APPLICATION OF ARCLESS SOURCE OF IMPULSIVE PRESSURE FOR EXPLOSION-PROOF TESTING OF HIGH-VOLTAGE OIL FILLED ELECTRICAL EQUIPMENT

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Explosion safety of oil filled equipment is an immediate problem in power energy sector. We cannot exclude the possibility of explosion of such equipment during operation, however it is possible to sufficiently reduce the explosion probability and material damage. A main problem related to creating explosion-proof electric equipment is the absence of efficient and well-developed test methods.

Keywords: paper-oil insulation; arc discharge; explosion safety; gas production; pulse pressure arcless source; transformer oil; transformer damages.

A North Siberian substation: transformer after explosion

INTRODUCTION

The transformers and other high-voltage oil filled electrical equipment (HV OFEE) service life may number ten or more years. During operation the paper-oil insulation (POI) [1] degrades due to internal discharges, heating, cavitation and other effects. Over the years the deteriorated insulation characteristics may lead to a higher critical level which may result in short circuit inside HV OFEE, which normally gives rise to the development of the ten to even thousand megawatt (MW) arc discharge. Such arc discharge contributes to intensive decay of electric insulating oil (EIO) and POI and generation of extensive gas volume. Since, as a matter of practice, the electric insulating oil is incompressible the gases cause pressure surge resulting in the HV OFEE explosive rupture. Hot gases escaped from the damaged transformer may intermix with air and flame up. The fire probability after explosion is around 15% [2], however the fire damage may be well-above the cost of damaged HV OFEE.

In case of severe accidents, the cost of equipment replacement may amount to tens of millions dollars. In this respect, the improvement of the HV OFEE explosion-proof level is a critical task for power energy industry.

The exploded HV OFEE degree of destruction is mainly determined by the energy amount Q_a generated by the arc discharge. Energy Q_a depends on the arc duration time t_a (or protective device actuation time), short-circuit location, external circuit characteristics. Based upon available literature data, possible value range for this energy exceeds two orders of magnitude of Q_a. For example, the energy value Q_a varies from 1 to 147 MJ for 735 kV voltage class power transformers [2]. The oil tank of this voltage class transformers explodes at 8 MJ arc energy, however the fire can develop if Q_a exceeds 14 MJ. As for 110–330 kV measuring transformers, the minimum energy Q_a is 0.3–0.5 MJ; however this energy may vary 3 to 10 MJ in 100 MVA distribution transformers. With the arc discharge in HV lead ducting this energy may amount to tens megajoule.

The HV OFEE operating conditions shall also take into account the potential for internal short-circuit, however, the respective technical and engineering solutions may help achieve remarkable decrease of accident and damage risk level. To confirm efficiency of these solutions an efficient test method is required to check the equipment exposed to the discharge arc high-pressure pulse. The standard explosion-proof test method is based on initiating electrical arc inside HV OFEE. However, the industrial standards that can regulate such tests have become null and void in Russia and former USSR countries for the past twenty years.

Works [3–6] document the results of the studies which establish an alternative method for the HV EFEO explosion-proof test. This method suggests that, following a short-circuit, the high-pressure pulse inside HV EFEO will be generated upon burning of explosive materials. The new method allows us to conduct the tests directly at the HV OFEE manufacturing or installation site while no expensive tests setup is required. Based to the estimates, the alternative method test is cheaper if compared to the standard test procedures.

An arcless pulse pressure source (APPS) to be used for the HV OFEE explosion-proof test have been developed by the Russian Academy of Science' Institute of High Temperatures. Up to the date those APPS's configurations have been trialed that allow conducting the HV OFEE explosion-proof tests with up to 5 MJ operating energy.

This work summarizes the study data of the arc discharge in transformer oil (these data were used for the APPS development) and pools the APPS usage experience in order to determine the explosion-proof level of a series HV OFEE.

The work analyzes the known methods for HV OFEE explosion protection. This method was used as a basis for the development of the HV OFEE explosion dynamic protection system (DPS). This work also integrates the DPS test data obtained with the use of APPS.

Subject to the accepted definition, the explosion-proof electric equipment is the equipment which structure could be damaged due to internal arc discharge, however its fragments shall be within the normative safety area near the equipment. The safety area size shall be calculated as the equipment sample diameter (width) scaled up by its two heights, but no less than by 1.8 m. The high pressure energy pulse, which satisfies the above stated equipment' damage conditions, can be considered as the equipment explosion-proof degree.

