Aspects and considerations for accurate measurement of very high efficiency

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***Abstract* – The requirement of very high efficiency has been a trend in power supply design in the past few years. Beside usage of proper topologies and highly optimized rectifier design, accurate measurement of efficiency becomes crucial. When approaching efficiencies of 96% and more towards 98%, even small measurement tolerances lead to significant different results. Also reproducibility of measurement results becomes a key factor for designing such high efficient rectifiers. During the design, typically small steps for improvement of the efficiency are being taken. In order to distinguish if such a step for improvement is successful or not, the measurement method for high efficiency becomes key. Using traditional measurement methods and approaches like for the efficiency range around 93% and below are not applicable and suitable any more. In the past, measurement of a rectifiers' efficiency might have been considered as a simple task to be done in any lab executed by any technician. With today's high efficiency rectifiers, proper measurement of the efficiency became very difficult and cannot be done without deep knowledge of influencing parameters for test setup, instruments and execution. The risk for wrong results is extremely high if the measurement is not done properly.**

Therefore, this paper describes aspects and considerations for measuring very high efficiency in an accurate way. The focus is set on two different measurement setups which are explained in detail. Furthermore, the advantages and disadvantages of different test equipment are evaluated. Finally, the different measurement methods are compared.

I. INTRODUCTION

The efficiency of power supplies (e.g. Telecom rectifiers) increased rapidly during the past years. Therefore, an adequate efficiency measurement became necessary. It has to be made sure that all design improvements can be evaluated in a proper and reproducible way. Now, the question is why exactly an accurate efficiency measurement is needed? This question can best be answered with a counter question which will be derived from the following example. The efficiency of a rectifier can be boosted from 96% to 96.1% with a concrete design change. This relates to a decrease of the input power from 1419.2W to 1417.7W for this rectifier. The reduction of the needed input power by 1.5W equals a reduction of 0.11%. The power analyzer used does have an accuracy of +/-0.2%, which is a standard value for a power analyzer. Now, the counter question is how can be ensured that it really is the desired design improvement which is measured and not just a difference caused by the equipments inaccuracy?

In order to explain different techniques for determining the efficiency η, the following simple equation is used.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{loss}} \tag{1}$$

The equation shows there are two options for calculating the efficiency. First, knowing the output power P_{out} and input power P_{in} or secondly knowing the output power and the power losses P_{loss}. This implies that the output power always has to be known and the final decision is whether the input power or the power losses are being measured.

When measuring an AC input power, it is crucial to also consider the power factor. Modern rectifiers do usually have an integrated active power factor corrector (PFC) so that the power factor is 0.99. Thus, the remaining reactive power is caused by the EMI input filter only. Depending on the reactive power drawn by a rectifier, equation (1) would not be applicable anymore since the power factor also has to be added.

II. MEASUREMENT TECHNIQUES

a) Measurement of input and output power

(1) Measurement of AC input power

There are two ways of measuring the input power. The first option is to measure the input voltage and the input current and multiply them. However, this method is not applicable if reactive power is present because the measurement error would be too big. The second option is to use a power analyzer which will directly calculate the input power while excluding reactive power. Since the measurement of the input power by using a power analyzer is easier, more comfortable and reduces reading errors, only power analyzers are being considered in the following paragraphs.

(2) Measurement of DC output power

In order to measure the DC output power the first option would also be the use of a power analyzer. The second option would be the use of a multimeter. But since the accuracy of certain multimeters for DC conditions is much better compared to power analyzers, the use of multimeters (and/or shunts) is being considered in the following paragraphs. Furthermore, the measurement of a large output current of e.g. 50A with a terminal of the power analyzer will cause the terminal to heat up because of the conduction losses. Using an external shunt with an additional multimeter will minimize the self heating effect and thus also the effect on the measurement results.

(3) Measurement equipment

The next paragraph will give an overview of different measurement equipment which is widely used for measuring rectifier efficiency. The different equipment is briefly explained based on its basic functions. Advantages and disadvantages as well as its influence on measurement accuracy are pointed out.

i. Power Analyzer

A power analyzer is able to determine the input power by computing the measured input voltage and current while also considering the power factor at the same time. Two things are of importance for determining the power analyzers accuracy σ_{PA}. The accuracy of the reading $f_{reading}$ and the accuracy of the selected measurement range f_{range}. The accuracy of the power analyzer can be determined by using equation (2):

$$\sigma_{PA} = f_{reading} + \frac{f_{range} \cdot range}{reading} \qquad (2)$$

Besides selecting a power analyzer with a high accuracy the user can also select equipment with a small grading of the measurement ranges. For instance if 15A are measured the resulting accuracy based on a 20A range is much better compared to a 30A range.

