ v_4(h, \Delta t = 5.2T, \psi_i = 0^\circ), h \in [0....0.9] \\ v_5(h, \Delta t = 5.1T, \psi_i = 0^\circ), h \in [0.....0.9] \\ v_6(h, \Delta t = 5T, \psi_i = 0^\circ), h \in [0.....0.9] \end{cases}$$

Fig. 7 shows that voltage sag depth influence on maximum inrush current is almost linear.

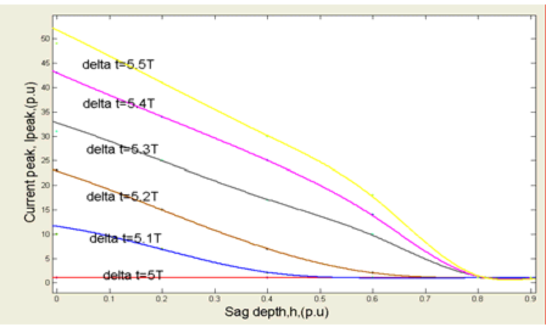


Fig. 7 Maximum inrush current versus different voltage sag depth (h=0-0.9)

C. Voltage Sag Initial Point on Wave Effect

To study initial point on wave influence, two series of voltage sags have been studied.

$$\begin{cases} v_1(h = 0.4, \Delta t = 5T, \psi_i = wt_i), t_i \in [0...T] \\ v_2 = (h = 0.4, \Delta t = 5.5T, \psi_i = wt_i), t_i \in [0...T] \end{cases}$$

Fig. 8 indicates that most unfavorable situations are occurred when

$\Delta t = nT + T/2$ and $\psi_i = w_{ti} = 0^\circ, 60^\circ, 120^\circ, 180^\circ, 240^\circ, 300^\circ$.

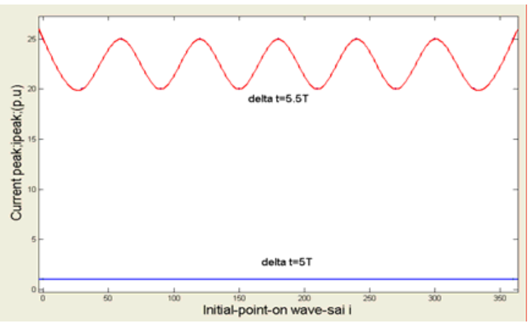


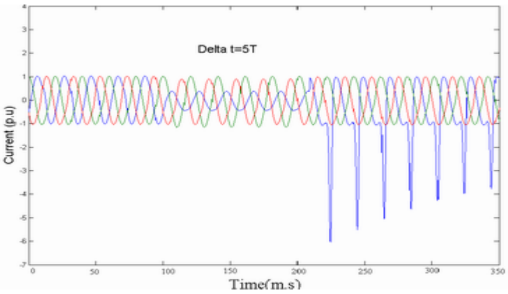
Fig. 8 Maximum inrush current versus different voltage sag initial point on wave

VII. UNSYMMETRICAL VOLTAGE SAGS

All types of voltage sags are simulated and voltage sag parameters variation influence on transformer's inrush current is studied. Effect of three types of voltage sag types (B, C and E_1) on transformer's inrush current are shown first. Effects of other types of voltage sag on inrush curent are studied in the following sections.

A. Voltage Sag Type B

Fig. 9 shows inrush currents when voltage sag type B with characteristcs (h=0.4, $\Delta t = 5T$) is applied to the simulated transformer. This figure shows that in opposite manner of symmetrical voltage sags, saturation is occured in transformer when sag duration is $\Delta t = nT$ (n=1, 2,...) and voltage type is B. Inrush current is produced when saturation is occured too.



$\Delta t = 5T$ Fig. 9 Three phase current for a sag type B: h=0.4

B. Voltage Sag Type C

Fig. 10 shows the transformer behaviour under voltage sag type C with characteristics (h=0.4, $\Delta t = 5.2T$). This figure shows that maximum current peak is occured when $\Delta t = nT + T/5$(n=1, 2, ...). In other manner for taking maximum inrush current in unsymmetrical voltage sag conditions, it is not essential that $\Delta t = nT$.

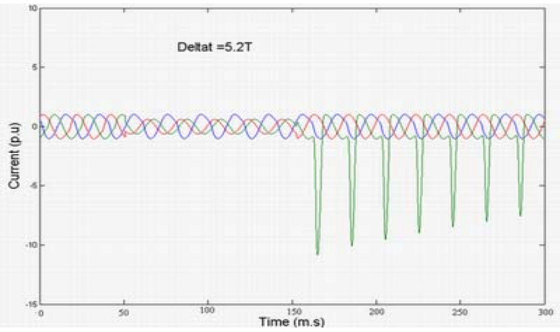


Fig. 10 Three phase current for a sag type C: h=0.4, $\Delta t = 5.2T$

C. Voltage sag type E_1

Fig. 11 shows the transformer behavior under voltage sag type E_1 with characteristics (h=0.4, $\Delta t = 5.4T$). It shows a case where one current peak is occured when the voltage recoveres. In three leg transformer one current peak is occured when the voltage drops and another current peak is produced when the voltage recoveres.

