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TESTING OF MODELS OF EXPLOSION PROTECTION SYSTEM FOR HIGH-VOLTAGE OIL-FILLED ELECTRICAL EQUIPMENT

SUMMARY

Explosions of high voltage oil-filled electrical equipment (OFEE) lead to a significant material damage. These explosions occur under action of an arc discharge (AD) which arises after internal short circuit. Modernization of OFEE design and protection systems is the possible way to achieve significant reduction of potential explosion and substantial reduction of material losses. Examination of perspective explosion-proof OFEE designs and new explosion protection systems demands the effective test methods. In present work results of development and application of an arcless source of pulse pressure (ASPP) are described. In ASPP the testing impulse is produced by the jet of powder gases (JPG) which arises at the combustion of explosive materials.

In this work results of experimental researches of AD in transformer oil (TO) at conditions typical for AD initial stage have been presented: current rise time was 3-5 ms, the maximum arc current was up to 30 kA, AD burning time was 3-20 ms. The energy released in AD amounted to 0.1 MJ. It was established, that electric field strength in AD column was about 0.2 kV/cm, gas producing factor in AD was 110 l/MJ, growth rate of pressure in TO was about 0.3 MPa/ms. These results allowed to create an ASPP with demanded parameters. Experiments proved that TO flow under action of AD and JPG are similar given that the same influence duration of the energy released in AD is equalled enthalpy of JPG at liquid inlet.

In this work the transformer fracturing behavior after explosion has been analyzed; and the requirements for protection systems have been formulated. By means of ASPP the breadboard model tests of two well-known OFEE explosion protection methods were carried out. In the first method it is assumed that the protection is reached due to fast dump of pressure inside of OFEE case when special membranes are opened. In the second protection method it is offered to establish porous coverings on internal surfaces of OFEE cases. Experiments were carried out on OFEE model with the characteristic size of 1 m at action energy up to 1.5 MJ. It was shown, that these systems cannot protect the transformer body from significant damages.

The dynamic protection system of transformer (DPS) has been described. The efficiency of this new system using ASPP has been verified in experiments with autotransformer of 25 MW. It was shown that DPS protects the transformer from considerable damages at least at dynamic impulse of about 3 MJ.

Key words: transformer explosion, arc discharge, dynamic pressure

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1. INTRODUCTION

Life time of transformers or other high-voltage oil-filled electrical equipment (OFEE) is about several decades. The gradual degradation of paper-oil insulation occurs under the influence of partial discharge, heating, cavitation and other factors in service [1]. Over time the deterioration of insulation characteristics exceed a critical level, that's why untimely out of service may cause arc discharge (AD) due to internal short circuit (ISC). Electric power of discharge may range from tens to hundreds MW. Large amount of hydrogen and hydrocarbon gases is formed due to decomposition of transformer oil (TO) under action of AD. Due to oil incompressibility gas formation causes the raise of pressure that quite often ends by explosion of OFEE body. Mixture of atmospheric air and hot hydrogen and hydrocarbon gases can ignite the inflammation. In this case the explosion damage increases many times. The possibility of inflammation after OFEE explosion is about 15% [2].

In case of severe accidents only direct costs determined by cost of the replacing equipment can amount to tens of millions dollars. Therefore the improvement of explosion protection for OFEE is very important for the electrical power industry. The lack of appropriate technical and organizational solutions will make this problem worse. Firstly, there is a general trend of increasing equipment capacity, and secondly, it's not always possible to provide an adequate renewal of equipment.

The destruction degree of OFEE is mainly determined by energy Q_a released in AD. The energy Q_a depends on AD duration (or action time of protection devices), point of ISC origin, characteristics of external circuit. According to the literature data range of Q_a possible values for industrial OFEE exceed by two orders of magnitude. For example, fixed Q_a energy values in 735 kV power transformers are in a range of 1 to 147 MJ [2]. 735 kV single-phase transformer tank exploded at AD energy level of more than 8 MJ, but fire started at energy level of more than 14 MJ. Q_a energy level of 110-330 kV instrument transformers is about 0.3 - 1 MJ, Q_a energy level of 100 MVA distribution transformers can be varied in the range of 3 - 10 MJ. Q_a energy level of more powerful transformers and boxes of bushings under AD can be tens of MJ.

