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Control of the Technical Condition of Power Transformers by Acoustic Diagnostics

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ABSTRACT

The relevance of the research is determined by the need to develop and consistently implement effective methods of the monitoring of the current technical condition of power transformer substations within the railway system of the Republic of Kazakhstan. The methodological approach in this research is based on combination of methods of system analysis of currently existing approaches to monitoring the current technical condition of power transformers using acoustic diagnostic methods with an analytical study of the fundamental possibilities of carrying out these operations within the railway system of the Republic of Kazakhstan.

During the experimental part of the study, acoustic sensors of partial discharges showed high efficiency in detecting partial discharges on the surface of the insulating layer of equipment of power transformer substations. This equipment, when using the acoustic emission testing method, demonstrated high performance.

Good results were also shown by the acoustic control method, since the promptitude of control and the possibility of taking readings without interrupting power voltage supply make it possible to reduce time of the experiment while obtaining high-precision results, to determine the causes of faults on the surface of the insulating layer of power transformers and to localise areas of occurrence of such defect most accurately.

Several proposals have been made on the role that the acoustic control method could play in the overall system for organising the inspection of the technical condition, operation, and repair of the electrical power equipment.

The results obtained indicate availability of various options for using acoustic emission testing methods and also confirm the need for their further improvement to achieve high quality of control of technical condition and functioning of railway power transformer substations.

Keywords: power transformer substations, train traction, railway rolling stock, acoustic diagnostics, acoustic emission testing, railway industry of the Republic of Kazakhstan, control of the technical condition.

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INTRODUCTION

Modern transformer stations are important for ensuring train traction within the system of electrified railways, for safe operational use of electric power equipment. This issue is quite relevant for the railway transport system of the Republic of Kazakhstan as well.

Most common and practically effective methods for monitoring the technical condition of power transformers comprise the method of acoustic emission testing, which involves location and point detection of the level of distributed sound discharges. Such discharges are those, shunting only a certain section of the insulating coating of a power transformer. They indicate the presence of local defects that require timely elimination. These can be weakening of the insulating coating due to formation of gas cavities, as well as to the appearance of sharp edges of metal structures [1]. Gas inclusions are weakened areas, regardless of the consistency of the insulating coating (solid or liquid), the weakening of which occurs due to a mismatch in the values of dielectric constant (permittivity) of the gas, as well as due to high electric field strength (intensity) that occurs in the inclusions, and which are several times higher than similar values at other points of the insulating coating. One should also consider the fact that the electric density index of a gas is significantly less than that of solid and liquid dielectrics. The occurrence of the described partial discharges is also possible in the immediate vicinity of the sharp edges of the electrodes, in the areas where the electric field strength increases significantly [2].

The need for timely monitoring of the technical condition of power transformers by acoustic diagnostics is largely due to frequent damage to the insulating coating of power transformers, which occurs due to frequent discharges in oil layers that are in direct contact with solid insulation. In such situations, stable conductive traces appear on the surface of a hard insulating coating. In such areas, due to the occurrence of excessive overvoltage, as well as ща operating voltages, surface-type discharges may occur, the development of which occurs continuously and ends with a breakdown of the insulating coating [3]. This indicates that partial discharges carry significant damage for the insulation of power transformers, due to the high probability of destruction of the insulating coating in certain areas and development of breakdowns in insulation gaps.

Technical personnel, whose direct duties include maintenance of power transformer substations, are forced to directly face the problems of breakdowns in the insulating coating, as well as the appearance of partial discharges in the insulating layer, at high and ultra-high voltage values in substation lines. This explains the need for timely and high-quality monitoring of the technical condition of power transformers by the method of acoustic diagnostics to prevent insulation breakdowns and ensure the uninterrupted operation of power transformer substations [4].

The current situation necessitates research, the main tasks of which are: assessment of the technical condition of modern power transformer substations that are used within the railway transport system of the Republic of Kazakhstan with an emphasis on identifying current problems in the technical condition of oil-filled equipment, performed during monitoring of partial discharges; development and implementation of acoustic measurement techniques intended for the diagnosis and analysis of partial discharges on the insulating coating of transformer substations, as well as for determining the specific location of transformer insulation defects; conducting scientific experiments aimed at studying the existing methods of monitoring of the existing equipment of power transformer substations.