Below table shows some accuracy data for different power analyzers later used for the calculations.

Device	**Accuracy on**		**Possible range for**	
	Reading	**Range**	**Voltage**	**Current**
Yokogawa WT1600	0.10%	0.05%	300V	10A, 20A
Infratek 106A	0.10%	0.01%	300V	10A, 30A
Yokogawa WT3000	0.02%	0.04%	300V	10A, 20A

Tab.1 Data of different power analyzers used for accuracy calculation for a line frequency from 45Hz to 66Hz

Fig.1 Power analyzer (Yokogawa, WT3000)

ii. Digital multimeter

In general there are two different types of digital multimeters available; hand held and table multimeters. Hand held multimeters are very easy to handle but their accuracy is relatively low. Their accuracy σ_{HMM} depends on their reading accuracy $f_{reading}$ and their number of least significant digit (LSD). The LSD represent the magnitude of uncertainty due to internal offsets, noise and rounding errors of the analog-digital-converter and the analog circuits of the hand held multimeter. The accuracy is influenced by the number of LSD n_{digit} and as well by the maximum number of analog-to-digital converter counts during full conversion $n_{resolution}$. Therefore, the total accuracy of a hand held multimeter can be determined as shown in equation (3) [1].

$$\sigma_{HMM} = f_{reading} + \frac{n_{digit} \cdot 100\%}{n_{resolution}} \qquad (3)$$

The hand held multimeter used for the final accuracy calculation is shown in figure 2. Table 2 shows the data used to determine the accuracy of this certain hand held multimeter for 600mV and 60V range.

Device	**Accuracy on reading**	**Number of LSD**	**Resolution**
Fluke 80 series V	0.3% @ 600mV 0.1% @ 60V	1	6000

Tab.2 Data of one hand held multimeter used for accuracy calculation


Fig.2 Hand held multimeter (Fluke, 80 series V)

Table multimeters are well known and their accuracy is much better compared to a hand held multimeter. An example of a table multimeter is shown in figure 3.

Fig.3 Table multimeter (Agilent, 34401 series)

The accuracy of a table multimeter σ_{TMM} can be determined in the same way the accuracy of a power analyzer is determined as shown in equation (4).

$$\sigma_{TMM} = f_{reading} + \frac{f_{range} \cdot range}{reading} \tag{4}$$

Table 3 shows some characteristics of different table multimeters which do have an influence on their accuracy.

Device	Accuracy on	
	Reading	**Range**
Agilent 34401A	0.005% @ 100mV 0.0045% @ 100V	0.0035% @ 100mV 0.0006% @ 100V
Agilent 3458 option 002	0.0005% @ 100mV 0.0006% @ 100V	0.0003% @ 100mV 0.00003% @ 100V

Tab.3 Data of different table multimeter used for accuracy calculation

The resulting accuracy for a 54V DC output voltage is +/-0.117% for the hand held multimeter and +/-0.006% for the table multimeter. This is a large accuracy difference and it becomes even more drastic comparing the values with the overall accuracy of different measurement setups shown in chapter III.

iii. Clamp meter

A clamp meter is a hand held multimeter which is clamped around an electrical conductor in order to measure a current through the conductor by using its electromagnetic field. A clamp meter could be used to measure the rectifiers output current but is not recommended for accurate efficiency measurement, due to its bad accuracy. In order to show the influence on the accuracy of efficiency measurement clamp meters are also discussed in this paper.

The accuracy σ_{CM} is determined with the same equation as the accuracy of a hand held multimeter.

$$\sigma_{CM} = f_{reading} + \frac{n_{digit} \cdot 100\%}{n_{resolution}} \tag{5}$$

The clamp meter shown in figure 4 is used for the accuracy calculation. The accuracy range for this certain clamp meter equals 2% for the reading value and 5 digits with a total resolution of 6000. A comparison of the clamp meter accuracy to the accuracy of the table multimeter and the power analyzer reveals that the clamp meter can not be recommended for very accurate measurement of the efficiency as shown later in chapter III.