Loss reduction can be achieved in several ways including creation of a non-explosive OFEE design and improvement of protection systems. The solution of this problem requires an effective test method for equipment under the impact of high pressure pulse which occurs in AD. The standard test method for explosion protection of OFEE is based on electric arc ignition in the internal volume of OFEE. Together with our colleagues in works [3-6] we presented the investigations which justified an alternative test model for explosion protection of OFEE. In this method a high pressure pulse which occurs after ISC was simulated by chemical energy of explosive materials (EM). The new method allows carrying out tests directly in place of manufacture or installation site of OFEE. Estimations show that the alternative tests will cost much cheaper than the standard ones.

Joint Institute of High Temperatures of Russian Academy of Sciences (JIHT of RAS) developed an arcless source of pulse pressure (ASPP) for explosion protection tests of OFEE. The proven designs of ASPP allow producing pressure pulses with energy up to 5 MJ. Tests of protection system prototypes were carried out in OFEE models at energy effect up to 3 MJ by now.

In this work we present test results of protection system prototypes for OFEE. This work also summarizes the research results of AD in transformer oil, which was the basis for creation of ASPP. According to accepted definition explosion-proof electrical equipment is electrical equipment, where may occur structural damage after ISC, however all its components must be inside the normalized safety area close to the equipment, which is calculated as the diameter (width) of the equipment increased by two of its height but not less than 1.8 m. The energy of pulsed pressure in which the destruction of the transformer satisfies this condition can be regarded as estimation of its explosion safety.

2. ARC DISCHARGE IN TRANSFORMER OIL

Our research results of AD in OFEE test model have been described in details in works [3-6]. The AD basic parameters resulting from these studies are presented below. Experiments [3-6] were carried out under conditions similar to conditions after ISC occurrence in industrial OFEE, where discharge current increases up to 10 - 30 kA in 3-10 ms. In our experiments the maximum discharge current reached 30 kA at the rise time of 1-3 ms. The total discharge duration was 3-20 ms. The maximum heat release in the arc Q_a reached 0.1 MJ. The capacitive storage with maximum charge voltage of 5 kV was used as energy source for AD. Available electric circuit allows simulating two half-wave of heteropolar current; however basic experiments were carried out with one half-wave voltage. The maximum of AD power was reached during the first half period, hereafter discharge voltage and power were reduced due to resistivity degradation of insulating fluid.

AD was ignited between two parallel brass electrodes about 20 mm in diameter. The distance between electrodes was varied from 17 to 30 mm. The electrodes were located in a chamber of 310 mm internal diameter and 61 liters volume. The volume of mineral TO was 35 liters. The remaining volume (26 liters) was filled with nitrogen at atmospheric pressure. The electrodes were close to the chamber axis. The distance from point of discharge origin to “liquid-nitrogen” interface was 100 mm.

AD current and voltage, the pressure in the body, the pressure of gas bubble above liquid were measured. Response time of pressure sensor was less than 0.5 ms. One pressure probe (PP) was installed close to body foot (PP1), the other was installed at 50 mm from upper level of the liquid (PP2). We used high-speed shooting of the discharge with a time resolution of 0.1 ms and motion of “liquid-nitrogen” boundary with a resolution better than 0.8 ms. The amount of hydrocarbon gases formed due to decomposition of TO was calculated from pressure increase in gas.

The arc discharge was initiated by applying voltage (≅ 3 kV) to a copper wire used for connecting electrodes of 0.1 mm diameter. Fig.1 and Fig. 2 present the experiment results. Fig. 1 shows “oscillograms” of current and voltage in AD. The discharge duration (≅ 7.5 ms) is close to half-wave voltage duration at power frequency. At start time the voltage oscillogram is on a sharp rise and then there is a rapid decline. The estimated high voltage peak duration (≅ 20 ms) is equal to electric explosion time of copper initiator.