The problem of existing research on the issues of monitoring the current technical condition of transformer substations is the lack of detailed and reliable, practically verified scientific developments using acoustic techniques of diagnosis of the technical condition of power transformers [5]. This work *intends* wherever possible to fill a certain gap in the study of the topic of using acoustic diagnostic techniques to solve problematic issues related to monitoring the technical condition of equipment of power transformer substations. The study used information obtained experimentally when conducting specific scientific experiments.

MATERIALS AND METHODS

The basis of the methodology of this research is a combination of *methods* of system analysis of currently used approaches to

monitoring the current technical condition of power transformers using acoustic diagnostic methods, with an analytical study of the fundamental possibilities for carrying out these operations within the railway system of the Republic of Kazakhstan.

The theoretical basis of the research includes available publications of domestic and foreign researchers devoted to various theoretical aspects of developing fundamentals and creating methods for monitoring the technical condition of power transformers by acoustic diagnostics.

During the study, the following sequence of stages of the work performed was established.

The first stage included theoretical study of available scientific publications devoted to research on the concept of acoustic diagnostics, as well as on the monitoring of the technical condition of power transformers using these techniques. The theoretical study preceded a systematic analysis of currently existing approaches to monitoring the current technical condition of power transformers using acoustic diagnostic technology, which was also consistently performed at this stage of the research work.

The next stage comprised an analytical study of the features of monitoring of the technical condition of power substations by the method of acoustic diagnostics within the railway system of the Republic of Kazakhstan. Besides, this stage of the research concerned an analytical comparison of the obtained preliminary results with the results of research by other scientists, who had also studied the possibilities of monitoring the technical condition of transformer substation equipment through the practical application of the acoustic diagnostics method. This ensured the quite objective perception of the results obtained in the context of their subsequent implementation for solving specific problems arising during operation of transformer substations within the railway sector of a particular state.

At the final stage, the results obtained earlier allowed to formulate final conclusions.

RESULTS AND DISCUSSION

Completing the tasks of the research comprised conduct of experimental studies involving the placement of acoustic-type sensors on several transformers used as the object of experimental study. «AC-Sensor» acoustic discharge sensors were used, designed for contact registration of partial discharge pulses on the surface of insulation and power equipment of transformer substations.

The methodology implied the following sequence of the study:

1. «AC-Sensor» which allows tracing the occurrence of partial discharges within the system, as well as characteristic acoustic impulses is attached to the device that records the level of partial discharges on the surface of the insulating layer of the power transformer. In case if it is possible to detect an area of partial discharges, several acoustic sensors of the specified type are located sequentially at a strictly defined distance from each other. The received acoustic signals are recorded and a clear sequence is built based on the received data.

2. The maximum allowable threshold value of the acoustic signal is experimentally determined, which can be further used for subsequent studies.

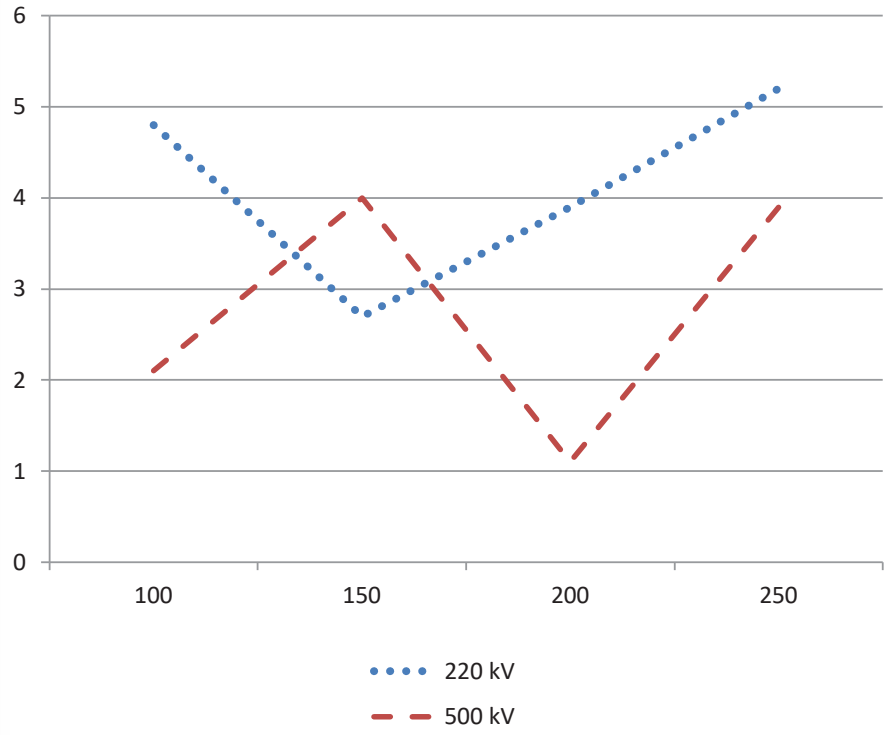
3. The threshold values of the settings are built directly in the areas of detection of partial discharges, the parameters of interference that occur when the signal level exceeds the specified threshold value are built as well. All these values are determined by the type of transformers and are calculated directly during the experiment based on specific initial data.

