The SDIPF reliability curve of old EHV power transformers

A historical review for utilities when developing specifications for new transformers - Part III

ABSTRACT

The further development of UHV and EHV transmission lines and the ageing of large power transformers (half of which are over 30 years old) keep the developers of specifications of new transformers working for many years to come. To help them, a historical overview of the failures of EHV transformers in the 20th century was made in terms of modern Asset Lifecycle theory embedded in the SDIPF curve (Specify – Design – Installation - Potential failure – Failure), has been made. The main causes of accidents were shortcomings in Specify and Design.

KEYWORDS:

bathtub curve, creeping discharge, EHV and UHV power transformer, failure, geomagnetic disturbances (GMD), geomagnetically induced current (GIC), GOST, harmonics, IEC, IEEE, internal insulation, safety margin, SDIPF reliability curve, ZTZ

Vitaly GURIN, Terrence O'HANLON

The first ZTZ transformers 330–500 kV and 735 kV transformers in Hydro-Quebec had massive failures, mainly due to insulation problems.

Polzuchy razryad damaged several dozens of ZTZ's ATs and GSUTs of 330–500 kV and several units of 220 kV transformers, and the damage of 330 kV units was much more significant compared to 500 kV transformers

5. Disadvantages of *Design* and *Production* – causes of failures of Zaporizhzhya transformers 330-500 kV in the 1960s

In the 1950s and early 1960s, in the USSR, 220 kV transformers were manufactured in accordance with GOST 1516-60 [1], in which the insulation levels were determined by the protective characteristics of lightning arresters of the RVS type. Given the higher insulation levels, the insulation reliability issues in these transformers were practically non-existent.

New, much better surge arresters of the RVM and RVMG types limited not only lightning surges but also internal overvoltages. This made it possible to significantly reduce the insulation levels and manufacture 330–500 kV transformers with transportation to the installation site in their own tank (previously, the first 400 kV transformers were transported in a semi-disassembled state). Note that the reduction of insulation levels improves the technical and economic characteristics of transformers. For transformers of 330 kV and above, each per cent reduction in test voltages due to a reduction in insulation distances allows reducing the total mass of the transformer by 0.4–0.7 % and increasing power with the same dimensions by 0.6–0.8 % [2].

The first 180 MVA 330 kV GSUTs and 240 MVA 330/150 kV autotransformers (ATs) left the factory in 1961, and the first 210 MVA 500 kV GSUTs and 250 MVA 500/110 kV ATs in 1963. The range of 330–500 kV transformers expanded significantly in the period up to 1966, when they were discontinued due to massive failures, mainly due to insulation problems.

Insulation of power transformers is cellulose-based, namely paper and paperboard, impregnated with oil. The most loaded insulation element is oil, the strength of which is 3-4 times less than the strength of impregnated solid insulation. Therefore, during overvoltage, the process of breaking electrical strength can begin with a breakdown of an oil layer or a narrow oil wedge (due to moistened cellulose fibres, pollution such as dust, carbon or metal particles) or a breakdown of gas bubbles with a diameter of more than 1 mm. Initially, these single breakdowns (measured as a PD of a few hundred pC) leave white (non-carburized) marks on the surface of the solid insulation, which, in the absence of repeated breakdowns, disappear without problems for the insulation. With frequently repeated breakdowns, solid insulation carburizes at the point of sparking. Further, this carburized part acts as a sharp conductive needle, which increases the electric field strength in the rest of the insulation. With successive overvoltages, carburized traces gradually but irreversibly propagate on the surface or in the depth of solid insulation. This process is reflected in measurements as unstable strong PDs of several units, tens and hundreds of nC [3]. Since this type of insulation breakdown has not one discharge channel but many in the form of a tree structure (Fig. 1), it is known as a breakdown due to treeing (the creeping discharge or ***polzuchy razryad*** in Russian). The development of a *polzuchy razryad* in time has a flashing, not a monotonous character (see Note 1).