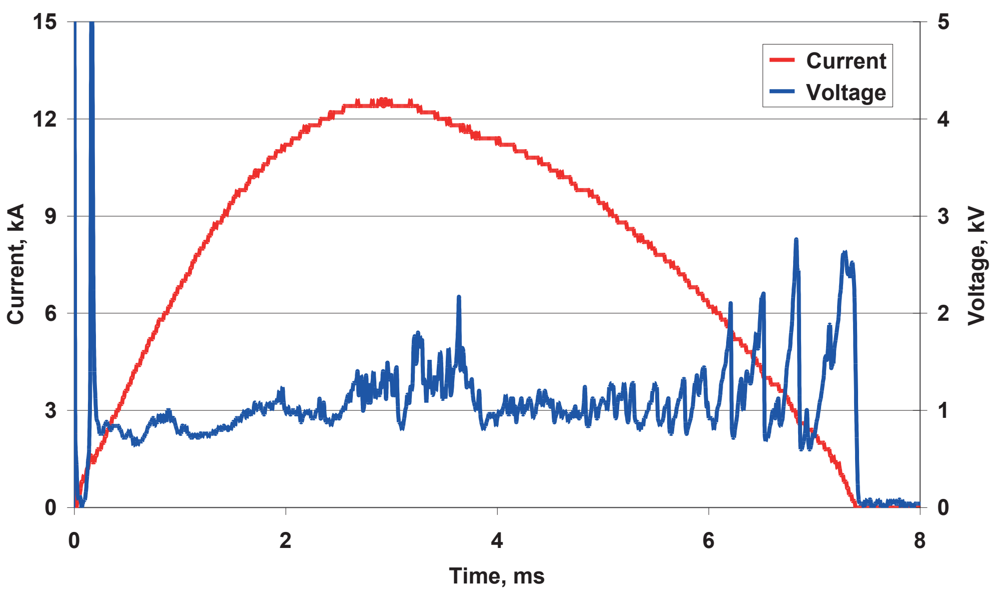

Figure 1 – Current and voltage oscillograms

There were some voltage pulsations at current fall time, which were probably associated with arc motion along the surface of electrodes. Arc velocity was about 20 m/s. Analysis revealed that AD column extends under action of its magnetic field with the result of AD voltage increase which causes shunt breakup with further voltage decrease. Estimations showed that typical electric field value in AD column was 0.1-0.3 kV/cm.

High-speed shooting of the discharge showed that plasma glow was concentrated close to electrodes at the beginning of the process. At this point the glow area started to expand at a rate of 0.3 km/s, however in 0.5 ms the rate decreased approximately threefold. Thus, the plasma expansion rate was much lower than the speed of sound in TO, which is about 1.4 km/s. Radiation flashed over the electrode spacing in about 1 ms after AD occurrence.

Fig. 2 shows "oscillograms" of pressure in TO measured by PP1. One may state that variation of pressure in TO is repetitively-pulsed. This fact is quite pictorial especially in the beginning of arcing which is about 3 ms. First pressure extremums (maxima and minima) followed at 0.8 ms interval and then one-step transition decreased to 0.6 ms. There is some correlation between the signals from pressure probe and the discharge voltage "oscillogram". Thus the first pressure maximum is equivalent of the "smeared" voltage maximum. There was a voltage jump up to 2.2 kV in 3.64 ms after arc ignition (Fig. 1) before the absolute pressure maximum in the oil, which was fixed in 3.71 ms after AD occurrence and amounted to ≅ 1.7 MPa (Fig. 2). Apparently, there were sound waves in the liquid under a sharp voltage decrease (breakdown).