4. All measurements are taken within a predetermined period.

The distribution of the detected damage to the insulating layer of power transformers was carried out directly by the classes of voltages characteristic of transformers of a certain class. The data obtained during this distribution are presented in Table 1.

Based on the results obtained in the course of the study using «AC-Sensor» acoustic sensors, a graphical dependence of partial discharge pulses on acoustic pulses that occur when sensors are placed on the surface of the insulating layer is plotted. The data is presented for two transformers with different voltage classes: 220 kV and 500 kV. A graphical dependence of this kind is shown in Pic. 1.

As can be seen from the data presented in Pic. 1, a uniform increase in the dependence of the indicators under consideration takes place in the case of the practical use of power transformers with a voltage class of at least



Pic. 1. Dependence of partial discharge pulses on acoustic pulses arising when sensors are placed on the surface of the insulating layer [compiled by the author].

500 kV. When using power transformers with parameters of other voltage classes, there is practically no systematic development of the dependence of partial discharge pulses on acoustic pulses that occur when sensors are placed on the surface of the insulating layer, which in some cases may indicate a high probability of breakdowns of the insulating layer of the power transformer and the emergence of an accident [6]. Besides, there are significant differences in the dependence of the studied parameters in a number of cases, which may indicate violations of the operational use of power transformers and problems with the quality of the material of the insulating layer, which extremely negatively affects the general condition of power transformer substations in the context of the prospects for their practical use in the future wihin the railway transport system of Kazakhstan.

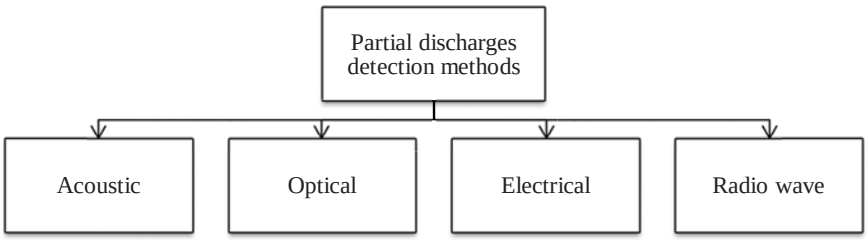
Methods for detection of partial discharges and their measurement are fundamental from the point of view of studying the prospects for monitoring the technical condition of the equipment of power transformer substations. Pic. 2 shows the main methods for monitoring partial discharges and their detection in the context of the prospects for their use for monitoring the technical condition of power railway substations. The acoustic control methods presented in this chart are the main ones in the context of the research and are the most promising ones in terms of the possibility of carrying out high-quality control of the technical condition of power transformers, without interrupting their operation and turning them off to perform the necessary study.

Acoustic methods for detecting partial discharges involve searching and successively

Table 1

Data on distribution of the damages of the insulating layer of power transformers detected during the experiment per voltage classes [compiled by the author]

Voltage class	110 kV	150 kV	220 kV	330 kV	500 kV	750 kV	1100 kV
Damage	42	28	34	15	6	1	5



Pic. 2. Methods of control of partial discharges and their detection [compiled by the author].

detecting, as well as measuring the magnitude of oscillations caused by partial discharges. The high frequency of such sound vibrations can only be determined using special recording equipment. In addition, the time and place of occurrence of such a discharge, as well as its power, are determined. In the future, the use of special equipment for recording changes in the amplitude of sound vibrations can be essential for obtaining high-precision results that reflect the real possibilities of using acoustic methods for detecting partial discharges.