ARC DISCHARGE IN TRANSFORMER OIL

Works [3–7] details the results of our studies of the arc discharge effect in the HV OFEE sample equipment. Further on we only present basic arc discharge characteristics detailed in the above mentioned documents. The test conditions are as close as those established in industrial HV OFEE after a short-circuit, when current can rapidly increase to 10–30 kA within 3–10 ms. The maximum arc current is 30 kA with 1–3 ms build-up time. Total arching duration is 3–20 ms. Maximum arc heat generation (Q_a) is 0.1 MJ. Up to 5 kV charge voltage capacitive storage is used as an energy source. In HV OFEE, the arc discharge power gains its peak during the second semi-period; then the arc discharge voltage and power are dropped due to decrease of specific electrical resistance of insulating liquid.

The arc discharge burns up between two Ø20 mm parallel brass electrodes, the distance between the electrodes varied 17 to 30 mm. The electrodes are installed in 61 liter chamber with ID 310 mm. The liquid volume is 35 l. The remaining volume (26 l) is filled with nitrogen under atmospheric pressure. The arc discharge spot to 'liquid-gas' interface distance is 100 mm. The discharge is initiated by applying (≈3 kV) voltage to the electrodes linked with a Ø0.1 mm copper wire.

During the test we measured the discharge arc current and voltage, pressure in the liquid and the gaseous cavity above it. The pressure sensor (PS) response time is less than 0.5 ms. One PS is installed near the chamber lower flange, while the second is 50 mm from the liquid upper level. We also made a video recording of the discharge development with 0.1 ms time resolution, and the 'liquid-gas' interface video recording with no less than 0.8 ms resolution. Grade GK transformer oil was used for the test under consideration.

Fig. 1 contains the arc discharge current and voltage oscilloscope patterns. The arc discharge time (≈7.5 ms) is close the current half-wavelength at industrial frequency. The oscilloscope patter depicts a sharp voltage rise at start up which follows by fast voltage drop after explosion of initiator and formation of plasma medium. Subject to the estimations, the high voltage peak duration (≈20 µs) is synchronous with the initiator electric explosion. The voltage ripples at the current decay pattern (Fig. 1) are, probably, due to the movement of the arc along the electrode surfaces. The arc movement speed is about 20 m/s. Based on the analysis data the arc column stretches out under own magnetic field, this rises the arc voltage and then results in the shunting breakdown and voltage drop. According to the estimates, the arc column typical electric field strength is 0.1–0.3 kV/cm.

CURRENT AND VOLTAGE OSCILLOSCOPE PATTERNS

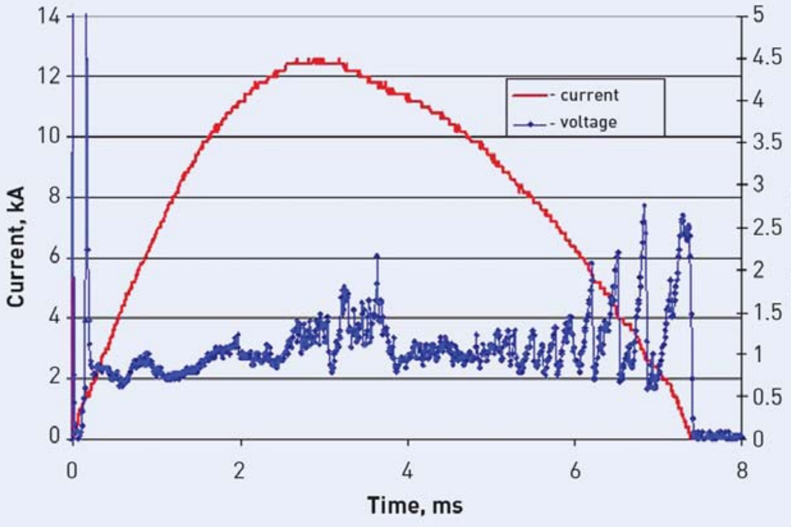

Fig. 1

High-speed video recording of the discharge shows that initially the plasma medium glowing occurred near the electrodes. A that moment the glowing area was expanding at the rate of ≈0.3 km/s, but, after 0.5 ms, this rate decreased approximately by three times, i.e. the plasma expansion speed is much less than the sound speed (≈1.4 km/s) in electric insulating oil [8]. The plasma radiation overlapped the inter-electrode space ≈1 ms after the arc discharge initiation.