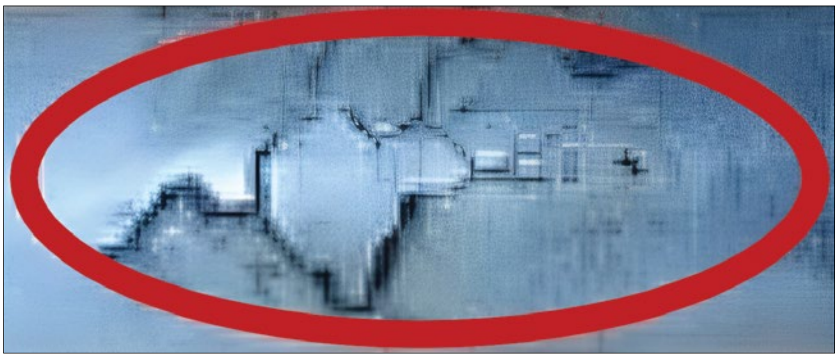

Figure 1. The polzuchy razryad

Note 1. In 1966, one of the authors measured the PD on a damaged 330 kV transformer (*polzuchy razryad*) delivered to a factory for repair. Before repair, the transformer was tested, including PD measurements. When maintaining the nominal voltage for an hour, only one short-term (about 2 seconds) PD flash of about 100 nC was observed. For the rest of the time, PD above 30 pC was not recorded. Dismantling showed extensive tree-like charred traces with a total area of about a square meter on the first cardboard cylinder of the main insulation under the HV winding.

Often, gas bubbles (hydrogen, methane) formed during strong PDs get stuck inside solid insulation or between pressed cardboard strips and remain undissolved, which significantly accelerates the process of insulation destruction up to the complete overlapping of the entire distance between the electrodes with carburized tracks and emergency shutdown of the transformer.

In total, *polzuchy razryad* damaged several dozens of ATs and GSUTs 330–500 kV and several units of 220 kV transformers (damage to interfacial insulation). The damage of 330 kV transformers was about an order of magnitude greater than that of 500 kV transformers. For both voltages of 330 and 500 kV, the damage of ATs was higher than that of GSUTs. The authors failed to restore the true number of damaged transformers. At that time, only ZTZ produced 330–500 kV transformers. But this period is not reflected in the reference list of this plant, which includes transformers starting only from 1970 [4].

Five 330 kV transformers failed due to a breakdown in the connection of two parts of the HV winding to the ground (Fig. 2). Usually, the number of turns in the Y-Bm section is 50 % of the total number of turns of the HV winding. Insulating gaps indicated by arrows in Fig. 2 are rated for 50 % ACSD applied to the HV terminal. In addition, these gaps must withstand the impulse voltage that occurs at the Vm point with 100% LI applied to the HV terminal. These failures were caused by the poor design of the isolation of these gaps (the design was later changed). Perhaps there was also an accumulation of water at the bottom of the tank, which penetrated through the upper seals of the bushings and caused a sharp decrease in the electrical strength of the insulation [5].

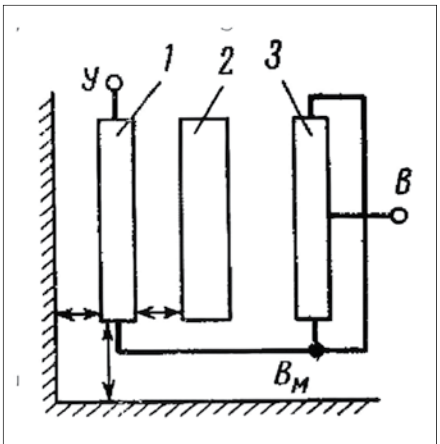

Figure 2. The layout of the windings in the GSUT in the case of a double concentric HV winding (1 - the inner part of the HV winding, 2 - LV winding, 3 - the outer part of the HV winding)

Similar damage occurred in autotransformers (Fig. 3). In these cases, the voltage value in the lower part of the windings depends on the ratio ACSD, and LI applied to the HV and MV terminals (330/110, 330/150, 330/220, 500/110 kV).

To eliminate *polzuchy razryad* problem, ZTZ underwent restructuring with improvements made in design, production processes, insulation drying methods, testing, and equipment

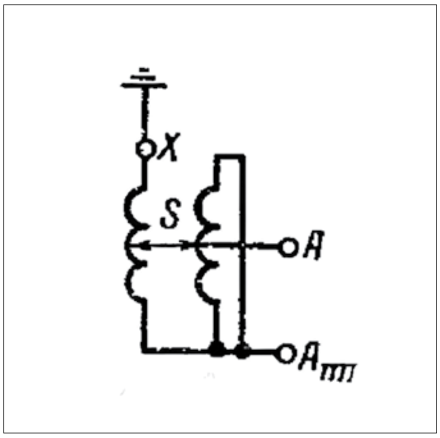

Figure 3. A typical AT winding connection diagram.