For practical use of each method, it is assumed to use sensors of various kinds, which basically use the principles of the transformation of acoustic and electromagnetic oscillations in a certain frequency range: microwave, high frequency, medium frequency, and low frequency. The range of these sensors can vary significantly depending on the type of transformer equipment and the features of its insulating layer. Also, when choosing a method and type of measurement, it is necessary to consider the tasks to be solved and the parameters of the electric power transformer unit of the railway transport facility. To determine the parameters of frequency discharges over short distances, microwave sensors demonstrate high efficiency. Moreover, they are very compact and can be easily placed in the internal space of power units, such as the stator of an electric motor.

Particular attention when recording partial discharges in the insulating coating of power transformers should be given to discharges of this kind that occur in oil layers that come into direct contact with solid-type insulation. In such cases, as a rule, damage to the solid insulating layer cannot be avoided, which implies the need for subsequent repair work to restore the damaged insulating coating. This causes a significant danger posed by partial discharges for electric power equipment, in the context of the possibility of its rapid destruction in certain areas and the occurrence of breakdowns of the insulating layer.

To avoid the occurrence of such a situation, it is necessary to implement a set of measures, in general, focused on:

• Monitoring of partial discharges to form a qualitative assessment of the technical condition of oil layers of the equipment of power transformer substations, as well as to assess the possibility of breaking the solid insulation layer due to the effect of partial discharges on oil layers.

• Implementation of equipment for diagnosing and analysing the magnitude of partial discharges and formation of defective areas in the insulating coating of power transformers on an industrial scale.

• Carrying out scientific experiments in the field of diagnosing the current technical condition of the equipment of power transformer substations and ensuring their subsequent uninterrupted operation, considering the possibility of destruction of the insulating layer.

The prospects for development of the railway system of the Republic of Kazakhstan are largely built on the high-quality work of electric power equipment, and in this context, the issues of monitoring the technical condition of power transformers by acoustic diagnostic methods play a crucial role, since they allow maintaining the functioning of all equipment of transformer substations at the proper level for a long period of time without carrying out major repairs and ensuring high-quality maintenance of equipment of transformer substations and timely detection of all possible failures in operational use.

Over the past few decades, the energy departments of individual enterprises of the railway industry and the energy sector of the

economy of Kazakhstan as a whole, have gradually begun to adopt tendencies towards a consistent transition from the practice of carrying out scheduled repairs, designed to prevent the occurrence of malfunctions of the electrical equipment of the railway transport and prevent the occurrence of problems in the energy system of the railway rolling stock, to identification and elimination of real errors in the technical condition of electrical equipment, which is mainly practiced in countries with developed economies and a well-functioning railway transport system. This state of affairs involves development and implementation of a set of methods for the timely diagnosis of the state of electrical equipment [7].

The uninterrupted operation of power transformers should be considered a factor that largely determines safety of operation of industrial enterprises, as well as the reliability and quality of the supply of electrical energy to organisations belonging to various economic sectors. The high-quality functioning of power transformers ensures the coordination of the operation of transformer substations with the system, as well as the transformation of a whole list of electricity parameters into those necessary for its subsequent practical application. A significant level of wear and tear of transformer equipment creates a potential hazard for both end users and personnel whose direct duties include servicing transformer substation equipment and monitoring their technical condition [8].

The energy security of rail industry enterprises using power transformers, which largely determine quality of power supply and reliability of operation of the entire power system of railway transport, requires establishment of a clear system for monitoring the technical condition of power transformers, through the use of various control methods, one of which is the method of acoustic diagnostics [9]. The use of transformers is risky in itself, and the high degree of risk of such use represents a significant danger both for the end consumers of electrical energy and for the maintenance personnel of transformer substations.