Fig.4 Clamp meter (Fluke, 375 series)

iv. Shunt resistor

Shunt resistors are a good instrument for the determination of the output current of a rectifier. This is especially valid for telecom rectifiers since they normally have an output current of between 15A and 120A. It can thus not be neglected any more that the self heating of measurement equipment has an effect on the determination of the current. Figure 5 shows an example of a precise shunt with low thermal resistance and temperature coefficient.

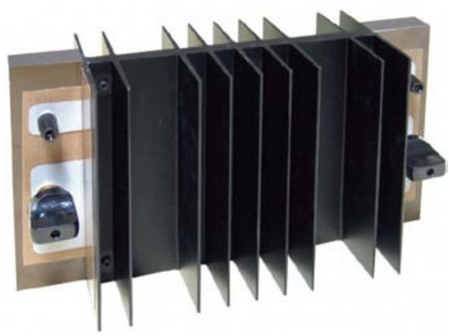

Fig.5 Precision high capacity resistor shunt (Burster, Model 1282)

The shunt itself can simply be seen as a resistor and the current running through a shunt does therefore create a voltage drop which is proportional to the current through it. An additional multimeter becomes necessary to measure the voltage drop. The additional multimeter does consequently also need to have a high accuracy so that the advantage of using a precise shunt is not lost. Taking the accuracy differences of hand held and table multimeters into account, it becomes very obvious that a table multimeter needs to be used. The use of a hand held multimeter would neutralize the good accuracy of the shunt resistor.

The accuracy of a shunt σ_{SH} depends on its electrical resistance R_{sh}, the current through it I_{sh}, its thermal resistance $R_{th,sh}$, the temperature coefficient α_{sh} and the resistance tolerance $f_{resistance}$. It can be calculated as shown in equation (6).

$$\sigma_{SH} = I_{sh}^2 \cdot R_{sh} \cdot R_{th,sh} \cdot \alpha_{sh} + f_{resistance} \qquad (6)$$

In order to have an idea of the different characteristics of the shunt used for the final accuracy calculation, table 4 is shown below.

Device	$\mathbf{R_{sh}}$ **[mΩ]**	$\mathbf{R_{th,sh}}$ **[K/W]**	$\boldsymbol{\alpha_{sh}}$ **[%/K]**	$\mathbf{f_{resistance}}$ **[%]**
Burster Type1240	0.5	11.0	0.001	0.05
Burster Type1282	1.0	1.0	0.001	0.02

Tab.4 Data of different shunt resistors used for accuracy calculation

Beside the additional multimeter required, the connection of the power and signals terminals to the shunt becomes crucial since they have a great influence on the measured voltage drop and therefore on its accuracy. The best connection technique used is the so called four-wire-measurement. This measurement technique uses separate connections for the power connectors and for the signal connectors. This allows the compensation of the contact resistance at the connection points of the power connectors. Furthermore, the power connections need to be very solid to ensure that they do not heat up the shunt resistor by the connections and thus influence its accuracy.

(4) Setup of measurement

As already mentioned in paragraph 3, the setup and therefore the connection of the equipment is one key point for having an adequate efficiency measurement. Even if the best equipment available on the market is used, its performance can be reduced if the setup is not done in a proper way. Therefore, anyone measuring efficiency must ask himself if he is using the best possible measurement setup. Is the influence by self heating minimized? Are the measurement points of the input and output power as close as possible to the rectifier inlets? If not, one might run the risk to measure not only the rectifier efficiency but also the losses of the connecting wires. Another question is if the measurement is done in a steady state of the rectifier. Or might for instance the rectifier temperature still increase and therefore influence the efficiency?

(5) Synchronous measurement

After different measurement tools have been explained, the next question is how to read off their results. The first possibility is to read off the values manually one after another and calculate them. But this method does have the drawback that the measured values will vary over time. Reasons for varying measurements are for instance unstable thermal conditions or an unstable voltage source. Therefore, it is not possible to calculate the efficiency for one certain condition since the data collection was not done at the same time.