Several 330 and 220 kV three-phase transformers had phase-to-phase insulation problems. These damages were attributed to the imperfection of the design of the spacer elements of the phase-to-phase insulation. Six damages to the longitudinal insulation of the 330 kV windings were attributed to defects in the winding wire. Six autotransformers 330 kV failed due to design flaws in the tap changer 110 kV (water ingress into the contactor) [5]. Part of the failures was caused by metal particles as a result of the destruction of low-quality oil pumps of the Elektroapparatura plant (Bendery, Moldova).

In the 1960s in the USSR, the quality of transformer insulation was tested only by the ACSD test. The design of the insulation was considered to be verified by type tests LI and chopped LI. (SI and ACLD have not yet been introduced into factory practice). Insulation margins for 220–500 kV transformers as a ratio of ACSD to the highest phase voltage Um /√3 are given in Table 1. As follows from column 4 of the table, this ratio (equal to 2.19) is the lowest for 330 kV transformers, which indicates the lowest margin of safety; it is 5 % higher for 500 kV transformers and 25 % higher for 220 kV transformers.

To eliminate the *polzuchy razryad* problem, a fundamental change in the ***Design*** of transformers and a restructuring of all technological processes for the production of ZTZ were required. It has become a rule to check the design of the main and longitudinal insulation on physical large-scale models; numerous techniques have been developed to ensure an acceptable voltage distribution along the winding are disc type, the requirements for winding wires have been tightened, samples have been created for making transitions in windings, bending wires, and soldering in windings; modern steel cutting machines were purchased, the design of the core was changed; old insulation drying methods have been improved, and new methods have been introduced (including drying with kerosene vapor), the residual pressure has been reduced from 20–30 mm to less than 1 mm Hg; at the test stations, a technique for measuring PD was mastered, including at 100 % ACSD, a technique for ASLD and an assessment of

Table 1. Margins of the safety of insulation of Soviet transformers 220-500 kV manufactured in the 1960s.

Rated voltage kV r.m.s.	Highest voltage Um / kV r.m.s.	Short duration (1 min) induced withstand voltage ACSD / kV r.m.s	ACSD / (Um / √3)
220	252	400	2.75
330	263	460	2.19
500	525	700	2.31

The improved *Design* was also applied to 500 kV transformers for Egypt delivery which began in 1967, and where more than 300 transformers were developed, manufactured and operated without problems.

the results of this test were developed; equipment was purchased and a method for testing SI was mastered by applying a pulse to the LV side of the tested transformer, which provided a longer test pulse and, accordingly, a more severe test than when a pulse was applied to the HV side; LI testing has become routine for GSUTs 330 kV and above; specifications for purchased bushings and oil pumps have been tightened; the requirements for the installation and maintenance of transformers have been tightened.

As a result of the change of ***Design*** and manufacturing, the accident rate of 330 kV transformers has sharply decreased without changing ***Specify***, and for 500 kV transformers, the insulation level has even been reduced (ACSD to 680 kV in GOST 1516-68, and after the introduction of metal-oxide surge arresters and up to 630 kV – GOST 1516.1-76). Everyone forgot about *polzuchy razryad*. For the period 1970–2018. ZTZ pro-

Figure 4. Hydro-Québec transmission system

duced 1047 transformers of 330 kV, 256 transformers of 400 kV, and 1612 transformers of 500 kV. About 2/3 of them have already passed the standard service life of 25 years, and some have been operating for 50 years or more.

The improved ***Design*** was also applied to 500 kV transformers for Egypt (Aswan HPP and other facilities), the delivery of which began in 1967 and amounted to 81 units. In the following decades, based on these improvements, 750 kV transformers (308 units) and 1150/500 kV autotransformers (18 units) were developed, manufactured and operated without problems.

Conclusions to chapter 5

1. The total number of damaged 330–500 kV transformers is more than 60 units. The reason for most of the failures was *polzuchy razryad*.
2. It turned out that the technical level of 220 kV transformers did not correspond to the reduced insulation strength margins of 330-500 kV transformers. Radical changes in ***Design*** of transformers and restructuring of all technological processes of ZTZ ***Production*** were carried out.
3. An important conclusion for engineers dealing with new specifications is that factory acceptance tests cannot guarantee the reliability and durability of an EHV power transformer if design and workmanship are poor. These shortcomings in our time are designed to eliminate such tools as the design review [6], the quality system documentation, and the quality plan, which are mandatory in the specification.
4. An important conclusion for the customer is that when choosing a transformer manufacturer, preference should be given to suppliers with a proven history of creating reliable transformers for operating conditions similar to your power system.