Fig. 2 describes the 'oscilloscope patterns' for the liquid pressure near the chamber bottom. It is clear that the arc pressure has the pulse and periodic dynamics. This is especially obvious at the start of the arc burning, within ≈3 ms, when the first six pressure extreme values (maximum and minimum vales) followed with almost a constant interval of ≈0.8 ms. There is a correlation between the PS signals and voltage oscilloscope patterns. Thus, the 'smeared-out' voltage maximum value corresponds to the initial pressure maximum value.
The absolute maximum pressure ≈1.7 MPa (Fig. 2) recorded 3.71 ms after the arc discharge preceded by the voltage jump up to 2.2 kV, which had happened 3.64 ms after the arc (see Fig. 1). It seems that, under a sharp voltage drop (breakdown), intensive acoustic waves are generated in the liquid.

ELECTRIC INSULATING OIL (EIO) PRESSURE NEAR THE BOTTOM FLANGE

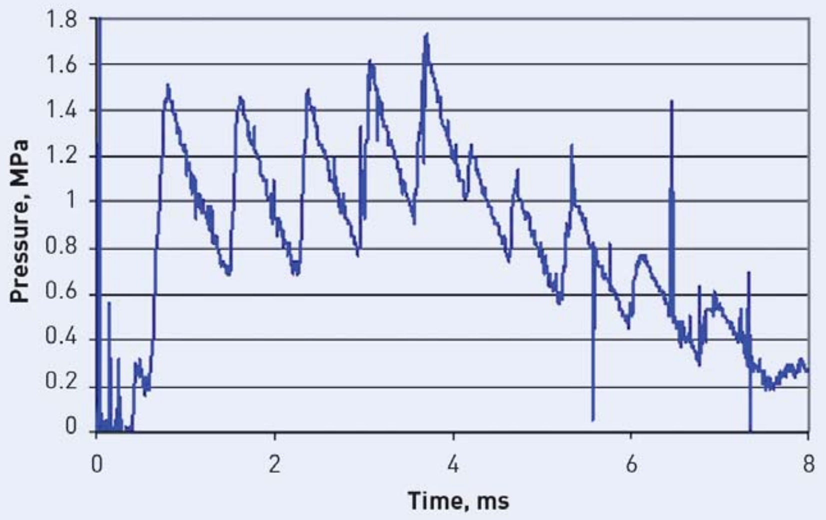

Fig. 2

The expanding gas-vapor bubble lifted the electric insulating oil which resulted in gas compression and boost of pressure the gas. As it can be seen in the video, the liquid level gradually goes up to the height of ≈0.1 m, and then the vapor-gas mixture outbreakes to the area filled with nitrogen. Here, the specific liquid rise velocity is 10–20 m/s. The available data allows estimating the arc discharge energy balance components. In the test under consideration the energy value Q_a is 64 kJ, while the maximum liquid flow kinetic energy is 3–5 kJ, i.e. 5–10% of all the arc discharge energy. The main portion of the Q_a energy is consumed for the arc discharge heating and decomposition.

After the discharge in the electric insulating oil, the excessive pressure of 10–50 kPa is observed in the nitrogen "cushion". This pressure value is proportional to the gas volume generated during the electric insulating oil decomposition. This oil decomposition process can be described as the gas producing factor B_g which represents the ratio of the produced gas volume to the arc discharge energy Q_a. Based on our data, $B_g = 0.11$ l/kJ.

The volume of the gases, proportional to the energy Q_a, defines a HV OFEE internal pressure value, that is why the energy Q_a can be considered as an explosion safety measure.

The completed tests help determine qualitative features of the arc discharge dynamic effect on HV OFEE casing. And the basic fact is that there is no explosive wave in liquid. The medium pressure buildup rate is 0.3–0.5 MPa/ms. While the pressure in the chamber builds up we can observe intensive acoustic waves. The maximum pressure on the chamber wall is ≈2 MPa. With the specific 'liquid-nitrogen' interface rate of 10–20 m/s the pressure can reach 5–10 MPa in the vapor-and-gas bubble.

PULSE PRESSURE ARCLESS SOURCE

The arc discharge studies results served as basic requirements to an arcless pulse pressure source which can be used to simulate the arc effects on HV OFEE. In APPS, the pressure pulse is produced during expansion of explosive gas flow (EGF) generated upon burning of explosive materials. Here it is essential that the pulse pressure has a long exposure time — about 50 ms. This condition excludes the necessity to use hexogene or trotyl to produce EGF with necessary explosive materials' parameters. During the test we used powder explosive which burns much slower compared to trotyl. The explosive material burning rate is 3.8 kJ/g, specific gas generation is 0.9 l/g.

