Diagnostics of Oil-Paper-Insulations Using Relaxation Currents

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Abstract: The dielectric response of oil-paper-models was measured with relaxation currents, also known as Polarisation and Depolarisation Currents (PDC). The measurements cover the influences of moisture content in cellulose, a wide temperature range, insulation geometry, ageing state and measurement voltage. At multilayer insulations the dielectric response appears to be nonlinear, i.e. modeling with equivalent circuits according to Debye is hardly possible. The transient behavior of oil conductivity was found to be the reason for nonlinearities and is explored more exactly. The obtained set of measurement data was applied on power transformers to determine water content in cellulose.

INTRODUCTION

Reliable assessment of the ageing state of high voltage power transformers is a basic condition for a failsafe and cost-saving service. Cost pressure of a free electricity market forces the power utilities to continue service even if the estimated life time is exceeded. For a safe service and low default risk enhanced diagnostic methods to evaluate the ageing state are necessary. One ageing indicator is water content in the solid part of the insulation (paper, pressboard). Water is an ageing product and accelerates the further deterioration of cellulose through depolymerisation. Dielectric methods applied on power transformers measure a superposition of conductivity and polarisation phenomena. Moisture in paper/pressboard is obtained by a comparison of measurement data to measurements on oil-paper-insulations with known moisture content. Previous investigations don't cover the whole temperature range occurring at power transformers and don't pay special attention to the properties of oil conductivity. Dependable and extensive comparison data to analyse onsite measurements involving a wider temperature range and the phenomena of oil conductivity are the goal of this investigation.

POLARISATION AND CONDUCTIVITY

Macroscopic polarisation The main insulation of power transformers consists of multiple layers of paper or pressboard (cellulose) immersed in oil separated by oil ducts. The time depending polarisation *P(t)* is caused by electronic, ionic, dipole, space charge and interfacial polarisation and is called dielectric response. At measurement times longer than 1 s the polarisation by space charge and at boundaries (interfacial polarisation) dominate the dielectric response. Interfacial polarisation is only effective because of the different conductivities of oil ($10^{-13} < \delta < 10^{-10}$ S/m) compared to cellulose ($10^{-16} < \delta < 10^{-13}$ S/m). Thus under an electric field ionic charge carriers in oil will become deposit at interfaces to cellulose and form a charged cloud. The dielectric properties of oil and cellulose and its polarisation phenomena depend on ageing state and water content. Sophisticated analysis methods can determine the water content of cellulose (paper / pressboard).

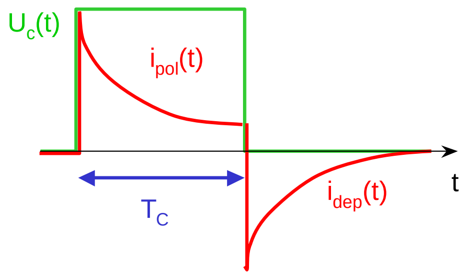

Fig. 1: Relaxation currents during and after charging with a DC voltage U_C for a time T_C

At Fig. 1 the polarisation current (or charging current) flows, if a DC voltage is applied on the insulation. Under application of a short circuit the discharging or depolarisation current flows.

Conductivity Polarisation processes are superimposed to a dc conductivity σ_0, which shouldn't depend on time. It represents the movement of free charge carriers in cellulose and in oil.

Insulation oil used in power transformers consists of saturated hydrocarbons as paraffin and naphtene and can neither conduct current nor solute water. External ingredients such as residues from refinery, pollution and particularly ageing products enable the oil to conduct ionic current and also to solute water. The dominating contribution is made by carbonic acids, an ageing product of oil oxidation. Carbonic acid and water can dissociate to ions and hence increase conductivity considerable.

$$H\text{-}COOH + H_2O \rightarrow H\text{-}COO^- + H_3O^+ \quad (1)$$

H-CO is the aldehyde group of a carbonic acid. It shall be pointed out, that only a combination of water and a dissociable substance will increase conductivity measurable. Some authors found out, that water won't increase conductivity. It will anyway increase conductivity because of its self-dissociation, but this is hardly measurable. In a combination with a dissociable substance like acid the conductivity will increase considerable.