6. Disadvantages of *Specify* – causes of failures of 735 kV transformers in Hydro-Quebec, Canada in the 1980s

The first ever 735 kV Hydro-Québec transmission system was commissioned in 1965. It transfers power from hydroelectric plants in northern Quebec to a loading zone in the south and is V-shaped, with La Grande generation on the western axis and Churchill Falls/Manicouagan on the eastern axis (Fig. 4). The length of the two main transmission lines is approximately 1000 km.

From 1965 to 1985, Quebec underwent a massive expansion of its 735 kV power grid and its hydroelectric generating capacity

Over the next twenty years, from 1965 to 1985, Quebec underwent a massive expansion of its 735 kV power grid and its hydroelectric generating capacity. In January 2000, TransÉnergie Corp. became responsible for the operation of the Hydro Quebec transmission network.

The authors were not able to find information about the transformer failures during the first 15 years of Hydro-Québec transmission system operation. The first failure reported in the literature occurred in December 1980 (see 6.1).

6.1. 735 kV transformers at James Bay – December 1980 and April 13, 1981

The 2012 Federal Register [7] reports *(quote)*: *"In December 1980, a 735 kV transformer failed eight days after a geomagnetic storm at James Bay. A replacement 735-kV transformer at the same location failed on April 13, 1981, again during a geomagnetic storm. However, analysts and tests by Hydro-Québec determined that GIC could not explain the failures, but abnormal operating conditions may have caused the damage."*

The same failures are described in the 2022 book "Extreme Space Weather" [8] *(quote)*:

"Expensive 735 kV transformer at Hydro-Quebec's facility on James Bay, Canada, failed during a great red auroral display in 1980. Four months later, another major auroral display occurred and destroyed the transformer's replacement."

6.2. The GSUTs 400 MVA, 735 / 13.8 kV at the La Grande-4

La Grande-4 (LG-4), part of the Hydro-Québec James Bay project, can generate 2,779 MW, and it was commissioned in 1984–1986. There is a disagreement between the scientific and engineering communities of view on the reasons for the failure of these transformers during the superstorm on March 13, 1989.

Experts in the field of geomagnetic storms believe [9,10] that with an instantaneous load shedding (Fig. 5) temporary overvoltages (load-rejection overvoltages) of 1.6 p.u. or more led to irreversible damage to the internal main insulation transformers.

2:45:24.996	Fault on La Grande 4 transformer T1, Phase C	~ 1.6
2:45:25.003	Fault on La Grande 4 transformer T3, Phase A	~ 1.8

Figure 5. The sequence of events: Hydro-Quebec blackout March 13, 1989 (Time, EST / Failure / Voltage level, p.u.)

Experts in the field of geomagnetic storms believe that with an instantaneous load shedding, temporary overvoltages of 1.6 p.u. or more lead to irreversible damage to the internal main insulation transformers

Malewski and colleagues from IREG (Institut de recherche d'Hydro-Québec) state that the failures of strategically important LPTs in the 735 kV Hydro-Quebec system have been going on for several years

However, Hydro-Quebec analysts and testers are confident that abnormal operating conditions may have been the cause of the damage [11]. A task force set up by the Power System Studies Department has been tracing the cause failure of six transformers to recommend suitable corrective measures. The study included a review of the equipment design, oil analysis of all the transformers LG-2, LG-3 and LG-4, characterization of the effect of particles on the dielectric withstand, and a special program of overexcitation tests. The personnel of the high-voltage and high-power laboratories as well as the Cables and Insulation Group contributed to this work. The results show that the cause of the transformer failures was the presence of aluminium particles produced by the vibration of steel tabulators in the aluminium tubes of the cooling circuit. Laboratory tests have revealed that a particle concentration as high as that suspected at the time of the failures reduces the dielectric strength of the oil by up to 30 %. The task force, therefore, recommended that to ensure the other transformers at LG-4 are reliable, the oil should be carefully filtered, and an induced voltage test at 1.6 p.u. be performed in situ.

