The SDIPF reliability curve of old EHV power transformers

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

ABSTRACT

The further development of UHV and EHV transmission lines and the aging of large power transformers (half of which are over 30 years old) will 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 Life-cycle 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

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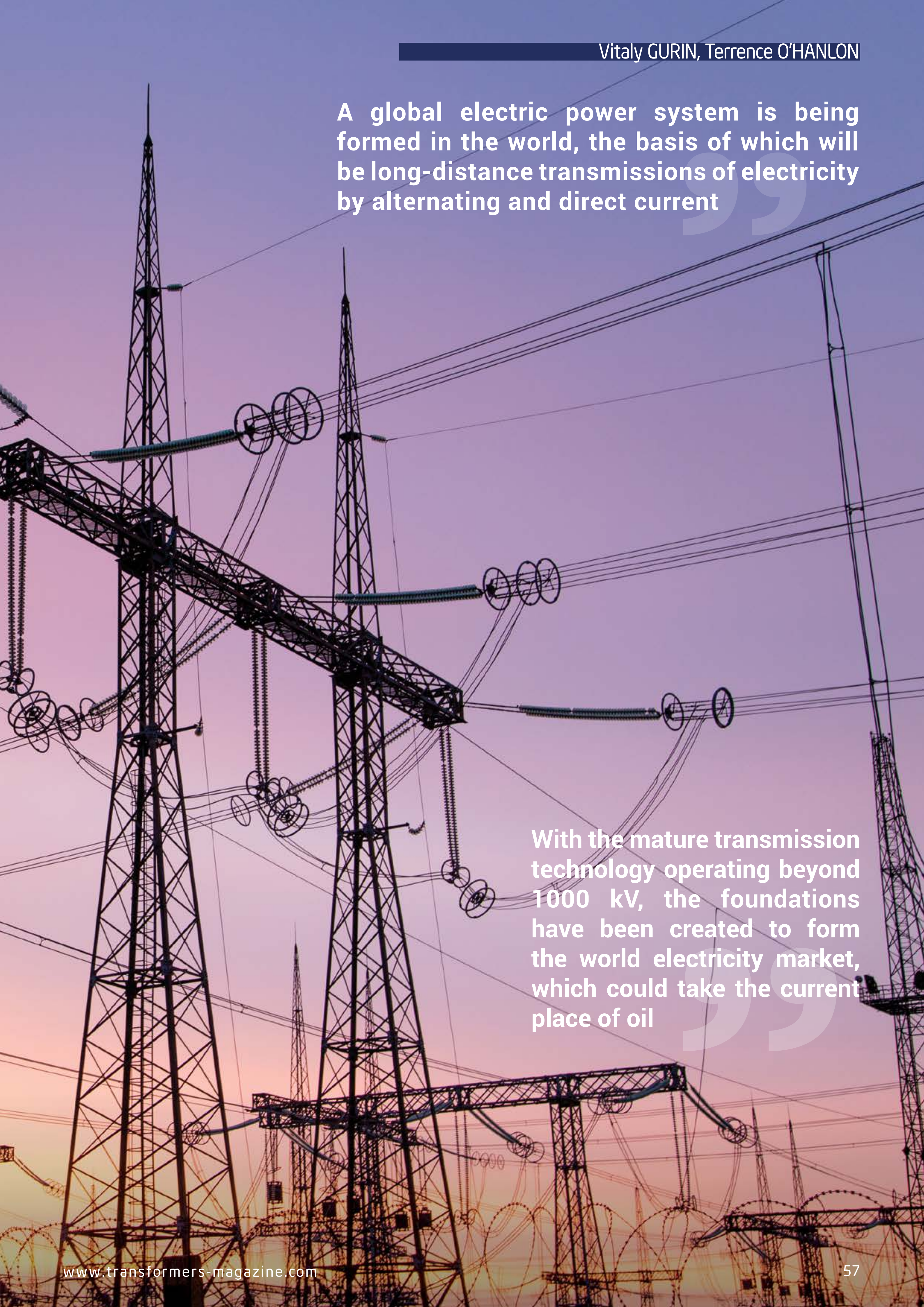

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With the mature transmission technology operating beyond 1000 kV, the foundations have been created to form the world electricity market, which could take the current place of oil

1. Introduction

Engineers for the development of specifications for new transformers will not be left without work for a long time, according to the authors, at least half a century. There are two reasons for this: the further development of electric power transmission over long distances and the aging of the existing fleet of power transformers.