The introduction of diagnostic equipment into the practices of monitoring the condition of transformer substations involves development of a series of preparatory measures aimed at obtaining information on current key issues: identifying the total number of power transformers with an expired service life that are capable of provoking an increased number of failures during their further use; the current quality of monitoring of the functioning of power transformer substations; detected cases of violation of the principles of operation of power transformer substations, in accordance with the provisions of state industry standards; the possibility of a gradual transition from the practice of carrying out scheduled repairs to repairs based on real problems of the technical condition of transformer equipment [10]. At the same time, it should be considered that operation of transformer equipment after the expiration of its warranty period is a generally accepted practice throughout the world, even though without taking appropriate measures to prevent and avoid accidents, it is associated with considerable dangers for the equipment of transformer substations. Another important aspect is the practical impossibility of replacing a large amount of transformer equipment in a short time; in addition, it is unprofitable from an economic point of view.

In modern economic realities, development and practical application of methods for monitoring the technical condition of equipment of power transformer substations are among the main tasks of the technical control services of enterprises using equipment of this kind in their practical activities. Unscheduled shutdowns of power transformer substations, which occur due to an emergency failure of transformer equipment, lead to significant material losses, and in some cases can result in unpredictable consequences [11]. In this context, the tasks of timely monitoring of the state of power transformers used in the railway industry are of particular importance, since they are inextricably linked with quality of functioning of railway rolling stock and contribute to an increase in the overall level of safety of the railway industry.

Over the past two decades, to diagnose the technical condition of power transformers, the method of registering partial discharges in high-voltage equipment of power systems has been used. Such a technique has shown high efficiency being directly used by various industries, including the railway transport system, thanks to the high results obtained. Besides, good results were achieved using the method of identifying zones of electromagnetic

activity, which was used exclusively on the surface of the transformer and involved the installation of measurement sensors on this surface, as well as of other measuring devices. Such measures made it possible to formulate a full-fledged conclusion regarding the technical condition of the power transformer assembly, in which defects, problems of the insulating layer, malfunctioning of the barriers and of the arc of the magnetic circuit, the appearance of sparks, etc., were found [12]. Information of this kind, along with data on the types of the discharge phenomenon taking place and its location, can be identified with the design features of both the transformer itself and its active part. Thus, performance reliability indicators can be predicted with a high degree of certainty since the conclusion regarding the possibility of further operation is formed based not on just general estimates of the characteristics of partial discharges but considering their exact location. In this context, it should be noted that the appearance of partial discharges in the places of fastening of the magnetic circuits of transformers is not of significant importance, since small values of partial discharges in the coiled insulation cannot cause significant damage to the structure.

Constant monitoring of the current technical condition of the equipment of power transformer substations of the railway transport system is one of the main tasks of the modern system for ensuring the energy security of the specified transport system. In this context, the control of the technical condition of power transformers by acoustic sounding seems to be one of the most favourable methods for ensuring the uninterrupted operation of the transport energy system, considering the peculiarities of functioning of railway transport under the modern economic conditions. In general, it is the high-quality and reliable operation of power transformers that is a necessary condition for consistent conversion of a series of energy parameters into the values necessary for the further use of electrical energy. At the same time, it is imperative to consider the degree of risk of using the equipment of transformer substations, since violations of the operating conditions of power transformer equipment can cause significant problems for both maintenance personnel and end consumers of electrical energy [13].

Modern equipment of power transformer substations, which are used in various nodes and facilities of the railway transport system, requires regular quality control of the technical condition of power transformer substations using the most modern diagnostic methods. The parallel use of various methods for diagnosing the technical condition of power transformer equipment makes it possible to obtain optimal results when comparing the effect of using several diagnostic methods, as well as to select the optimal control method based on the realities of the current situation. In addition, diagnostics of the state of transformer equipment is necessary for timely detection of defects that can have detrimental consequences from the point of view of safety of operation of power transformer substation equipment. In this context, during the diagnostics and after its completion, special attention should be paid to organisation of high-quality repairs and elimination of detected defects, which subsequently will ensure full functioning of power transformer substations for a long time [14].