6.3. Works by Malewski [12, 13]

Malewski and colleagues from IREG (*Institut de recherche d'Hydro-Québec*) state that the failures of strategically important LPTs in the 735 kV Hydro-Quebec system have been going on for several years. In a 1990 CIGRE report, the authors write that *"Hydro-Quebec recently lost six generate transformers rated 400 MVA, 735/13.8 kV, which developed a breakdown of the main insulation"*. Fig. 6 shows one of the types of faults in the HV winding.

The failure rate of 735 kV power transformers in operation is four to five times higher than in a low-voltage transmission system. Transformers from different manufacturers are damaged. No correlation with any particular brand.

The initial investigation did not provide clear answers as to why so many EHV units failed. Almost every fault has a specific cause, such as oil, contamination, prolonged overload and localized overheating, dynamic winding stress, etc. These are undoubtedly good reasons, often confirmed by post-mortem analysis, but these problems are not unique to 735 kV transformers.

Growing concerns about the reliability of the 735 kV EPS and the too-high rate prompted Hydro-Quebec several investigations of the cause of the problem. The adopted insulation coordination method was reviewed, and system transient studies were initiated.

The IEC [14] and ANSI [15] standards allow a large tolerance in choosing the actual value of the test voltage, which is specified

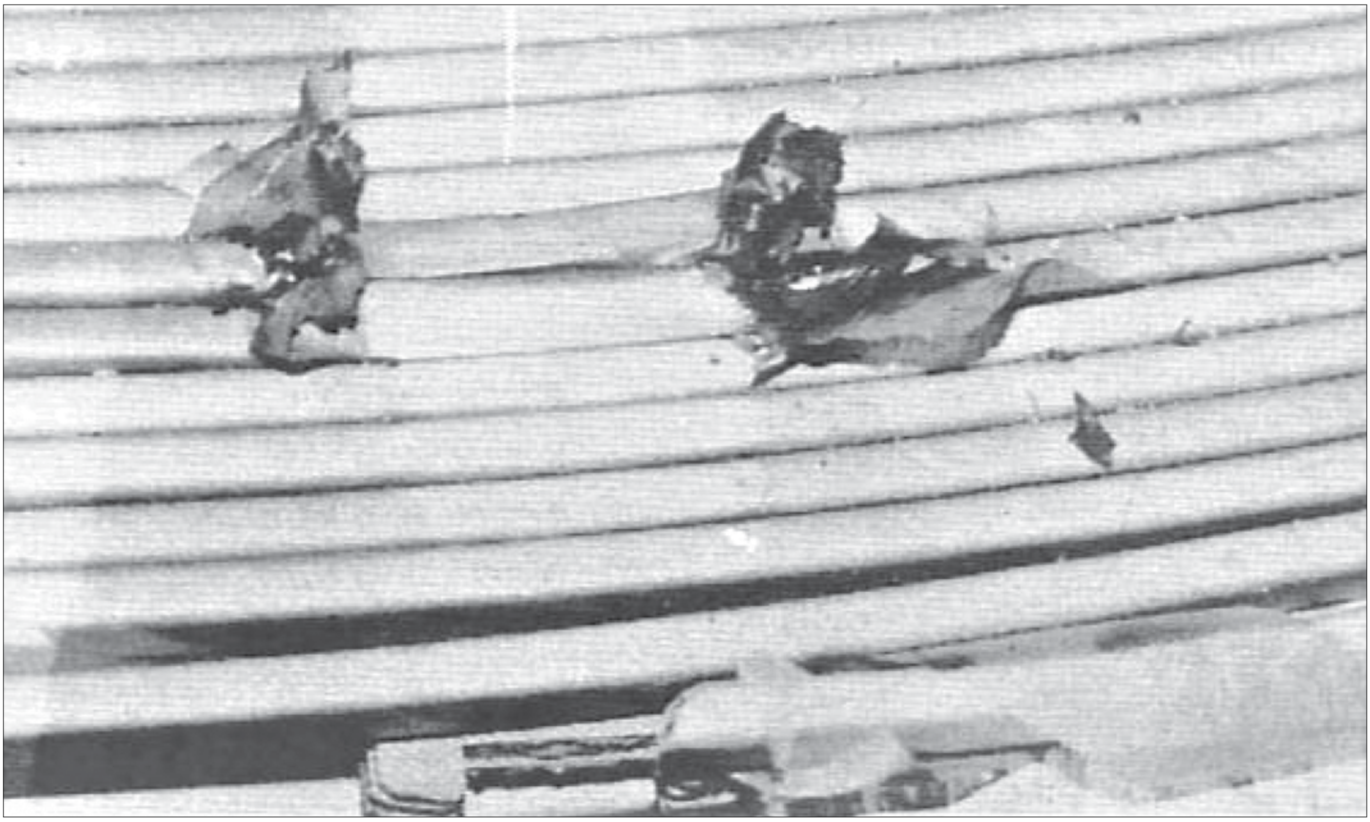

Figure 6. Turn-to-turn punctures found in the discs adjacent to the site of the fault of the main insulation [13]