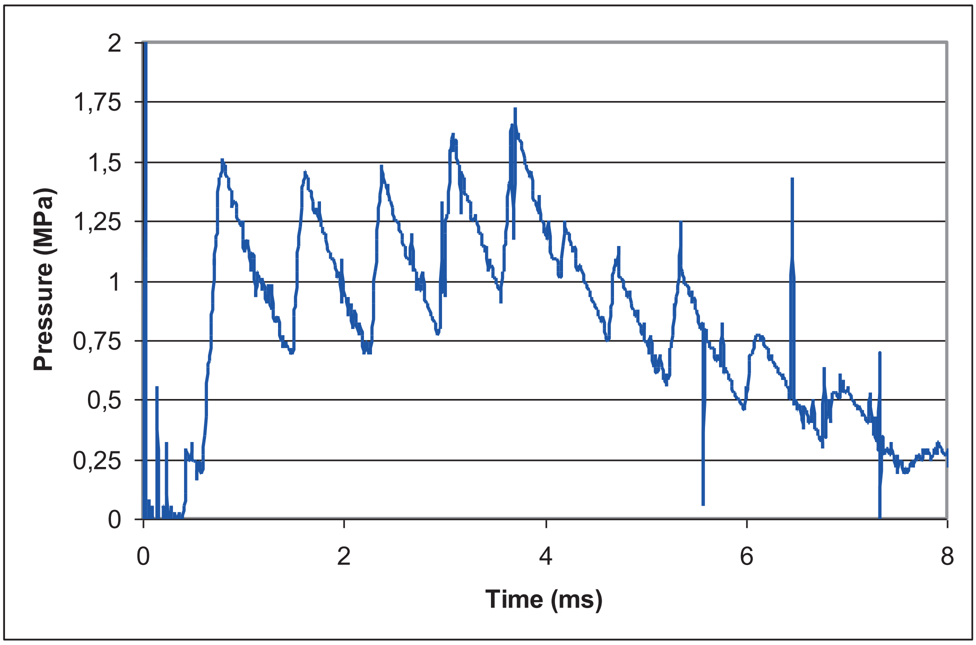

Figure 2 – Pressure in TO close to the foot of the chamber

Oil moves under the influence of expanding gas-vapor bubble, which leads to gas compression and pressure increase. According to high-speed shooting the liquid level climbs uniformly up to 0.1 m of height and then vapor-gas mixture ruptured to nitrogen volume. Typical liquid rise velocity was about 10 m/s and the kinetic energy of oil motion was 5-10 % of total energy released in AD. The main part of the energy Q_a was spent on oil heating and its decomposition.

After discharge the overpressure in nitrogen “blanket” was at 10-50 kPa level which is proportional to gas volume released due to TO decomposition. The gas formation process under AD is usually characterized by coefficient of gas formation B_g, which is the ratio of released gas volume to AD energy. According to our data B_g = 0.11 l/kJ.

Carried out experiments allow us to define qualitative features of AD dynamic effect to OFEE body. The main feature is the lack of shock waves in liquid. Perhaps a shock wave occurs at the moment of initiator explosion, but it quickly degenerates into a sound wave. The average pressure rise rate in liquid is 0.3 - 0.5 MPa/ms. At the background of increasing pressure of body walls there are intensive sound waves. The maximum pressure of body wall in our experiments was about 2 MPa. The pressure in the arc burning zone (vapor-gas bubble) was slightly higher. The pressure estimated from the velocity of “liquid- nitrogen” boundary (10-20 m/s) should be 5 - 10 MPa.

3. ARCLESS SORCE OF PULSE PRESSURE (ASPP)

The research results of AD have determined the requirements for arcless source of pulse pressure (ASPP) for simulating AD effect in OFEE. In ASPP the impulse pressure is created by the enlargement of JPG which is formed due to combustion of explosive materials (EM). It is important that duration of pulse pressure effect should be about 50 ms. This requirement eliminates the use of explosive materials like TNT or hexogen in JPG generator. Therefore in our experiments we used gunpowder as EM, because it burns much slower than TNT. Gunpowder efficiency is 3.8 kJ/g; the specific gas production is 0.9 l/g.

The generator of JPG has high-pressure chamber, from which the products of EM combustion are flown through a Laval nozzle. The magnitude of impulse pressure and its duration can be controlled by changing parameters such as nozzle area, EM mass, EM allocation in combustion body and ignition methods. Experiments with JPG were carried out in the same chamber as experiments with AD. JPG generator was attached to one of the lower windows of chamber, so that the region of JPG influence on the liquid was the same as under AD. Enthalpy *Q* of JPG was varied in the range of 10-50 kJ. TO and water were used as working liquids.

Pressure was measured at characteristic points of the chamber, the motion of liquid under JPG influence was studied using high-speed shooting. According to measurements jet pressure at the liquid inlet achieved about 10 MPa through about 1 ms. Duration of jet exposure to the liquid was varied from 20 to 60 ms. The typical pressure on the chamber walls was about 1 MPa. Motion of "liquid-nitrogen" boundary under JPG influence immersed in the liquid was the same as under AD under the same energy effect. This boundary while remaining flat was climbed with velocity of 10-20 m/s. It should be noted that there were no essential differences between water and TO response for JPG impact.