Interpretation of measurement data Relaxation measurement results are usually presented in a log/log scale with charging and discharging current over time as depicted in Fig. 2. According to the common inter-pretation scheme the first 1-100 seconds are influenced by oil conductivity. The end value of polarisation current is determined by the pressboard resistance and therefore by moisture.

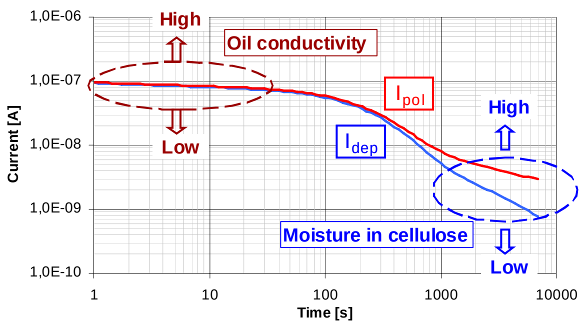

Fig. 2 Interpretation of PDC measurement data

The pressboard resistance can be extracted from the difference of polarisation and depolarisation currents.

$$R_{PB} \approx \frac{U_C}{I_{Pol} + I_{Depol}} \quad (2)$$

Dielectric response in time domain To cover the physical phenomena of relaxation and conductivity currents in mathematical expressions, one may start with the famous equations of Maxwell. The field *E(t)* generates a current density *J(t)* as a sum of conduction and displacement currents.

$$J(t) = \sigma_0 E(t) + \frac{dD(t)}{dt} \quad (3)$$

The electric displacement *D(t)* in a dielectric consists of a part that is also present in vacuum and the macroscopic polarisation *P(t)* [1].

$$D(t) = \varepsilon_0 E(t) + P(t) \quad (4)$$

The polarisation *P(t)* depends on the polarisability or susceptibility χ of the material, that covers all kinds of polarisation processes in a dielectric. It is zero for ideal vacuum.

$$P(t) = \varepsilon_0 \chi(t) E(t) \quad (5)$$

The relation of susceptibility χ to relative permittivity ε_r is given by:

$$\chi(t) = 1 + \varepsilon_r(t) \quad (6)$$

The dielectric response function can be defined as the derivative of ε_r.

$$f(t) = \frac{d\chi(t)}{dt} = \frac{d\varepsilon_r(t)}{dt} \quad (7)$$

A step response function *1(t)* as a unit step for the electric field strength E_0 can be applied on the dielectric.

Then polarisation processes in time domain develop as follows:

$$P(t) = E_0 \varepsilon_0 \chi(t) 1(t) \quad (8)$$

According to [1] it is possible to derive any time dependent polarisation *P(t)* for any time dependent excitation *E(t)*.

$$P(t) = \varepsilon_0 \chi(0) E(t) + \varepsilon_0 \int E(\tau) f(t-\tau) d\tau \quad (9)$$

A permittivity for very high frequencies can be defined as:

$$\varepsilon(\infty) = 1 + \chi(\infty) \quad (10)$$

The combination of (3), (4), (7) and (10) gives:

$$J(t) = \sigma_0 E(t) + \varepsilon_0 E(t)[\varepsilon(\infty)\delta(t) + f(t)] \quad (11)$$

With a charging voltage step *δ(t)* of magnitude U_C at time $t = t_0$ and a geometric capacitance C_0 the polarisation current can be written as:

$$I_{pol}(t) = C_0 U_C \left[\frac{\sigma_0}{\varepsilon_0} + \varepsilon(\infty)\delta(t) + f(t) \right] \quad (12)$$

In practical cases the middle part with *ε(∝)* cannot be measured because of its very short duration and very large dynamic range [1].

If a short circuit is applied on the measurement object at charging time $t = t_c$ the depolarisation current i_{dep} can be recorded.

$$I_{Depol}(t) = -C_0 U_C [f(t) - f(t + t_C)] \quad (13)$$

The very short discharging current pulse depending on $C_o[\varepsilon(\propto)]$ cannot be measured and is neglected in (13). A complete discharging of the dielectric is necessary before any measurement.

MEASUREMENT SETUP

Meter for relaxation currents A very sensitive ampere meter (electrometer) is needed to measure relaxation currents. Within this research work a Keithley 6517A was used. This electrometer is also applicable as a voltage source and therefore very suitable for PDC measurements. The specifications are: Resistance measurements up to 10^{16} Ω, Current measurement range 1 fA to 20 mA, build in 1 kV voltage source.