The EGF generator is a high-pressure chamber with an expanding nozzle (de Laval nozzle) used for the explosive material combustion products to flow out. The pressure pulse value and duration can be controlled by varying the nozzle section area, explosive material weight and distribution in combustion chamber. The test was conducted in the same chamber which was used for the arc discharge tests. The EGF generator is connected to one of the windows so that the EGF impact area is, approximately, the same as for the arcing. Electric insulating oil and water are used as process liquids. During combustion of explosive material the calculated heat output Q varies from 10 to 50 kJ.

We measured pressure in the specific chamber points, and we also made high-speed video recording of the liquid flow under the EGF effect. Based on the measurement results, the flow pressure is 10-20 MPa at the inlet to the liquid; it takes about 1 ms for this pressure to set. The flow to liquid exposure time varies from 20 to 60 ms. Typical pressure value for the chamber walls is 1 MPa. Under the EGF effect the flow parameters of the 'liquid-gas' interface, submerged to the liquid, are similar to the arc discharge effect with the same impact energy. This interface remains flat and rises at 10–20 m/s. It should be noted that there is no noticeable difference for the response of water and electric insulating oil to the EGF effects.

The completed tests show that we are able to somehow simulate hydraulic flow of liquids under the EGF and arc discharge effects. Equivalency of liquid flow under the EGF and arc discharge effects can be obtained by equality of both energy and exposure time. If this condition is met, the EGF generator (APPS) can be used to simulate the arc discharge effects on the HV OFEE casing. First APPS's units were designed to 0.5 MJ impact energy; in modern APPS the energy is increased by an order of magnitude (Fig. 3).

We use APPS to assess explosion safety of series HV OFEE [6, 9] and to test efficiency of available and future HV OFEE explosion protection means [10]. HV OFEE can also be utilized to obtain input data for the development and verification of numeric methods for calculation of advanced HV OFEE design and explosion protection systems.

EXPLOSION-PROOF TEST OF SERIES HV OFEE

HV OFEE were used to test explosion safety of series instrument current transformers (CT), voltage transformer (VT), and coupling capacitors (CC). Detailed test results are presented in the works [6, 9], here we will submit only summarized data. The tests procedure was agreed with PJSC FGC UES, part of PJSC Rosseti Group of Companies. Names of manufacturing plants and tested equipment, typical current values at internal faults and expected specific arc energy values are presented in Table 1. The arc energy is estimated based on the short-circuit current and HV OFEE data submitted by manufactures. For these tests the instrument transformers were filled with grade GK electric insulating oil; phenyl-xylyl-ethane-based dielectric liquid was filled to CC.

During the test, PS were installed inside HV OFEE at various distances from the EGF inlet point; we also conducted a high-speed recording from two mutual-perpendicular locations, the time resolution was less than 3.3 ms. Contact detectors were installed on the tested equipment c/w protective bellow compensating valves to record the valve motion. The EGF impact area corresponded to the most probable short-circuit range.

Table 1 also indicates the APPS exposure time estimated based on PS data. Short pulse duration (10 ms) for the CC tests means that the CC casing is damaged during the tests, which resulted in pressure discharge. In both cases, the casing fragments were thrown outside the standard safety area. That is why the coupling capacitors type CMA-110/√3-6,4 and type CMA-166/√3-14 are not explosion-safe with impact energy 1 and 1.5 MJ respectively. Fig. 4 illustrates CMA-166/√3-14 coupling capacitor (CC) after being tested with impact energy 1 and 1.5 MJ. Repeated tests with lower APPS energy show that the coupling capacitors type CMA-110/√3-6,4 and type CMA-166/√3-14 are not explosion-safe with impact energy 0,5 and 1 MJ respectively.

When testing NKF-110 II G voltage transformers (VT) (make — KO 'Zaporozhie High-Voltage Equipment Plant' (ZZVA)) the VT casing was partially damaged which resulted in the release of electric insulating oil, however, all disintegration products, including the electric insulating oil were within the standard safety zone.