2. Growing demand for new power transformers

2.1 Status and development prospects of EHV and UHV voltage power transmission

A global electric power system is being formed in the world, the basis of which will be long-distance transmissions of electricity by alternating and direct current. The transmission at voltages of 1,000 kV and ± 800 kV can be considered mastered. A transmission line with a voltage of ± 1,100 kV is being built. The target is to master the voltage of 1,500 kV. China has become the world leader in this field. DC transmission lines at UHV will create continental and transcontinental connections. The field of application of AC transmission lines EHV and UHV is the efficient distribution of electricity over a large area [1].

In China, the first 500 kV AC transmission line was commissioned in 1981, 750 kV in 2005, and 1,000 kV in 2009. In 2010, the first AC step-up transformer was successfully developed in China, allowing 1 GW 27 kV generators to be connected directly to the 1000 kV UHV network. Previously, connections were made by two-stage transformation (27/500 and 500/1000 kV), which required an intermediate transformer and more complex circuitry. At present, eight 1000 kV alternating current transmission lines have been built in the PRC with a total length of about 5,310 km and the length of individual lines from 240 to 1,050 km, with an average value of about 660 km.

However, the first EHV transmission lines were created in the USSR, Canada and the USA.

In the USSR, in 1956, an AC transmission line Kuibyshevskaya HPP–Moscow with a voltage of 400 kV and a length of 815 km was put into operation, which in 1959 was, for the first time in the world, used for transferring at 500 kV. In 1967, a 750 kV AC test transmission line Konakovo–Moscow, 87.7 km long, was put into operation, and in 1975, a 750 kV transmission line Leningrad–Konakovo with a length of 525 km was put into commercial operation. On the world's first transmission line, 1,150 kV Siberia–Kazakhstan–Urals with a length of 2,344 km at a voltage of 1,200 kV, the sections Ekibastuz–Kokchetav (since 1985) and Kokchetav–Kustanai (since 1988) operated. However, after the collapse of the USSR in 1991, the entire transmission line was switched to a voltage of 500 kV. Now in Russia, system-forming functions and intersystem communications are performed mainly by 500 kV transmission lines. Their total length exceeds 40,000 km (single-circuit version), while the length of 750 kV transmission lines is about 4,000 km.

The world's first industrial 735 kV AC transmission line was built in Canada in 1965. The development of the 735 kV network in the eastern part of the Canadian power system was driven by the need to transfer electricity from large hydroelectric power plants on the rivers of northwestern Quebec to power centers located at a distance of 1,000 km. six main transmission lines – 735 kV were built (see further chapter 6). In the eastern part of the country, the 500 kV network has become widespread.

In the US, two AC voltage systems are being developed: 115-230-500 kV and 156-345-765 kV (see further chapter 7). The first 500 kV transmission line was put into operation in 1965, and the 765 kV transmission line in 1969. The role of backbone and intersystem connections is performed by power lines 345–765 kV.

There is a 400 kV AC network in Eastern Europe, although, before the collapse of the USSR, small sections of 750 kV power lines operated in Poland, Hungary and Bulgaria as a link to the Ukrainian power system. In Ukraine, the main networks are 330 and 750 kV. In Western Europe, the main network is considered to be 220–380 kV. Networks of higher voltage are not widespread. This is due to the fairly even distribution of electrical loads and power plants in Europe and the high density of electrical networks. The rapid development of electricity generation based on RES in the north of Europe urgently requires the transfer of large volumes of electricity to the central and southern regions.

Intensive power grid construction based on UHV power lines is being carried out in many Asian countries, in addition to China. The backbone of Japan's backbone network is 275 and 500 kV transmission lines, and those of South Korea are 345 kV. At the same time, in Japan, in 1993, a 1,000 kV AC transmission line was put into operation, linking the Kashiwazaki nuclear power plant with Tokyo. In South Korea, since 2004, a 765 kV AC transmission line has been in operation. Their main task is to supply power from large nuclear power plants.

In India, Asia's third-largest electricity producer, the backbone grids are 400 kV and, since the year 2000, 750 kV. It is planned to create a large National network of 1,200 kV superhighways.

Powerful electric power systems are being formed in South America, primarily in Brazil and Argentina. The highest AC voltage in Brazil is 765 kV. There is also a 500 kV line network, separate 400 kV lines and a 345 kV network. Argentina is developing a 500 kV AC network. The total length of the relevant transmission lines in the country has exceeded 10 thousand km. The development of the existing gigantic hydropower potential stimulates the construction of powerful DC power lines on the continent

The African continent is on the verge of explosive growth in power consumption and, accordingly, power grid construction. Many countries have already mastered extra-high voltage. In Egypt, AC networks with a voltage of 500 kV are used, in South Africa – 400 and 765 kV, in Nigeria, Zambia, Zimbabwe and some other countries – 330 kV, in other countries – 220–230 kV. The huge hydropower potential of equatorial Africa, as well as in South America, predetermines the need to build long DC transmission lines to transmit electrical power to remote consumption centers.