The experiments proved the possibility of hydraulic similarity of liquid motion under the JPG and AD effect. The equivalence of the liquid motion under effect of JPG and AD was achieved if the energy and exposure duration were equal. In this context JPG generator (ASPP) can be used in explosion protection tests for simulating AD effect in OFEE.

Fig. 3 presents ASPP for energy of 5 MJ before the control test.

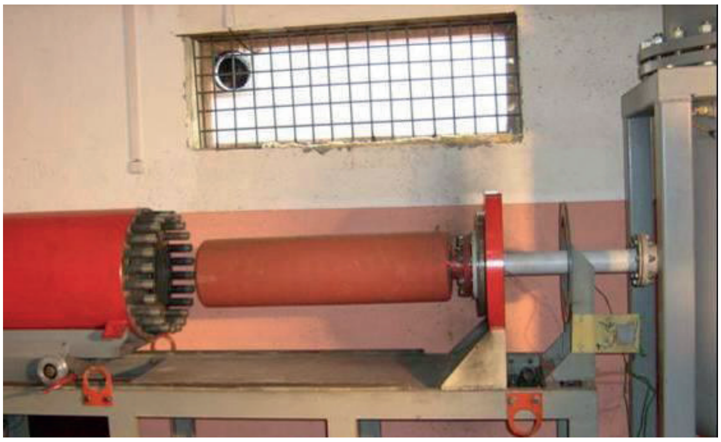

Figure 3 – ASPP for energy of 5 MJ

ASPP can be used for series of tasks aimed to improve the explosion protection of OFEE:

- test of OFEE production samples;
- examination of explosion protection systems and devices efficiency;
- elaboration of OFEE new constructions with high level of explosion protection;
- basic data acquisition for development and verification of numerical methods for OFEE perspective constructions and explosion protection systems etc.

Experience of ASPP application in the tests of explosion safety of OFEE industrial samples has been described in the works [3, 4].

4. PECULIARITIES OF TRANSFORMER DESTRUCTION AFTER EXPLOSION

According to analysis of published studies, the most vulnerable elements of ISC in power transformers are bushings, oil-filled cable boxes and tap changers [2]. AD develops close to the point of a short circuit origin between transformer body ("the ground") and construction elements under high potential. The length of arc column defining AD voltage depends on OFEE construction and may range from 0.1 m to 0.3 m. AD continuously and randomly moves along internal surfaces of the transformer due to magnetic forces and convective flows. Since the typical velocity of AD is about 10 m/s and the time of its “lifetime” is about 50 ms, the surface area of the transformer under AD effect is about 0.1 m^2. Therefore AD exists inside the volume of 10-30 liters. This fact explains the shock wave absence in OFEE despite the high power of AD.

Pressure equalization time inside transformer tank is estimated as double time of maximum sound wave transmission between opposite walls of the transformer. Pressure equalization time in typical instrument transformers of 110 and 330 kV which explosion safety has been analyzed in work [4] is about 1 ms. This time is much less than arc duration. Pressure equalization time in distribution transformers is about 15 ms. It means that there is a significant difference of pressure in large transformers during arcing. The maximum value of pressure is achieved in region of AD action. These estimations show that transformers with tank volume less than 1 m^3 should be damaged quite uniformly across the surface under the pulse pressure influence. Such faults were recorded during our safety tests of instrument transformers [4]. Faults of large transformers are local where the damaged area is less than 10% of total surface area. The example of such damage is shown in Fig. 4.

Figure 4 – Transformer in Western Siberia Substation after explosion

The maximum valid overpressure for transformer body depends on design, location and pulse duration. According to general requirements for transformer its body deformation occurs in elastic zone with static overpressure of 0.05 MPa. The tank rupture under dynamic loading can be expected if overpressure above 0.5 MPa lasts for more than 5 ms.

Apparently most probable conditions for transformer explosion are in the range of 10-30 ms after AD ignition. At early stage of AD burning for about 10 ms, internal pressure of the transformer does not reach critical values. The probability of explosion is decreased about 30 ms after arc ignition. Firstly, at that time the AD power is significantly reduced due to conductivity increase of insulating liquid. As a result there is a decrease of gas formation rate in AD and changes in pressure growth rate. Secondly, there is an increase of internal volume of the transformer tank due to its deformation under high pressure influence. This additional volume partially compensates for pressure growth due to decomposition of TO.