Measurement cell for cellulose samples To avoid disturbances by parallel current paths a guarded measurement cell is needed. The measurement cell was aditionally shielded by a climatic chamber as depicted in Fig. 3. For automated measurements a control and data acquisition software was programmed in HP VEE®.

Fig. 3 Measurement cell in climatic chamber

Measurement cell for oil conductivity Measurements on dielectric liquids are very sensitive to disturbances. A guarded measurement cell derived from IEC 247 was build. The gap between the cylindrical electrode is 2 mm. The capacitance in air C_0 is 59,5 pF, obtained from calculations and verified by measurements.

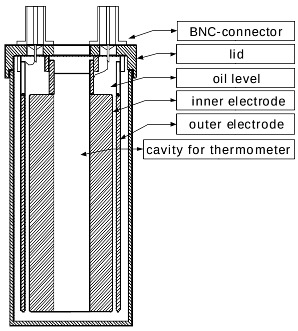

Fig. 4 Guarded coaxial measurement cell

The oil conductivity was calculated with the following equation:

$$\sigma(t) \cong \frac{\varepsilon_0}{U_C C_0} i(t) \qquad (14)$$

MEASUREMENT OBJECTS

To obtain measurement data for different moisture content, geometry condition, insulation temperature and measurement voltage models made by pressboard and paper were used. Nynas Transformer Oil Nytro 10 GBN with a moisture content of < 20 ppm served as insulation oil. Ageing was done by heating of oil immersed cellulose at 130°C for 3 months. The depolymerisation degree of aged samples with high water content was decreased from 1000-1400 to 200-400.

Table 1 Investigated cellulose samples and models

	Pressboard	Paper
New, moisture content [%]	0,6 / 1,0 / 2,0 3,0 / 4,0	0,6 / 1,0 / 2,0 3,0 / 4,0
Aged, moisture content [%]	0,6 / 4,0	0,6 / 4,0
Geometric condition (pressboard to oil)	17 % and 30 %	

To investigate oil conductivity different types of oil were measured like described in the following table. The water content was measured with coulometric Karl Fischer Titration $C_{W,KFT}$ and with a capacitive Probe made by Vaisala (HMP228) $C_{W,rel}$. The neutralisation number *NN* gives the acidity of the oil in mg KOH / g oil.

Table 2 Investigated oil samples

Type	Condition	$C_{W,KFT}$	$C_{W,rel}$	NN
Shell Diala D	new, wet	30 ppm	32 %	-
Aged	aged, wet	59 ppm	32 %	0,09
Aged	aged, dry	< 5 ppm	1 %	0,09

RESULTS AND DISCUSSION

Influence of Moisture Content

The following figures show the polarisation and depolarisation currents under the influence of moisture in pressboard at an insulation temperature of 23°C. A clear dependence on moisture content is visible, the amplitude increases with moisture and the currents reach their final value faster. Depolarisation currents show the same initial amplitude as polarisation currents. They decrease faster at samples with a higher moisture content. The electrometers settling time of 2,5 s causes errors during the first seconds of the measurement.