Thus, according to the author [1], the foundations have been created for the formation of the world electricity market, which can become a new global energy product and, under certain conditions, take the current place of oil. The need for new power transformers, and hence for engineers for the development of specifications for new transformers, will only increase.

2.2. Expected increase in problems with electricity supply in the world

These problems are not new, they have plagued certain parts of the world for a long time. There have been power outages in India, Australia and Texas recently, just to name a few. Over time, power outages will worsen as loads increases due to ever-increasing electricity consumption (for example, the proliferation of electric vehicles) and aging assets. We are interested in the most expensive asset of electrical power systems (EPS) – large power transformers (LPT). According to literature data, about 400,000 transformers with a maximum capacity rating of 100 MVA or higher and a maximum voltage rating of 100 kV or higher are in operation around the world. At least half of them are over 30 years old (figures 1, 2, and 3).

Many experts predict that the number of failures per year LPT will exceed 2 % in the near future. At the same time, failures of relatively new transformers with an age of less than 30 years will increase faster since they have a shorter service life due to a smaller margin of safety. This is because, in the last half-century, in a competitive environment, manufacturers have focused on the lowest cost of production and not on increasing the reliability of LPT.

In order to avoid failures due to LPT aging at the Bratsk HPP in the USSR, generator step-up transformers (GSUTs) were replaced with new ones after the expiration of the standard service life (25 years) of old transformers. In the recent past, 750 kV substation transformers (ST) in Ukraine have been partially replaced with new ones. These replacements were technically untenable and proved prohibitively expensive. Other mitigation options are the rapid refurbishment and upgrading of LPTs that are reaching the end of their lives. These options also have technical and financial limitations. Other options for mitigating failures are online refurbishment and upgrading of near-end-of-life LPTs. These options also have technical and financial limitations.

Although isolated examples of super-long-lived transformers are known (the Belgian transformers at Dneproges-1 are over 80 years old, and two 132 kV English Electric transformers manufactured in 1912 working in Australia for 100 years), a massive gradual renewal of the trans-

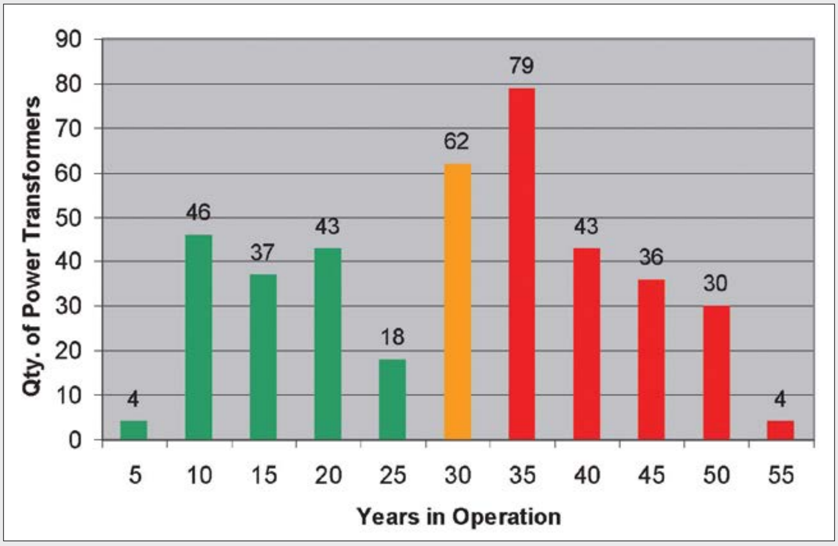

Figure 1. A German utility: 48 % of power transformers (PT) have reached a critical lifetime (> 35 years), only 32 % are uncritical (< 20 years) (Source: Tettex Instruments)