In the view of foregoing considerations, we can lay down basic requirements for OFEE explosion protection systems:

- the response time for internal pressure increase should not exceed 5 ms;
- the system should limit the pressure in the transformer tank at the level of 0.3-0.5 MPa;
- the protection system should be installed close to problem areas of the transformer in case it is not possible to protect the entire internal surface.

5. MODEL TESTS FOR EXPLOSION PROTECTION OF OFEE

Well-known explosion protection methods of OFEE are focused on formation of additional volume ΔV for expansion of TO in case of internal pressure growth under AD. The effectiveness of the protection system can be estimated from:

$$k = \frac{\Delta V}{B_g Q_a} \tag{1}$$

The k value that may called a protection system reliability parameter presents itself as the ratio of TO additional volume of and gas volume $V_g = B_g Q_a$ released due to TO decomposition under AD. Approximately we can take as follows:

- k>0.7-0.8, tank deformation is elastic and the equipment is explosion proof;
- 0.3 <k <0.7, the considerable plastic deformation of the transformer body should be taken of;
- k <0.1-0.3, explosive destruction of the transformer body should be expected.

Tentatively we can take typical values of protection system reliability as $k_1 \cong$ 0.7-0.8 и $k_2 \cong$0.1-0.3.

There are two ways of additional volume formation for TO. The first method is based on using porous coverings on the internal surfaces of OFEE body [7]. It is expected that porous material is compressed under high pressure influence resulting in formation of necessary volume. In consequence pressure growth inside the body is limited. Some additional protective effect can be achieved if significant part of TO flow kinetic energy will spend on compression of the porous material. "Porous covering" method may be effective in case substantial compression of porous material takes place at a relatively low overpressure – approximately 0.3-0.5 MPa.

The second method of protection is so-called "protective membrane" method. Principle of method is installation of protective membranes on OFEE body which are destroyed under action of AD pulse pressure and used for TO flow to special container [8]. It is considered that this way internal pressure of OFEE can be kept within acceptable limits. The second protection method is widely used, for example in SERGI Transformer Protector System.

We have presented briefly the tests of the described protection systems in the work [4]; these results are discussed in details below.

In the experiments with porous covering method we used OFEE breadboard model in the form of steel cylindrical tank of 0.95 m^3 volume and of 1.45 m height. Tank diameter was 1 m, thickness of wall was 7 mm. The cover has been screwed to a sidewall by 24 bolts with thread diameter of 12 mm. The plate of elastic foam plastic of 50 mm thickness has been glued on a steel cover of a breadboard model. The foam was made from extruded crumb with 0.04 kg/dm^3 density. The tank was filled with water. ASPP was installed at a distance of 0.2 m from the top cover. Estimated energy of ASPP pulse was 0.35 MJ.

After test the cover of tank has lifted in 0.8 meters: only 3 bolts from 24 has survived, the cover deflection has amounted to 50 mm, the foam plastic plate has destroyed into small fractions. Hence this protection method cannot protect OFEE body from considerable deformation under action of the high pressure pulse. This result was quite expected. Indeed for the effectiveness of this protection system needed volume increase which is accessible for the liquid due to compression of porous material for its compensation in 3-5 ms - the time of pressure rise in the liquid. It is possible either at slow pressure rise rate of 0.1 MPa/ms, or at small sizes of the protected model of 0.1 m.

In general, the efficiency of the discussed protection system cannot be sufficiently high. This fact can be illustrated by following calculations. If the typical size of transformer tank is a, then the possible increase of available oil volume under covering of transformer internal surface with damper material of maximum compression h will be:

$$\Delta V \cong 6a^2 h \tag{2}$$

The porous covering uniformly compresses under action of pulse pressure only if tank size is under ≅ 0.5 m. Taking for calculations $a \cong 0.5$ m and $h \cong 0.02$ m and using formula (2) we find that ΔV ≅ 30 l. It may be enough to protect the transformer from the explosion at AD energy of 0.5 MJ ($V_g \cong$ 55 l).

At the increasing size of transformer tank after short circuit occurrence the covering can be effectively compressed only close to the short-circuit origin with total area of 1 m^2. In this case the additional volume will be ΔV ≅ 20 l. The effectiveness of this protection system under AD with energy $Q_a \cong$ 1 MJ ($V_g \cong$ 110 l) will be $k \cong 0.2$, i.e. even at a relatively low AD energy we can expect explosive destruction of tank.