Another possibility is to connect all measurement equipment to one common computer and read off their values at the same time by using their RS232 interfaces. Even though reading the values at exactly the same time might not be easy to realize, the values can at least be read off in a very narrow time range of less than one second. Finally, the data are sent to the computer. The efficiency and some other data can be calculated very fast, easy and also roughly at the same time.

Besides the advantage of easy and simultaneous measurement there are also some other benefits. For instance the source and load of the rectifier can also be influenced by the common computer by using their RS232 interfaces. Therefore, different efficiency curves for varying input voltages and load conditions can be done automatically.

Figure 6 shows an example of a user interface for an automatic measurement tool. The input voltages, currents and power for a three phase input as well as the output power are measured. The resulting efficiency is then calculated based on the measured data. It is also possible to show some trends of efficiency versus time or load.

Fig.6 User interface of an automatic measurement tool

b) Measurement of output power and power losses

The example already used in the introduction will be used to explain the advantage of measuring the power losses instead of the input power. In the example the efficiency was increased by 0.1% up to 96.1%. The efficiency increase results in a change of the input power of 0.11%. But the increase of the efficiency can also be explained by the difference of the power losses. For this certain example the power losses need to be reduced from 56.8W to 55.3W or in other words by 2.64%. If you now compare the reduction of the input power (0.11%) with the reduction of the power losses (2.64%) it might seem easier to measure the power losses compared to the input power. But this conclusion needs to be handled carefully since the measurement of the power losses is not easy and very time consuming.

The best option to measure the power losses is to measure the heat generated by the rectifier in order to determine its efficiency. The measurement of the generated heat is done by using a calorimeter. The following picture explains the operating principle of a calorimeter.

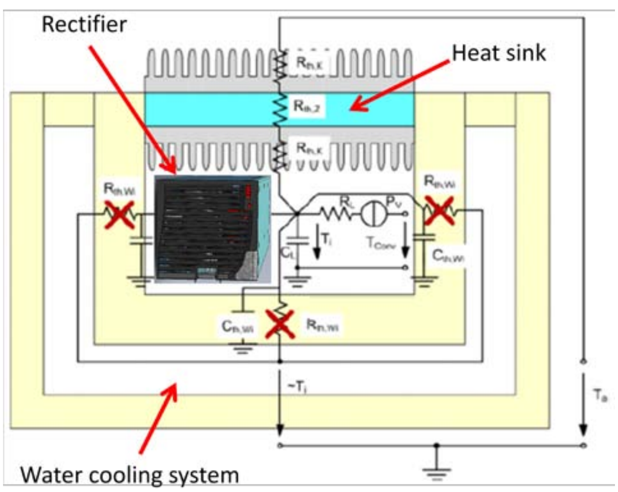

Fig.7 Principle construction of a calorimeter [2]

The heat generated by the rectifier which is to be measured can only exit the calorimeter via the heat sink mounted on top of the calorimeter. This implies that the box excluding the heat sink, wherein the rectifier is placed, needs to have heat insulating characteristics. In the example above this is nearly reached by having a water cooling system around the box with the rectifier. The great advantage of using a water cooling system compared to an air cooling system is the adaptable thermal resistance by using a controllable water pump. This leads to a wide range for the efficiency measurement. Now, the heat flow through the heat sink is measured and by knowing the thermal resistance of the heat sink, the power losses of the rectifier can be determined. The resulting accuracy of such a system including measurement of the DC output power equals ±0.05% in total.

The Swiss Federal Institute of Technology in Zürich/Switzerland has built such a calorimeter. A more detailed explanation of the calorimeter can be found in the reference [3].

III. DIFFERENT MEASUREMENT SETUPS

Throughout the next subchapter different measurement setups are shown and explained briefly. Some pictures will ensure a better understanding of the setup. Finally, the resulting accuracy of the different setups is determined for a typical load condition of a certain telecom rectifier. The rectifier does have a 25A / 54V output and the rectifier is powered by a 230V voltage source.

a) Measurement setup 1

The first setup is most probably the worst case setup if an accurate efficiency measurement is required. Reason is that the shown ampere meter is a clamp meter (Fluke, 375 seris) with a low accuracy. The used power analyzer (Yokogawa, WT1600) is one with a medium accuracy. Furthermore, the used voltmeter is just a hand held multimeter (Fluke, 80 series V) also of low accuracy.