The tests helped us determine explosion-proof level of the tested equipment and find solutions to improve the equipment withstandability to pulse pressure effects. Thus, the initial TT design type TFRM 330 (KO ZZVA) was 'rejected' — after the high-pressure pulse was applied, the electric insulating oil jet sprayed out of the TT casing for more than 30 m. The manufacturer made necessary improvements to the TT design. Subject to the repeated test results this transformer is approved as explosion-safe upon 1 MJ energy impact, with additional 'safe capacity' for 1 MJ power requirement.

PULSE PRESSURE ARCLESS SOURCE 5 MJ BEFORE PROOF TESTING

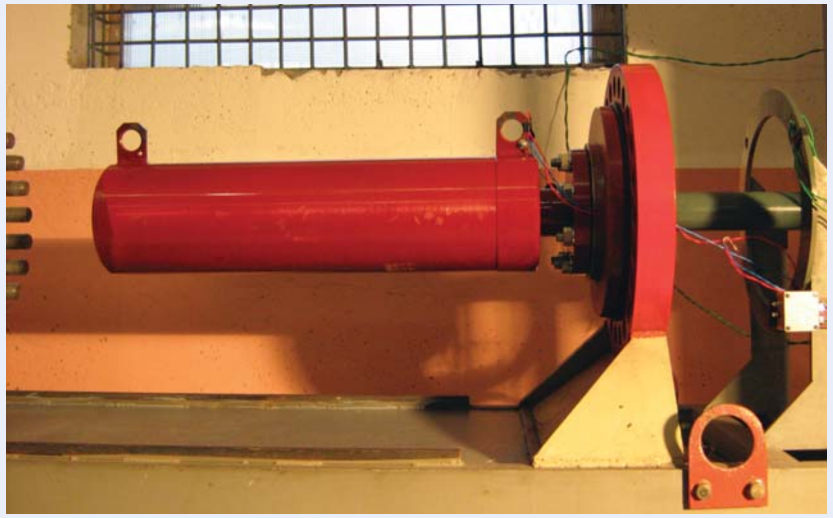

Fig. 3

HIGH-VOLTAGE OIL FILLED ELECTRICAL EQUIPMENT TESTED WITH APPS

Item No.	HV OFEE denomination	Maker	Short-circuit current range, kA	Energy Q_a, MJ	APPS exposure time, ms
1	CT type TBMO-110	JSC Ramensky Electrotechnical Plant Energy	1.5–3	0.4	60
2	CT type TFRM 330	KO ZZVA	5–10	1	60
3	VT type NKF-110 II G	KO ZZVA	15–20	1	70
4	CC type SMA-110/√3-6,4	JSC UKKZ	1–2	0.5; 1	50; 10
5	CC type SMA-166/√3-14	JSC UKKZ	2–3	1; 1.5	50; 10

Table 1

CC TYPE SMA-166/√3-14 AFTER THE TEST: 1 MJ (LEFT) AND 1.5 MJ (RIGHT)

Fig. 4

SPECIFIC CHARACTERISTICS OF TRANSFORMER EXPLOSIVE RUPTURE

Based on available literature sources it is known that the power transformer internal faults are more frequent in HV leads, oil filled cable trays and on-load voltage control devices (LVC) [2]. The arc discharge is produced near the short-circuit spot — between transformer casing ('earthing') and high-potential structural elements. The arc column length which determines the arc voltage may vary from 0.1 to 0.3 m depending on HV OFEE design. The arc discharge constantly and chaotically moves on the surface under ponderomotive and convective forces. Since the arc discharge (AD) typical speed is about 10 m/s, while its 'lifetime' is ≈50 ms, the transformer surface area exposed to AD is ≈0.1 m^2. That is why the arc discharge (AD) moves inside the volume of about 10–30 l. In particular, this fact explains why there are no impact waves indie HV OFEE despite high AD power.

After the short-circuit the transformer casing serves as one of AD electrodes. As a consequence, the high pressure area is adjacent to the transformer wall, this points to the fact that AD produces a local effect to the transformer casing. The time required to balance the pressure inside the transformer tank is estimated as a double time period for which the acoustic wave passes the maximum distance between the transformer opposite walls. For instrument transformers up to 330 kV with 0.5 m^3 tank volume (similar to those discussed in the previous section) the pressure balance time is ≈1 ms, i.e. this is much lesser than AD combustion time. As for size VII distribution transformers, the pressure setting time is ≈15 ms. This means that there is high pressure drop in large transformers, and the peak pressure drop is in the AD combustion area. Based on these estimations the following fact can be pointed out: the pulse pressure will destroy ('blow out') small-sized transformers in a relatively smooth manner across the entire surface. We observed such types of damages during our tests of instrument transformers.