In summary, porous coverings which are compressed at pulse pressure of 0.3-0.5 MPa having an effective Young's modulus of 0.5 MPa, may be used in explosion proof transformers with the tank size up to 0.5 meters if expected AD energy does not exceed 0.5 MJ. In addition this porous covering material has to maintain its properties during continuous operation.

Fig. 5 shows OFEE breadboard model which was used in the test of protective membrane method. The OFEE model had the form of steel cylindrical vessel of 1.4 m diameter filled with water. The thickness of model steel cover was 12 mm. The air volume has been separated from the water by an aluminum membrane with the thickness of 0.2 mm and diameter of 200 mm. The concrete blocks with mass of 70 kg have been installed at a distance of 300 mm from the cover to simulate transformer windings. Area of ASPP effect was between concrete blocks and cover at 0.2 m distance from the roof opening – opposite the pressure probe PP2. PP1 detected pressure in air bubble behind the membrane, PP3 and PP4 measured pressure in liquid from far field of ASPP effect. The action of pulse pressure on OFEE body was recorded by high-speed shooting. Energy of ASPP was 1 MJ, pulse duration was 50 ms.

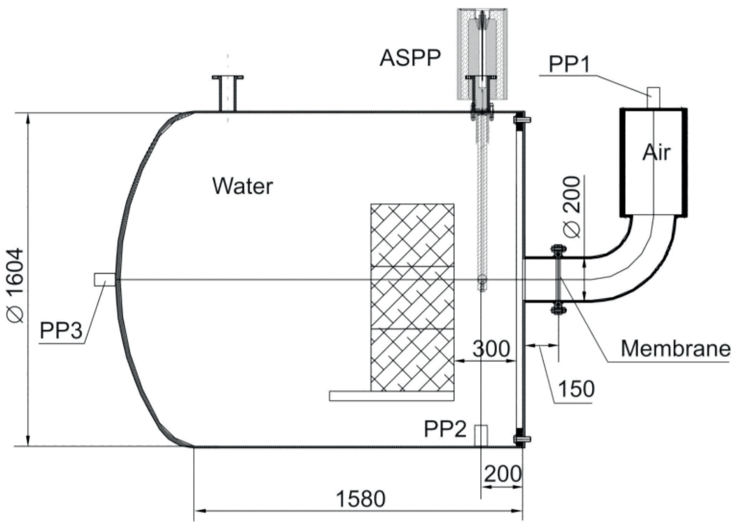

Figure 5 – OFEE breadboard model for tests using protective membrane method

Membrane contact sensor recorded its rupture in 3 ms after ASPP start. The water flow rate through membrane calculated due to air pressure changes in air bubble behind the membrane was 20 m/s. Pressure maximum in the liquid reached 1.8 MPa. High-speed shooting showed that the deformation of OFEE body had lasted for 10-15 ms. After the test we established that the residual deformation of steel cover was about 40 mm and concrete blocks were moved for 50 mm. The conditions for the discussed protection method in this test were optimal: a thin membrane of a large diameter was installed right in front of the epicenter of the pressure rise. However the present protection method was not effective enough.

The explosion prevention system in Fig. 5 is a simplified version of SERGI Transformer Protector (TP) system. This protection system is used in energy utilities of Russia in recent years, but the experience of its operation is not encouraging. On September 22, 2009 there was an explosion of AT-1 - 330 kV tank due to ISC at substation "Mashuk", where this system was installed. SERGI gave an explanation of this rupture in the report [9]. According to this report there was a peak current of 10 kA and arc duration of 60 ms at the time of rupture. In the analysis of TP system SERGI experts assumed the AD voltage was 37 kV, so that the energy released in AD was about 11 MJ. This AD voltage value seems conservative, because it was calculated without taking into account the voltage loss in inductance. According to our estimations the AD voltage was significantly lower, so that the total AD energy was about 4 MJ. The volume (gaseous products of fluid decomposition) was about 0.45 m3 under this Qa energy.