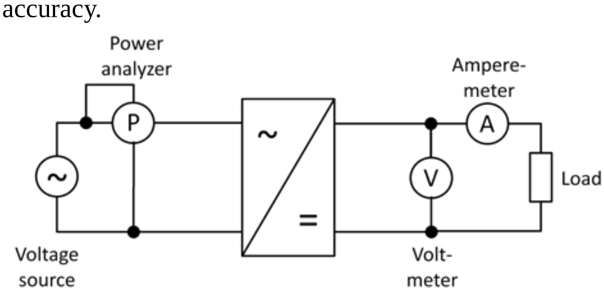

Fig.8 Measurement setup 1

In general, the influence each equipment has on the accuracy needs to be included in the calculation of the measurement accuracy of the overall setup. This is done as shown in equation (7).

$$\sigma_1 = \pm\sqrt{\sigma_{PA}^2 + \sigma_{HMM}^2 + \sigma_{CM}^2} \qquad (7)$$

Using the resulting accuracy of the different equipment, the following accuracy is calculated.

$$\begin{aligned} \sigma_1 &= \pm\sqrt{0.207^2 + 0.117^2 + 2.083^2}\,\% \\ \sigma_1 &= \pm 2.097\% \end{aligned} \qquad (8)$$

By looking at the results of equation (8), the resulting accuracy is the worst compared to the other explained setups. This becomes even more dramatic since normally, the efficiency improvement by a certain design change is in the range of 0.1%. By looking at equation (8) in more details it becomes clear that the major factor for the bad accuracy is the clamp meter accuracy σ_{CM} of 2.083%.

b) Measurement setup 2

The clamp meter, which had the worst accuracy in measurement setup 1 is now replaced by a shunt resistor. In order to measure the voltage drop across the shunt resistor (Burster, Type 1240), an additional hand held multimeter (Fluke, 80 series V) is used. The used power analyzer is still the same as in setup 1 (Yokogawa, WT1600). Figure 9 shows the measurement setup 2.

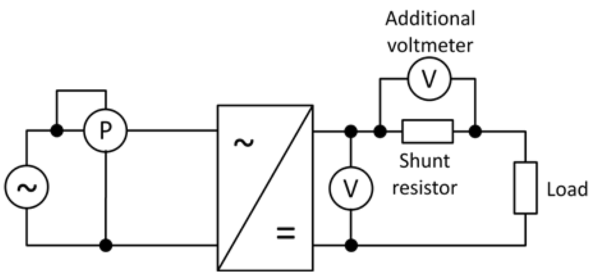

Fig.9 Measurement setup 2

The equation (9) shows the accuracy calculation for setup 2.

$$\begin{aligned} \sigma_2 &= \pm\sqrt{\sigma_{PA}^2 + \sigma_{HMM1}^2 + \sigma_{SH}^2 + \sigma_{HMM2}^2} \\ \sigma_2 &= \pm\sqrt{0.207^2 + 0.117^2 + 0.053^2 + 0.317^2}\,\% \\ \sigma_2 &= \pm 0.4\% \end{aligned} \tag{9}$$

By looking at the equation above it can first of all be seen that even though the same type of hand held multimeter is used, the resulting accuracy σ_{HMM1} for the output voltage is roughly three times better than the accuracy σ_{HMM2} of the multimeter used to measure the voltage drop across the shunt resistor. As explained before this is due to the different measurement ranges.

Now, it also becomes obvious that the bottleneck for a high accuracy is the accuracy σ_{HMM2} of the hand held multimeter for measuring the voltage drop of the shunt resistor.

c) Measurement setup 3

In order to increase the accuracy further, the hand held multimeters are replaced by table multimeters (Agilent, 34401A series) for the next measurement setup. The principle measurement setup is the same as used in figure 9 and the overall accuracy is determined as shown below.

$$\begin{aligned} \sigma_3 &= \pm\sqrt{\sigma_{PA}^2 + \sigma_{TMM1}^2 + \sigma_{SH}^2 + \sigma_{TMM2}^2} \\ \sigma_3 &= \pm\sqrt{0.207^2 + 0.006^2 + 0.053^2 + 0.033^2}\,\% \\ \sigma_3 &= \pm 0.216\% \end{aligned} \tag{10}$$