Damages of large-sized transformers are typically local, and the damaged surface area is not more than 10% of entire transformer surface. An example of such type damage is presented in page 66.

Maximum excessive pressure withstandable by transformer casing depends on its design, short-circuit location and pulse duration. Subject to general requirements there shall be elastic deformation of the casing under excessive static pressure of 0.05 MPa. Plastic deformation can be observed when the excessive static pressure is over 0.2 MPa. Dynamic loading of the casing may result in explosion damage if more than 0.5 MPa excessive pressure is maintained for more than 5 ms.

It is most probable that potential explosion conditions are produced 10 to 30 ms after AD. During the initial AD combustion phase, approximately within the first 10 ms, the pressure cannot reach critical values in the transformer. At a later AD phase, approximately 30 ms after, the explosion probability decreases. First, the AD electric power dramatically decreases due to the growth of insulating liquid electrical conductivity which results in a lower rate of gas generation in AD as well a slower pressure buildup rate. Second, the tank size expansion effect (due to deformation) is observed by that time. This additional volume partially compensate for pressure buildup due to electric insulating oil decomposition.

Based on the above facts we can state the following basic HV OFEE explosion-safety requirements:

- time required to response to pressure buildup in the tank shall not exceed 5 ms;
- the system shall limit maximum tank pressure to 0.3–0.5 MPa.

If the entire transformer surface can not be protected a protection system must be installed in the vicinity of specific/problematic transformer units.

TEST OF PROTOTYPING EXPLOSION PROOF SYSTEMS

All currently known HV OFEE protection systems are focused on creating additional volume ΔV for expansion of electric insulating oil if the pressure builds up after AD.

The following relation is used to assess efficiency of protection system:

$$k = \frac{\Delta V}{B_g Q_a} \qquad (1)$$

Relation k, which can be presented as a protection system reliability ratio, is a relation between the additional volume filled by electric insulating oil to the gas volume produced due to the electric insulating oil decomposition. We can use two specific reliability ratios, k_1 and k_2, in accordance with the following definition:

- if $k > k_1$, the HV OFEE tank features, in general, elastic deformation, and the equipment is explosion-proof;
- if $k < k_2$ the tank explosive damage can be expected;
- with intermediate reliability ratio ($k_2 < k < k_1$) major plastic deformation of the casing is expected.

The following specific reliability ratio $k_1 \approx 0.7–0.8$; $k_2 \approx 0.1–0.3$ are accepted as provisional.

Two method for producing additional volume for electric insulating oil are discussed in available literature sources. The first method is based on using damper porous material on transformer internal surface [11]. It is expected that, under high pressure, this material compresses and produces necessary additional volume. Additional protective effect can be gained if the material compression ratio is rather high so that a major part of the flow kinetic energy will be consumed for compression. The 'porous coating' method is only effective provided that sufficient compression of porous material takes place with a relatively low overpressure — approximately 0.3–0.5 MPa, and hence the modulus of rupture shall not exceed 0.5 MPa.

The second protection method is a so called 'burst membrane' method. It includes installing protective membranes on the HV OFEE casing; the membranes are destroyed upon AD pulse pressure, and the electric insulating oil will leak through the membranes to a special tank [12]. This protection method is used, for example, in SERGI's Transformer Protector system.

Summarized test results of the described protection systems are presented below [10].

For the 'porous coating' test we used a HV OFEE mockup steel, cylindrical tank, volume = 0.95 m^3, height = 1.45 m with a cone nozzle in the bottom. The volume diameter is 1 m, wall thickness is 7 mm. The upper cover is fixed to cylinder with 24 bolts M12. Thickness 50 mm foam plastic plate made of density 0.04 kg/dm^3 pressed granulate was glued to the cover internal surface. The tank was filled with water. APPS was installed 0.2 m from the cover, the APPS designed energy value is 0.35 MJ.

During the tests, the tank cover (near APPS) was lifted by 0.8 m, while only 3 of 24 fixing bolts remained undamaged. After the test it was discovered that one of the cover ends curved by 50 mm, the foam plastic material crushed to fine fraction. This tests shows that a porous wall does not protect HV OFEE casing. We expected such result. In fact, in order to ensure efficiency of this system it is necessary that, during the period while the pressure builds in the liquid (3–5 ms), the increase in volume due to compression of porous environment would compensate for the pressure boost. This can be achieved either with a relatively slow pressure boost, not more than 0.1 MPa/ms, or with a small protected area of about 0.1 m^3.