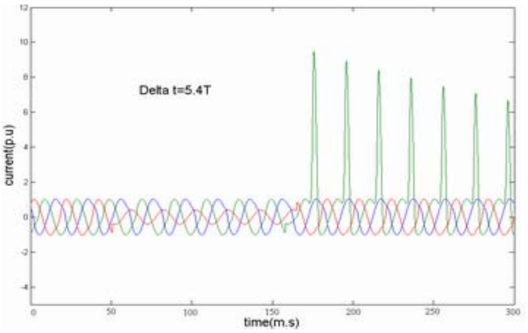


Fig. 11 Three phase current for a sag type E_1: h=0.4, $\Delta t = 5.4T$

VIII. VOLTAGE SAG DURATION INFLUENCE

Fig. 12 shows three phase current when duration of voltage sag type B is varied. It shows that saturation is occurred when $\Delta t = nT$ with n=1, 2,... while in voltage sag type A no current peak was occurred. In opposite manner of type A, maximum current peak is occurred when $\Delta t = nT + T/5$.

The transformer behavior caused by sags type E (E_1 and E_2) is shown in Fig. 13 where the results are similar to type B. In this case, it is not required that $\Delta t = nT$ in order to acheive maximum inrush current in unsymmetrical voltage sag conditions. This figure shows that transformer behavior is periodic (ie the same behavior is observed for $\Delta t = 5T$ to $\Delta t = 5.5T$ and $\Delta t = 5.5T$ to $\Delta t = 6T$).

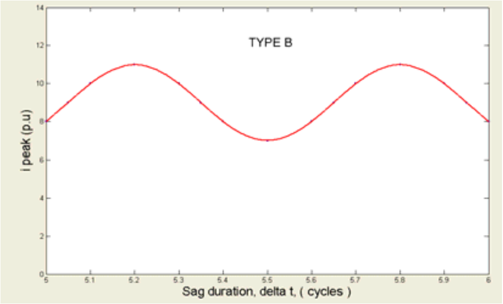


Fig. 12 Sag duration influence on the current peak for sag type B with h=0.4

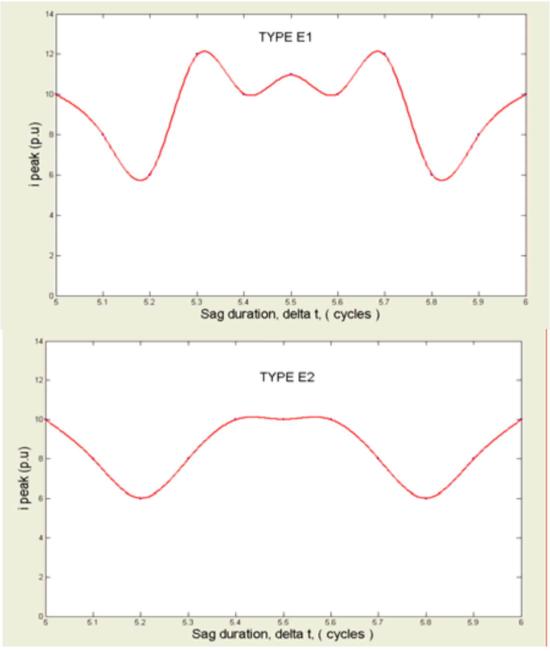


Fig. 13 Sag duration influence on the current peak for sag type E_1 and E_2 with h=0.4

IX. CONCLUSION

The behavior three phase five leg transformers under different types of voltage sag is investigated in this paper. Symmetrical and unsymmetrical voltage sags are simulated and applied to the transformer model which was implemented in MATLAB_SIMULINK environment. In order to produce different types of voltage sag a block is created in Matlab which takes the voltage sag parameters related to the different voltage sags. Transformer saturation, dc magnetic flux variations, inrush current peak etc are studied using various simulations. It is shown that the voltage sag depth has direct role on increasing the current peak when the voltage recovers. However, the current peak and saturation are highly depended on the initial point on wave during recovery process. It is shown that no saturation is occurred when $\Delta t = nT$ and maximum current peak is produced when $\Delta t = nT + T/2$. According to the simulation results, voltage sag depth influence on inrush current peak is almost linear. Furthermore, initial point on wave can produce higher inrush current in five leg transformers as compared with three leg transformers. Simulation results show more symmetrical shape of inrush current curves versus initial point on wave and sag duration as compared with three leg transformer.

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