A considerable improvement of the overall accuracy has been achieved and compared to the former measurement setup the accuracy is as twice as good. However, the question still is if the accuracy is good enough? Coming back to the example given in the introduction where a design improvement results in 0.1% efficiency increase the accuracy in efficiency measurement needs to be better than the result shown in equation (10). In order to improve the accuracy further, it needs to be known which device now is the bottleneck. Equation (10) shows very clear that the overall accuracy of 0.216% is dominated by the accuracy σ_{PA} of the used power analyzer (Yokogawa, WT1600). The power analyzer is thus the bottleneck of measurement setup 3.

d) Measurement setup 4

The power analyzer used in setup 3 is now replaced by a power analyzer with better parameters to further increase the accuracy. The now used power analyzer (Infratek, 106A series) has the same reading accuracy but the accuracy of the range is improved by factor 5.

$$\begin{aligned} \sigma_4 &= \pm\sqrt{\sigma_{PA}^2 + \sigma_{TMM1}^2 + \sigma_{SH}^2 + \sigma_{TMM2}^2} \\ \sigma_4 &= \pm\sqrt{0.121^2 + 0.006^2 + 0.053^2 + 0.033^2}\,\% \\ \sigma_4 &= \pm 0.136\% \end{aligned} \tag{11}$$

As the equation shows, the accuracy is again improved a lot but it is still dominated by the accuracy of the power analyzer σ_{PA}.

e) Measurement setup 5

The measurement equipment used for this setup does have some of the highest accuracies for such equipment available on the market. The power analyzer used is a high-end power analyzer from Yokogawa (WT3000). The table multimeter used for the output voltage and shunt voltage measurement does have a very high accuracy for the reading and range (Agilent, 3458 with option 002). Finally the used shunt resistor (Burster, type 1282) has a low tolerance on its resistance value. The thermal resistance is also much better compared to the shunt used before.

The following equation shows the accuracy calculated for the setup 5.

$$\sigma_5 = \pm\sqrt{\sigma_{PA}^2 + \sigma_{TMM1}^2 + \sigma_{SH}^2 + \sigma_{TMM2}^2}$$
$$\sigma_5 = \pm\sqrt{0.105^2 + 0.001^2 + 0.021^2 + 0.002^2}\,\% \quad (12)$$
$$\sigma_5 = \pm 0.107\%$$

The improvement from ±0.136% to ±0.107% by using high end measurement equipment is most probably the best which can be reached by using conventional equipment and measuring the input and the output power. If an even higher accuracy is desired the before mentioned calorimeter needs to be used.

IV. COMPARISON OF THE MEASUREMENT TECHNIQUES

As mentioned in the subchapters above there are two possibilities to determine the rectifiers' efficiency; the measurement of the input power or the measurement of the power losses. Also, the output power needs to be measured for both possibilities. For a rectifier this is a smooth DC signal and therefore, the measurement equipment is highly accurate. But the real challenge is to measure either the input power or the power losses.

For measuring the input power there are several equipments available on the market. If the right equipment is selected an accuracy of ±0.107% can be reached. By using such a setup and also having an automatic measurement tool, the measurements can be done time effective and easy. But of course the accuracy is limited and if a small efficiency difference of 0.1% needs to be verified this might not be the best setup. Nevertheless, this is a good solution of the fast verification of design improvements. The measurement should always be done with the same equipment. This makes it more reliable as any deviation caused by the equipment will be the same for each measurement.

The right equipment to measure the power losses is a calorimeter. This allows for an accuracy of ±0.05%, even though the measurement is time consuming. However, it is the best solution for a very precise verification of the efficiency.

V. CONCLUSION

This paper has discussed aspects and considerations for measuring very high efficiency in an accurate way.

Two different possibilities and their advantages and disadvantages were discussed. The first possibility discussed was the measurement of the input and output power by using conventional equipment. The improvements caused by using different power analyzers, multimeters and shunt resistors were calculated and explained. The second possibility discussed was measuring the output power and the power losses by using a calorimeter.

By means of several influence factors of measurement equipment and their set up it was shown how the accuracy is influenced. The best accuracy which was reached measuring the input and output power was ±0.107% and it was ±0.05% using a calorimeter.

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