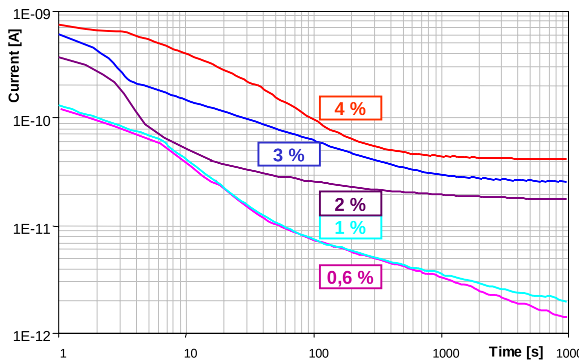

Fig. 5 Polarisation currents under the influence of moisture

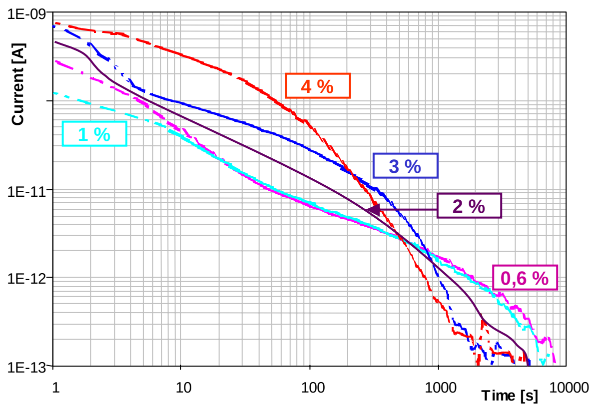

Fig. 6 Depolarisation currents under the influence of moisture

Influence of insulation temperature

Out of the large quantity of measurement results Fig. 7 depicts exemplarily the massive influence of temperature on PDC at a moisture content of 4 %. Hence the conductivity of pressboard and oil will increase significantly with temperature, the currents increase too. Polarisation processes occur much faster, the final value as an equivalent for pressboard resistance and moisture content in paper is reached earlier with increasing temperature.

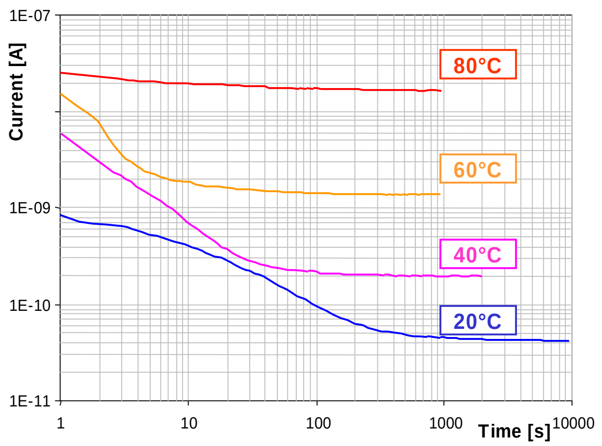

Fig. 7 Polarisation currents for 4 % moisture content at different temperatures

Power transformers are operated at elevated temperatures of 30-80°C middle oil temperature. Because of the intense influence of insulation temperature a reliable temperature compensation is essentially needed to interpret measurement data.

To distinguish between the influence of moisture and of insulation temperature is hardly possible. Thus a reliable temperature measurement is of utmost importance.

Pressboard versus Paper

Fig. 7 shows the polarisation and depolarisation currents of pressboard compared to kraft paper at the same moisture content of 4 %. The end values, reflecting resistance and moisture content are the same. The differences in the shape of the curve (time range between 5 and 400 s) are due to interfacial polarisation processes that have a more evident influence on pressboard models.

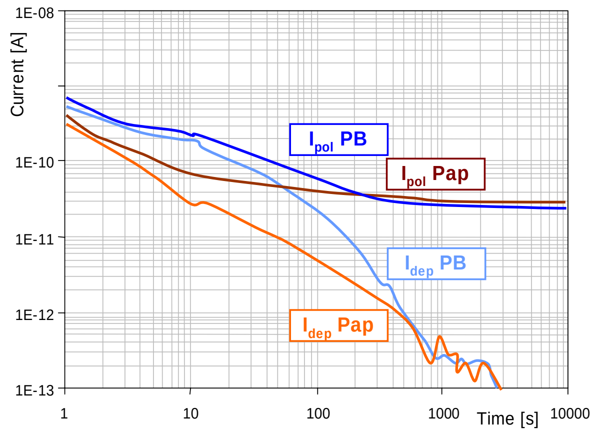

Fig. 8 Polarisation and depolarisation currents of pressboard and paper at moisture content of 4 %

Influence of ageing state

Fig. 9 compares PDC at new and aged pressboard. The initial amplitude and the end values are higher for aged materials. This may be explained by ageing by-products in cellulose, which increase the conductivity additionally to moisture. These ageing byproducts are e.g. carbonic acids. Cellulose absorbs them even if they originally descend from the oxidation of oil. This behaviour is published in [2] too.