The following estimates are used to illustrate low efficiency of this method. If a transformer typical size is a, then, if its internal surface is coated with a damper coating with maximum compression h, possible increase of available volume for electric insulating oil is:

$$\Delta V \cong 6a^2 h \qquad (2)$$

Under the pulse pressure effect the coating will be equality compacted only if the tank volume is up to ≈0.5 m^3. Taking into account that a≈ 0.5 m and h ≈0.02 m, using (2) we can calculate that ΔV ≈ 30 l. This can be enough to ensure effective explosion protection with the arc energy of 0.5 MJ (Vg ≈ 55 l, k ≈ 0.6).

For larger sized tanks the coating is effectively compacted only near the short-circuit location with a total area of about 1 m^2. In this case the additional volume ΔV is ≈20 l. With AD energy Q_a≈1 MJ (Vg≈ 110 l) the protection system efficiency is k ≈ 0.2, i.e. explosive rupture of the tank can be expected.

In general, the porous coatings that can be compressed under 0.3–0.5 MPa pulse pressure, with 1 MPa modulus of rupture, can be used in explosion protection systems for HV OFEE' tanks up to 0.5 m^3 if the expected AD energy is not more than 0.5 MJ.

Fig. 6 illustrates HV OFEE mockup system used for the 'burst membrane' test. This mockup model is equipped with a cylindrical tank filled with water. The tank was covered with a thickness 12 m steel cover. Centered hole 200 mm in diameter was covered with 0.2 mm aluminum foil.

Concrete blocks that serve as transformer winding were installed 300 mm from the cover. The APPS operating range was between the concrete blocks and the cover, 0.2 m from the cover centered hole, opposite pressure sensor D2. Pressure sensor D1 was used to sense the pressure in the air space behind the membrane, pressure sensors D3 and D4 were used to measure the pressure in the liquid, away from APPS. The high pressure energy is 1 MJ, while the pulse duration is 50 ms.

The on-membrane contact sensor recorded the membrane rupture 3 ms after startup of APPS. The water through membrane flow rate (measured based on the air pressure in the cavity behind the membrane) is 20 m/s. Liquid pressure is 1.8 MPa. Based on the high-speed recording data, the HV OFEE mockup casing deformation lasted 10–15 ms. Upon completion of the test it was discovered that the steel cover permanent deformation is approximately 40 mm. For this test we tried to create "ideal" conditions for the protection method under consideration: a large diameter thin membrane was installed opposite the pressure boost epicenter. However, this system could not protect the tank from major deformation effect.

HV OFEE MOCK-UP USED TO TEST A BURST MEMBRANE-TYPE PROTECTION SYSTEM

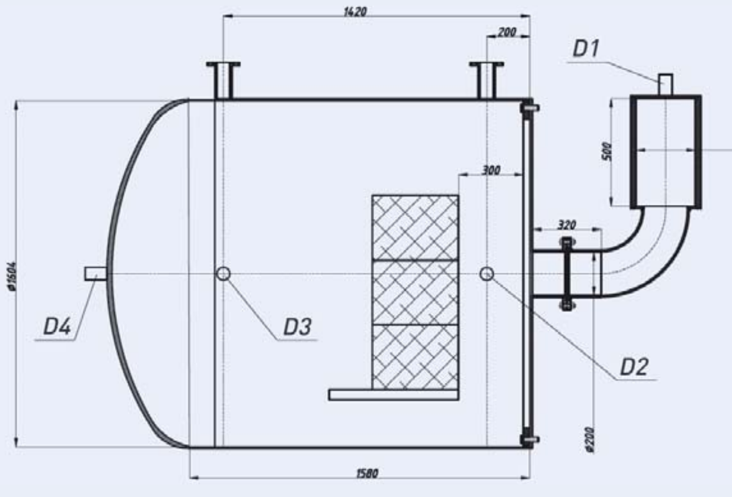

Fig. 5

The explosion protection system in Fig. 5 is a simplified version of the Transformer Protector (TP) system which is being delivered to Russian energy plants within the past years. However, we can not confirm that this system is successful in operating environments. Thus, on September 22, 2009 internal fault at substation (SS) Mashuk resulted in explosion damage of autotransformer AT-1 casing with installed TP system. SERGI's experts explain the failure of TP system in their report [13]. In accordance with the reported data [13] the AD current was 10 kA, AD combustion time — 60 ms. When analyzing the TP system operation the experts proceeded from the assumption that AD voltage was 37 kV, so, Q_a energy was about 11 MJ. 37 kV voltage value, obtained with no due consideration for voltage drop on inductive impedance, seems to be over-estimated. Based on our estimates, AD pressure was much lesser, so AD energy was about 4 MJ. With this energy value Q_a the volume of the generated gases is ≈0.45 m^3.