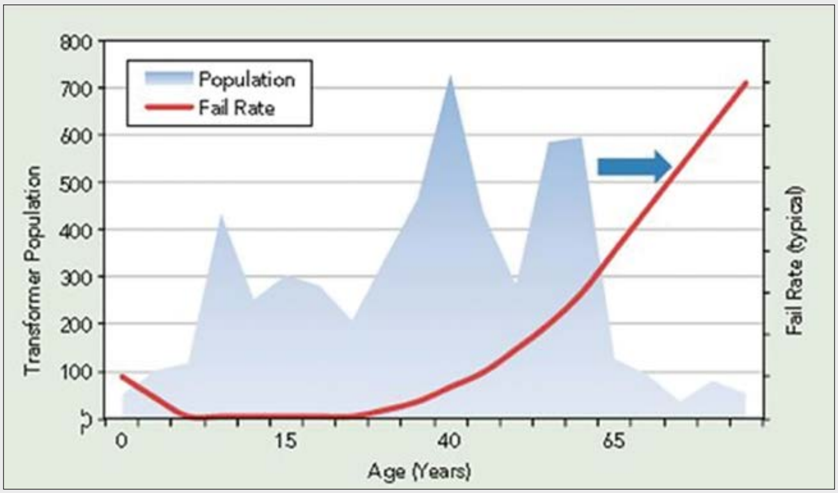

Figure 2. AEP's base of transformers entering a late-life higher failure rate – 33 % of transformers are 50 years or older, and nearly 18 % are 60 years or older. Failure rate rises rapidly after age 40 (Source: American Electric Power (AEP)).

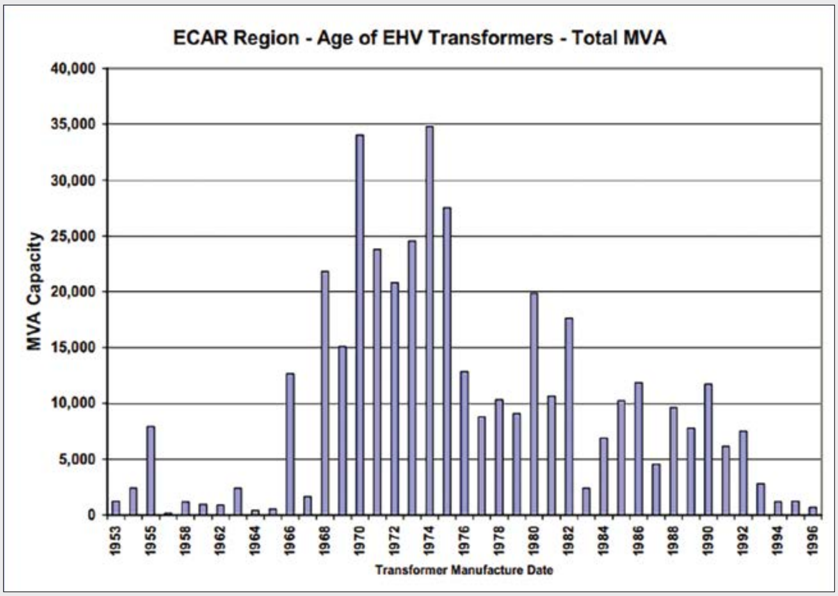

Figure. 3. Age / manufacture dates of installed EHV transformers (345 kV and above) for Europe and Central Asia Region (ECAR). Weighted average age is greater than 30 years (out of a ~40 years of economic life) (Source: ECAR report).

former fleet is inevitable, starting with assets whose condition is of concern. At the same time, utilities are faced with the task of developing technical conditions that should ensure the reliability of new transformers and their durability for at least 40 years. In addition to new specifications, in order to assess the technical condition of the system and predict future failures, reliable information about past failures and the current state of transformers is also necessary for any EPS. The analysis of operating experience helps manufacturers to improve their products. In addition, national and international standards are improved based on service experience and reliability data.

The era of the fourth industrial revolution involves access to the negative experience of operating PT. Openness is increasingly entering the mainstream, pushing aside corporate thinking and models of the past, opening up new opportunities for sharing this information to ensure the reliability of EPS and improve transformers.

In the Soviet press, there was practically no information about the EHV transformers that failed. Only Lokhanin [2], a quarter of a century later, acknowledged the existence of “mass accidents with 330 kV transformers in the USSR” in the 1960s but provided only fragmentary data on these failures. Within the framework of CIGRE, the first international survey of failures of large power transformers (without the participation of the USSR) was for the period from 1968 to 1978 [3]. Then, for a long time, CIGRE could not perform a similar general analysis due to difficulties in collecting information, and incomplete or inconsistent answers during surveys. The second survey took place between 1996 and 2010 [4]. Namely, in the period between these two surveys, peaks of the accident rate of EHV transformers were in Canada and the USA.

To supplement Lokhanin’s information, one of the authors, a young test engineer in the 1960s, had to strain his memory and ask old friends, literally bit-by-bit restoring information about the failures of Zaporizhzhya transformers. The authors could not find information from manufacturing plants about failures of UHV transformers in North America, which is not surprising since we are talking about patented designs. The author found this information from specialists in space weather and geomagnetic storms, operational personnel and employees of scientific and technical institutions.

Thus, the need to replace old power transformers will lead to the need for engineers involved in developing specifications for new transformers.

To better understand the causes of failures of UHV transformers in the 20th century, in the second part of this article, to be published in the next issue of Transformers Magazine, we will consider some important provisions of the theory of reliability, which has undergone significant improvements in recent decades (chapter 3).

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