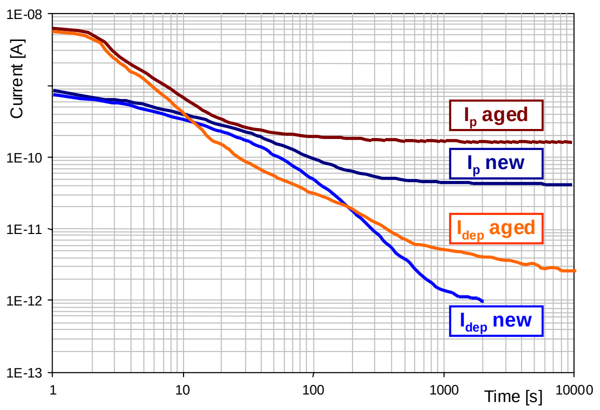

Fig. 9 Comparison of PDC for new and aged pressboard with 4 % moisture content

Measurement of oil conductivity

Fig. 10 shows the conductivity versus time for the different oils. It is obvious that moisture *and* ageing (carbonic acids) increase conductivity. Especial at new and dry oils the conductivity follows a step function, it decreases with measuring time. This effect can be explained with space charges. Under the influence of an electric field the ions travel to the electrodes and form a charged cloud. This cloud hinders the ions in travelling to the electrodes and thus decreases the bulk conductivity. With a low measurement voltage of 10 V (means field strength of 5 V/mm) this effect occurs at later times (t > 8000 s) as at higher voltages of 140 V (field strength 70 V/mm). So oil conductivity depends on measurement time and field strength.

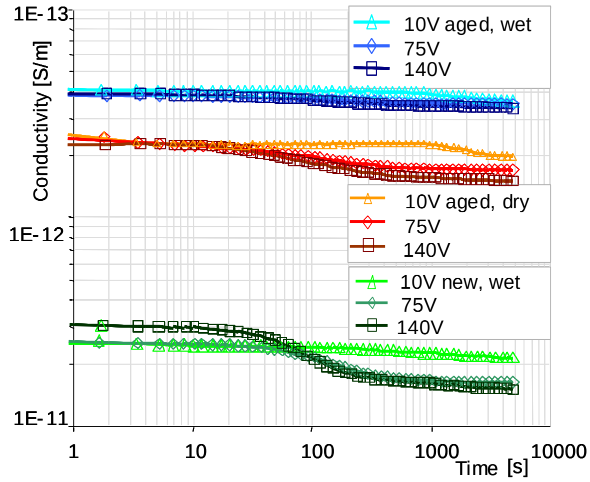

Fig. 10 Oil conductivity in time domain under different conditions

Influence of geometry

Fig. 11 depicts the influence of insulation geometry G on polarisation currents. G0 means only pressboard (100 %), G1 contains an amount of 33 % barriers and G2 20 % barriers to oil. With an increasing portion of insulation oil (oil duct) the longer the current remains nearly constant (at G2 up to 20 s). This is caused by interfacial polarisation at the interfaces between oil and pressboard and by the transient behaviour of oil conductivity. Furthermore it is clearly visible, that the main influence is the *existence* and not the *width* of an oil duct.

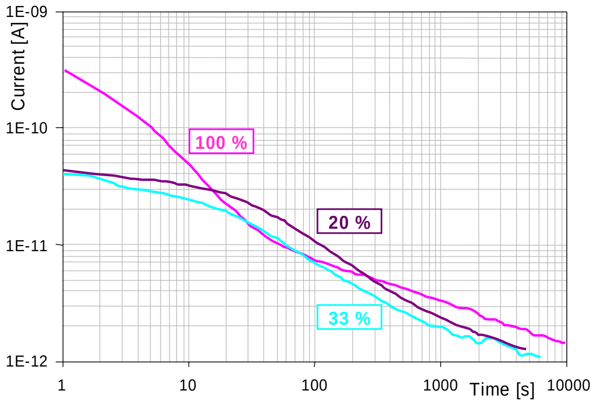

Fig. 11 Influence of insulation geometry on polarisation currents at 0,6 % moisture

Linearity of dielectric response

It is common to describe polarisation processes in oil-paper-insulations by a linear model of R-C-networks as originally published by Debye and very often replicated [3], see Fig. 12. Anyway some authors observed a nonlinear behavior of multilayered oil-paper-insulations [4], [5].