Subject to [13], diameter 8 inches burst membrane (≈200 mm) ruptured ≈4.5 ms after SC, under excessive pressure of 0.08 MPa. Some volume of electric insulating oil leaked through the ruptured hole, this resulted in the tank 'depressurization' after 112 ms. The tank peak pressure is 0.6 MPa. According to the experts [13], this TP prevented fire development though it failed to protect the HV OFEE casing against explosion rupture. However, based on the data [13] on the electric insulating oil flow velocity, less than 25 l of oil passed through the membrane during AD combustion period. That is why the reliability ratio k ≈0.05 is valid for the protection system made of (1); thus, TP is not able to protect the HV OFEE tank against explosion rupture. The probability of fire development after explosion is not more than 15% [2], in addition to this the energy value Q_a is relatively low.

DYNAMIC PROTECTION SYSTEM TESTS

Based on the analysis data the known HV OFEE explosion protection systems are not effective, new systems should be developed. This section summarizes test data of the dynamic protection system (DPS) developed by Shatura branch of JIHT RAS. The DPS key elements are movable spring loaded blocks (Fig. 7), total area is 1 m^2, installed on the transformer side surface near most probable short-circuit locations. Maximum shift of the block, impacted by the pulse pressure, is ≈0.3 m.

The DPS tests were conducted on (AT) 25 MVA decommissioned transformer, however all interior structure elements were retained. The autotransformer (AT) with installed DPS elements and blue protective housing is presented in Fig. 6. 16 movable blocks are installed under the round housing, and 35 blocks are under the square housing (see Fig. 6). Protective chamber with APPS inside is presented in Fig. 7 (left side). No DPS systems installed at transformer rear sides, special protection diagram is installed only on 1 of 3 high-voltage leads.

For this tests we used APPS of 1 to 3 MJ and from 30 to 50 ms exposure period. High-speed video recording (up to 2000 frames per second), four pressure sensors and motion sensors data were used for efficient diagnostics of the tank casing deformation process. For this test the AT tank was filled with water.

A series of ten tests was conducted. The pressure pulse was applied to most probable short-circuit locations on both transformer sides, including HV lead. We applied high pressure to the AT rear wall with DPS installed: we observed major plastic deformation of the casing and partial damage of structure elements, however, there were no leakages. Based on the available video recording data, the DPS blocks start to move approximately 5 ms after HP pulse is applied.

Main test results:

- maximum pressure in AT rises almost proportionally to the APPS energy: the peak pressure is 0.5 MPa at 1 MJ, and 1 MPa at 3 MJ;
- major deformation of AT casing w/o DPS takes place 20–30 ms after HP pulse is supplied;
- motion speed of the DPS spring loaded blocks increases upon increase of the APPS energy, i.e. 30 m/s at 3 MJ;
- DPS actuation time is much lesser compared to the factory-made explosion protection system (membrane);
- DPS, installed opposite the pressure pulse injection area, protects the AT casing against major plastic deformation up to the pulse energy of 3 MJ.

Based on the estimates and taking into account the tested configuration, the DPS reliability ratio is k 0.5. The explosion protection reliability can be improved by 30–50% if DPS is installed on both transformer sides and all HV leads.

DYNAMIC PROTECTION SYSTEM (VALVE UNIT W/O HOUSING)

Fig. 6

AUTOTRANSFORMER WITH DPS BEFORE TESTS

Fig. 7

CONCLUSIONS

It is shown that the pulse pressure arcless source can be used to simulate the AD dynamic impact on high-voltage oil filled equipment. This pressure source was used to estimate explosion-proof levels of series instrument transformers and coupling capacitors; existing and advanced explosion protection system models underwent testing.

Burst membrane was used as a mockup protection system for oil filled equipment. The test results show that the membrane does not protect the casing against major deformation and damage.

Test data of dynamic protection system on 25 MVA autotransformer give us grounds to anticipate that this system protects the autotransformer casing against explosion damage with the impact energy at least 3 MJ.

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