in the customer's specification. This tolerance and the ratio R of the standard test voltage to the operating voltage for different transmission levels are shown in Fig. 7.

Although the final decision on transformer insulation and, therefore, the margin of safety is in the hands of the user, any increase in the test voltage leads to a significant increase in the cost of the EHV transformer, which is already the most expensive device in the substation. Thus, economic considerations have forced the public to compromise their testing requirements and compensate for the reduction in insulation strength of the transformer by using less expensive but presumably reasonably efficient arresters and circuit breakers.

Also, in the highly competitive transformer market, designers cannot afford more insulation than is required to pass the four critical tests: ACSD, SI, LI, and chopped LI.

For detailed studies of internal high-frequency oscillations in the winding, excited by a steep overvoltage applied to the HV terminal of transformers, an automatic measuring system has been developed that digitally records the transient processes generated during switching in the system and during lightning strikes. The severity of these transients was assessed by comparing them with factory test voltages. Critically stressed areas of insulation inside the transformer were determined: a) using a digital winding model, which gives the amplitude and shape of the wave appearing on the insulation of each winding element both at operating voltages and during tests; b) direct measurements on open windings during the study of damaged 735 kV transformers at the Hydro-Quebec repair facility and during the manufacture of a 735/13.8 kV 400 MVA transformer at the manufacturing plant.

The main conclusions from the works of Malewski:

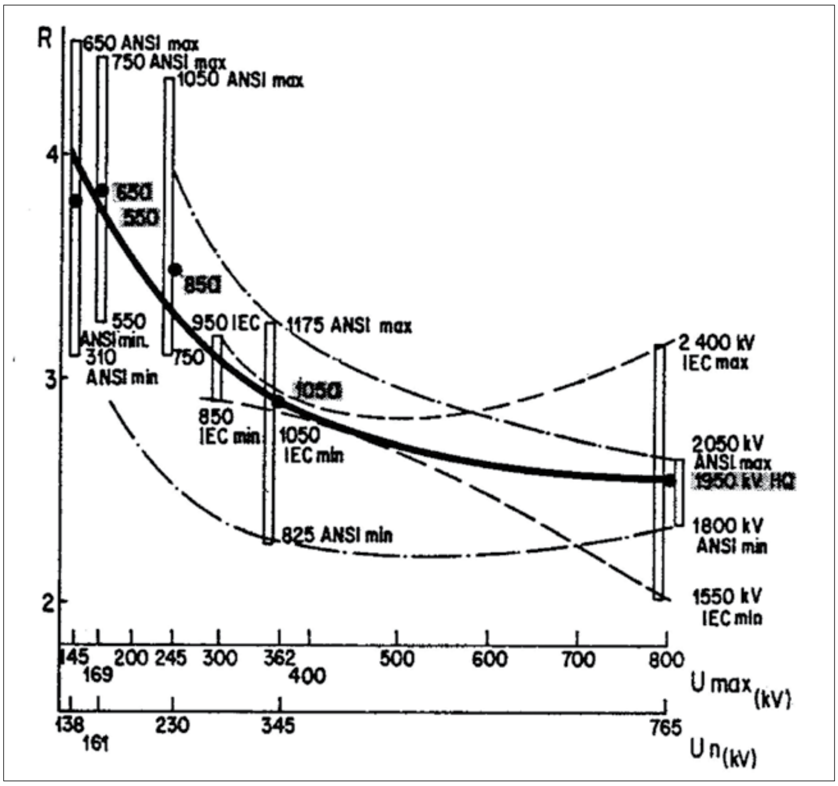

Figure 7. Ratio R of the impulse test voltage (BIL) to the rated system voltage Un plotted against the maximum system operating voltage Um. The limits of the BIL voltage Specified by IEC and ANSI are indicated together with the levels Specified by Hydro-Quebec (*Source*: [12])