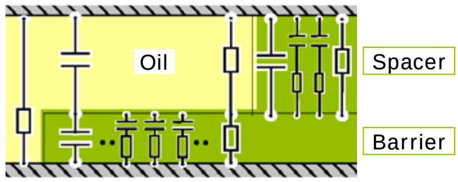

Fig. 12 Linear model of a multilayer insulation [4]

Fig. 13 shows a comparison of polarisation currents at pressboard models with and without oil duct. The relation “1” (red dashed line) means a linear behavior. This is more or less given for a pressboard insulation without an oil duct. Due to the dependence of oil conductivity on time and field strength the behavior of an insulation with oil duct is nonlinear and cannot be modeled according to Debye (brown line). The nonlinearities increase with field strength and could be neglected only for values lower then 10 V/mm.

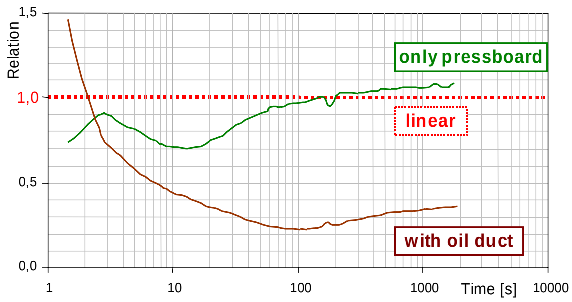

Fig. 13 Nonlinear behaviour of oil-paper-insulations with multiple layers at a field strength of 100 V/mm with and without oil duct

APPLICATION ON POWER TRANSFORMERS

The gathered data shall enable the user to analyse data measured at power transformers and estimate moisture in cellulose. As an example this analysis is shown at the following Fig. 14.

The measurement curve “unknown” is compared to a curve with known moisture content (1 %). The deviation is only small. Therefore the moisture content of the measured insulation system should be around 1 %.

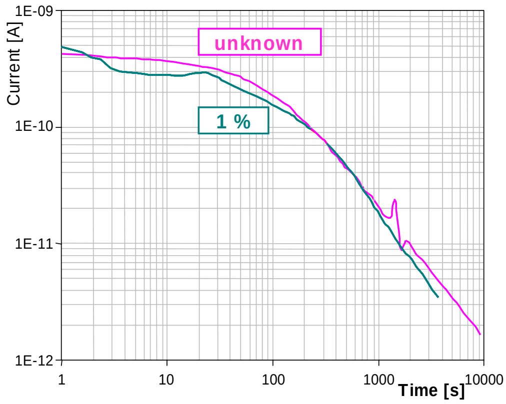

Fig. 14 Measurement analysis by comparison of depolarisation currents

CONCLUSIONS

The goal of this investigation is a data pool of relaxation currents to evaluate onsite measurements at power transformers. Models made by oil immersed paper and pressboard with the parameters moisture content, insulation geometry and ageing state were used and measured at different insulation temperatures and measurement voltages.

(1) Moisture clearly changes the relaxation currents at longer measurement times. The first amplitude is governed by oil conductivity.

(2) Insulation temperature increases the conductivity of cellulose and oil. The polarisation processes occur much faster. A distinction between the influence of moisture and of temperature is hardly possible. Thus a reliable temperature measurement is of utmost importance.

(3) Beside some changes in the polarisation process there is no noticeable difference in the dielectric response of Kraft paper compared to pressboard.

(4) Ageing increases the initial and end amplitudes for polarisation and depolarisation currents. This might be explained by ageing byproducts like carbonic acids present in cellulose.

(5) The goal for the investigations on oil conductivity was a more reliable interpretation of measurement data obtained from dielectric diagnostic methods. Therefore oil conductivity with its nature, special phenomena and the influences on dielectric methods was explored. Oil conductivity is made by ions made from dissociation of ageing products like carbonic acids and water. The conductivity phenomenon depends on moisture, ageing state, measurement time, field strength and of course temperature. Best results were obtained for a field strength below 5 V/mm and in a time range of $1\ s < t < 20\ s$.

(6) The implementation of oil ducts leads to a multilayer insulation and therefore the macroscopic polarisation becomes dominated by interfacial polarisation. Rather the existence of oil ducts then their geometry causes the major influence.

(7) Oil conductivity depends on time and field strength and causes therefore a nonlinear dielectric response. A linear modelling by means of R-C-networks according to Debye is hardly possible.

(8) The results obtained from the measurements shall be implemented in a software to analyse onsite measurement data and evaluate the water content and therefore ageing state of oil-paper-insulations in power transformers.

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