According to data [9] the protective membrane of 8 inches diameter (≅ 200 mm) was destroyed in 4.5 ms after short-circuit occurrence at pressure of 0.08 MPa. There was TO flushing through the opening which caused "depressurisation" of transformer tank in 112 ms. According to this report [9], even though the TP system did not protect the HV OFEE body from explosion, it prevented the fire occurrence. However, the data in the report [9] raise some doubts. According to this data the maximum oil flow rate through the destroyed membrane does not exceed 20 m/s. According to calculations based on values of

TO velocity [9], approximately 25l of TO leaked through the diaphragm under AD. Therefore, the reliability coefficient of the protection system (1) is $k \cong 0.07$, that's why TP couldn't protect OFEE tank from explosion. As for the lack of fire, the probability of its occurrence after rupture does not exceed 20%, so we cannot give a credit to TP system especially as Q_a energy is relatively small.

6. TESTS OF DYNAMIC PROTECTION SYSTEM

The previous analysis shows that well-known OFEE explosion protection systems are not effective enough and it's a necessary to develop new protection systems. This section briefly describes tests results of dynamic protection system (DPS) developed by JIHT of RAS. The main elements of DPS are spring-loaded moving blocks (Fig. 6). The blocks were installed on the side wall of transformer body close to the most probable place of ISC occurrence. The maximum displacement of the blocks under influence of pulse pressure was about 0.3 m. Protection of bushings was carried out using special membranes.

The tests were carried out in autotransformer (AT). The autotransformer of 25 MWA was out of service, but all elements have been preserved inside the body. Fig. 7 shows the autotransformer with established DPS elements (guard vessels are painted blue). There were 16 moving blocks under circular guard vessel and 35 blocks under rectangular guard vessel (Fig. 6). There was an ASPP inside the protective chamber from the left. DPS wasn't installed at the back side of the transformer; it was installed at one of three bushings.

ASPP with energy of 1 to 3 MJ and exposure duration of 30 to 50 ms was used in the tests. High-speed shooting (up to 2000 frames per second), four pressure probes and displacement sensors were used for diagnostics of the tank deformation. The AT tank was filled with water.

Series of experiments (10) were carried out. The pressure pulse was supplied to most likely points of short circuit origin from both sides of transformer including the bushing area. Plastic deformation of the tank with partial destruction of the structural elements but without leaks was recorded under pulsing of AT back side without DPS. High-speed shooting recorded that blocks began to move in 5 ms after ASPP start.

Figure 6 – Dynamic protection system (valve blocks without guard cover)

Figure 7 – Autotransformer with DPS before tests

According to results of these experiments it was established that:

- Pressure maximum in autotransformer increases approximately proportionally to ASPP energy: under the energy of 1 MJ pressure maximum is about 0.5 MPa, under the energy of 3 MJ the pressure exceeds 1 MPa.
- The basic body deformation without DPS begins in 20-30 ms after ASPP start.
- Displacement velocity of DPS blocks increases with ASPP energy increase: maximum velocity of blocks reaches 30 m/s at ASPP energy of 3 MJ.
- DPS has much lower response time in comparison with the factory explosion protection system in form of protective membrane.
- DPS installed in front of ASPP protects the body from plastic deformation under pulse energy up to 3 MJ.

It was estimated that DPS with tested configuration has reliability coefficient $k \cong 0.5$. The reliability of explosion protection can be increased from 30 up to 50% in case DPS is installed on the both sides of the transformer and all high-voltage bushings.

7. CONCLUSION

1) Dynamic effects of arc discharge (AD) and jet of powder gases on transformer oil have been investigated. It has been shown experimentally that these effects are quite similar under conditions of equal energy of action and its duration.
2) Arcless source of pulse pressure (ASPP) which may be used to estimate the explosion safety of OFEE under energy up to 5 MJ has been created. ASPP can be applied as an alternative to existing method which is based on AD initiation inside the equipment.
3) It has been experimentally shown that the protection method in the form of porous coverings on internal surfaces of OFEE which can be compressed under high pressure pulse cannot be effective for large transformers.
4) Test models of “protective membrane” method have shown that this method didn’t protect OFEE body from considerable plastic deformation which may cause explosion. Reliability parameter of this protection method does not exceed 0.1.
5) Dynamic protection system (DPS) of OFEE explosion prevention has been described. Tests of DPS installed on the autotransformer of 25 MWA have shown that DPS prevents the explosive destruction of the autotransformer body at least at the energy of 3 MJ.

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