At the same time, the system of monitoring of the technical condition of power transformer substations increases the efficiency of the functioning of power transformers of railway transport facilities, since the frequency of checks, combined with their quality and focused character, allows preventing the occurrence of damage and other design defects, which eliminates the subsequent occurrence and development of problem situations, associated with violations of the rules for the operation of transformer equipment. In this context, it should be noted that power transformers belong to the group of electrical equipment with the highest frequency of damage [15]. Studies conducted at different times have demonstrated that high-voltage transformer bushings are characterized by the greatest damageability, since they account for about 22 % of all damages, while windings account for approximately 16 %, and on-load tap changers (OLTC, intended for voltage regulation at load) account for 13,5 %. It is noted that such damage occurs with the same frequency in transformers with different service life, while in relation to transformers with a service life of 10 to 30 years, it is true that they have the highest frequency of failure of the on-load tap-changer equipment. It was

also noted that after 10 years of operation of power transformer substations, the frequency of damage to high-voltage bushings increases. In this case, one should take into account the fact that the most significant problem of power transformers, leading to disruption of their operation, sometimes for a long time, is a short circuit [16]. According to the analytical information received, damage to the windings of power transformers leads to short circuits in 80 % of all cases of violations and of the total number of damages to transformer windings, damage to high-voltage inputs – in up to 89 % of all cases, failure of the on-load tap changer – in up to 25 % of all cases, while damage to other nodes, as well as errors during installation, various situations that arise during the operation of equipment and its repair together give up to 36 % of all cases of short circuits [17].

Carrying out high-quality diagnostics of the current technical condition of power transformers used at various railway facilities often requires the use of special devices, as well as additional methods for locating electromagnetic activity zones on the surface of the transformer. The set of methods used to ensure high quality of checking the technical condition of power transformers, involving the use of acoustic diagnostic techniques and related ones, provides a wide variability of monitoring data, that provides possibility to obtain a complete picture of the current state of the power supply system of various railway transport facilities and of the prospects for development of the industry in the future [18].

Maintaining the high quality of work on diagnosing the state of electrical equipment and ensuring a high level of work on prevention of breakdowns of power transformers during operation is facilitated by special experimental studies aimed at establishing the relationship between the technical condition of transformer substations and quality of functioning of the energy system of railway transport as a whole [19]. The conduct of research of this kind makes it possible to assess the quality of work of transformer substations and to form a set of measures aimed at improving the functioning of transformer substations, considering the need for repair and recovery work in case of breakdowns of the main equipment of power lines. In this case, repair and recovery work should be carried out considering the features of specific types of transformers and the degree of breakdowns, and the quality of repair of equipment of power transformer substations is closely related to the efficiency of determining the causes of breakdowns in electrical equipment, as well as the time of their detection [20].

Thus, the issues of monitoring the technical condition of power transformers by the method of acoustic diagnostics require a detailed study to form a qualitative understanding of the issues of ensuring energy security and the integrity of the most important nodes and objects of railway transport, which include the equipment of power transformer substations. At the same time, the level of safety of these facilities should be correlated with the level of implementation of measures aimed at maintaining safety of the entire energy system.

CONCLUSIONS

The study of the key aspects of monitoring the technical condition of power transformers by the method of acoustic diagnostics led to the following conclusions.

«AC-Sensor» resonant acoustic partial discharge sensors have shown high efficiency in detecting partial discharges on the surface of the insulating layer of power transformer substation equipment. This explains broad prospects for the use of sensors of this type in the future, when conducting experimental research and work to determine the main features of the technical condition of power transformers using acoustic diagnostic methods. This equipment has demonstrated high performance when this method was directly used.

In general, the acoustic method of control has shown good results, since its main advantages, such as the efficiency of control and the possibility of taking readings, while maintain a continuous supply of power voltage, can reduce in general time of the experiment and to obtain high-precision results. Besides, the method of acoustic diagnostics and the use of «AC-Sensor» partial discharge sensors have shown high efficiency in determining the causes of faults on the surface of the insulating layer of power transformers, as well as the possibility of the most accurate localisation of areas of occurrence of such damage.

Subsequent diagnostic examinations of power transformers used within the railway transport system of the Republic of Kazakhstan,

using acoustic diagnostic techniques can significantly expand the understanding of the possibilities of using this technique to resolve issues of assessing the technical condition of modern transformer substations.

The results obtained during the research, can serve in future as a qualitative theoretical basis for further research on the problems and issues of monitoring the technical condition of power transformers, performed using various modern techniques, which are capable to bring research in the field of ensuring safety of the operational use of electric power equipment used in the railway transport system today to a qualitatively new level.

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