Final decision on transformer insulation and safety margin is in the hands of the user, while the increase in the test voltage leads to a significant increase in the cost of the EHV transformer

- Insulation strength margins of 735 kV transformers are significantly lower than those of transformers of lower voltage classes. This is due to the lower test voltage levels of 735 kV transformers.
- Switching overvoltages generated by circuit breakers can reach high levels comparable to the applied voltage during testing at the factory.
- The highest level of transients occurs during the shutdown of autotransformer 735/345 kV on the 345 kV side. This procedure should be excluded.
- Even in cases where the generated transients in the system do not exceed the protection level and the arrester does not operate, steep overvoltages can cause dangerous internal resonant oscillations in the HV windings.
- It is necessary to update the technical specifications for new EHV transformers.

NOTE 2. The authors regret that they were not able to discover the following source, which is directly related to this chapter:

Baril, C. A., Jolicoeur, A. Kamel, N. McGillis, D., *Analysis of the Reliability Performance of 735-kV Transformers of Hydro-Québec*, COPIMERA, Cartagena, October 1989.

6.4. About the number of failed transformers 735 kV

A 2021 paper on transformer failures with oil spills [16] reported (*quote*): *"According to a Hydro-Quebec survey of 74 major failures in their 735 kV network. The main cause of oil spills is tank rupture, representing 68 % of cases. Bushing failures cause 24 % of spills, and the remaining 8 % are due to failure of other components (valves, radiators, pressure vents or gaskets)"*.

For even more interesting information about the total number of failures of

735 kV transformers, see the 2006 book on optimizing power system reliability and economics [17]. The book gives an example of calculating the probability of failures of PT in the form of exercise 3.2 (*quote):*

"Example 3.2 – 735 kV Power Transformers

Assume that one wants to determine the probability of having in the present year. The number of major failures of 735 kV power transformers is based on a total of 600 units. Observations during a certain period have shown 100 major failures of 735 kV power transformers over a total of 4,000 transformer-years."

Conclusions to chapter 6

1. There were ~ 100 major failures of 735 kV transformers from various manufacturers, including 74 oil spills, over a total of 600 units.
2. Various reasons for failures are given: geomagnetic storm, major auroral display, temporary overvoltages (load-rejection overvoltages), abnormal operating conditions – aluminium particles, long-term overload and local overheating, dynamic load on the windings, oscillatory transient, having a frequency close to the natural resonance of the winding.
3. However, no one doubted the insufficient safety margin of the insulation of 735 kV transformers.
4. An important conclusion for engineers dealing with new specifications is *Specify's* shortcomings in terms of internal insulation requirements have been a major cause of 735 kV transformer failures in Canada. Impulse test voltage (BIL) has been and remains a paramount specification requirement.

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Authors

Vitaly Gurin graduated from Kharkov Polytechnic Institute (1962) and graduated from school at the Leningrad Polytechnic Institute. Candidate of technical sciences in the Soviet scientific system (1970). For 30 years, he tested transformers up to 1,150 kV at ZTZ, including the largest one of that time in Europe, and statistically analysed the test results. For over 25 years, he was the Executive Director of Trafoservis Joint-Stock Company in Sofia (the diagnosis, repair, and modernisation in the operating conditions of transformers 20–750 kV). He has authored about 150 publications in Russian and Bulgarian and is the main co-author of GOST 21023.

Terrence O'Hanlon, CMRP, is the Publisher of Reliabilityweb.com®, RELIABILITY® Magazine and Uptime® Magazine. He is certified in Asset Management by the Institute of Asset Management and is a Certified Maintenance & Reliability Professional by SMRP. Mr. O'Hanlon is the acting Executive Director of the Association for Maintenance Professionals (AMP). He is the executive editor and publisher of the 5th edition of the Asset Management Handbook. He is also a voting member of the US TAG (PC251) for ISO 55000 - ASTM E53 Asset Management Standards Committee. More recently, Mr. O'Hanlon has been selected as the sole US Representation through ANSI for ISO Working Group 39 to create a standard for competence in assessing and certifying asset management programs known as ISO 17021-5. Mr. O'Hanlon is also a member of the Institute of Asset Management, American Society of Mechanical Engineers, The Association of Facilities Engineers, Society of Maintenance and Reliability Professionals and the Society of Tribologists and Lubrication Engineers.