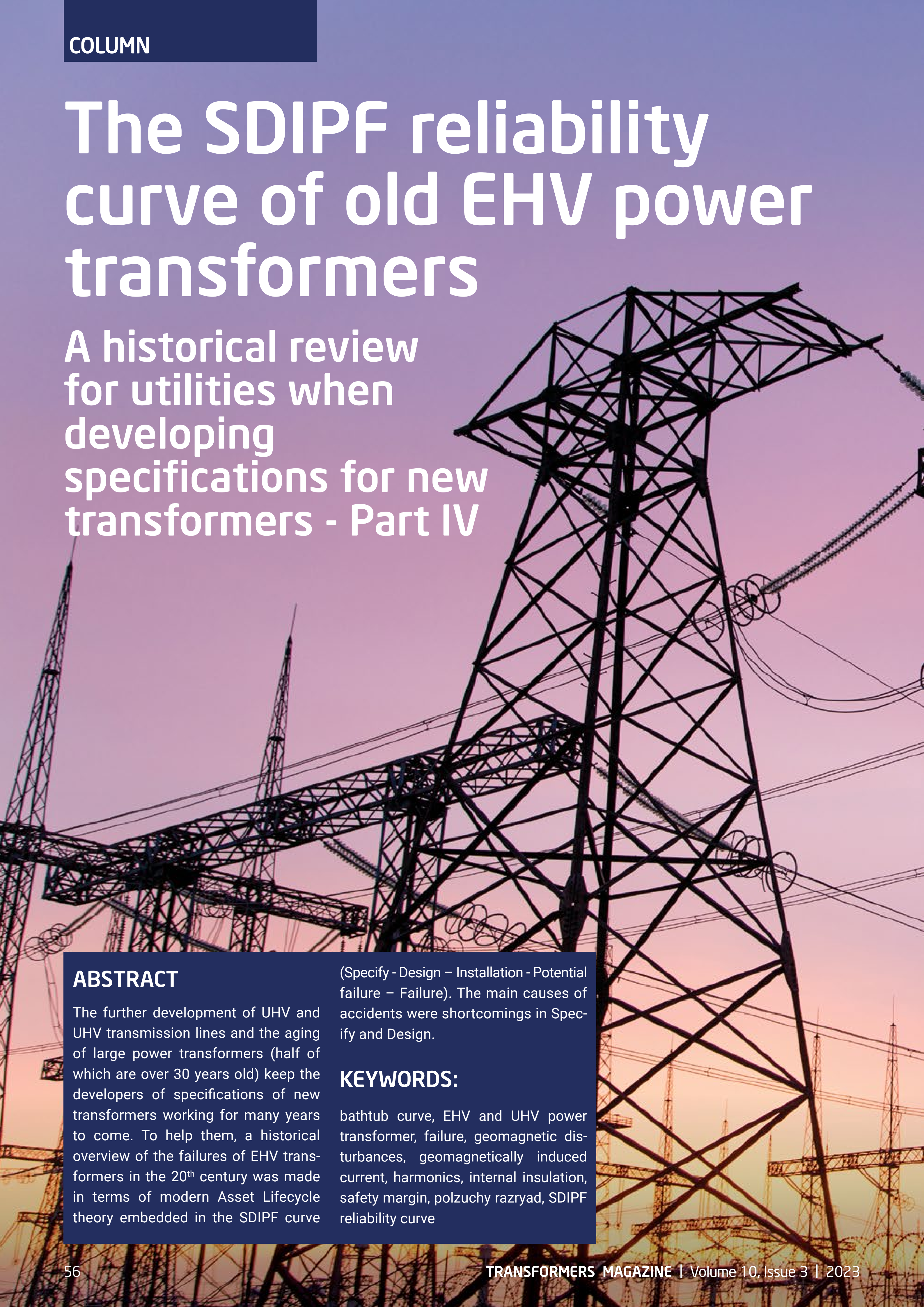


The SDIPF reliability curve of old EHV power transformers

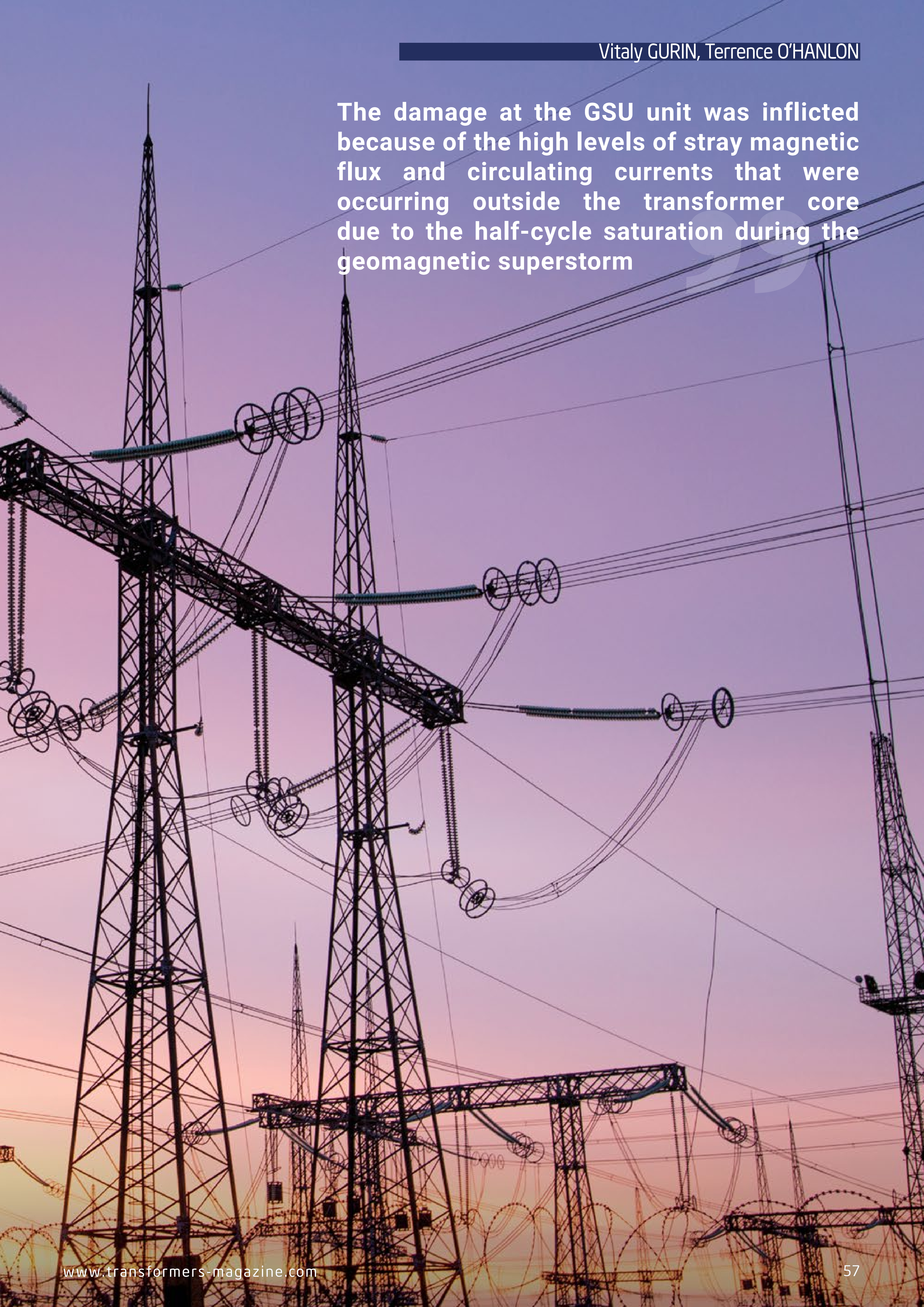
A historical review for utilities when developing specifications for new transformers - Part IV

ABSTRACT

The further development of UHV and UHV transmission lines and the aging 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). The main causes of accidents were shortcomings in Specify and Design.

KEYWORDS:

bathtub curve, EHV and UHV power transformer, failure, geomagnetic disturbances, geomagnetically induced current, harmonics, internal insulation, safety margin, polzuchy razryad, SDIPF reliability curve



The damage at the GSU unit was inflicted because of the high levels of stray magnetic flux and circulating currents that were occurring outside the transformer core due to the half-cycle saturation during the geomagnetic superstorm

> **On 19 September 1989, a geomagnetic disturbance event caused significant GIC flows in the neutrals of the transformers located at the Salem substation, causing minor damage**

7. Disadvantages of *Specify* - causes of failures of LPT and 765 kV transformers in the USA in the 1980s

The geomagnetic superstorm on 13–14 March 1989 also caused the failure of many LPT and EHV transformers. They needed to be replaced, which was something that the US electric power industry was not ready for [1, 2].

7.1. Failures of LPT transformers

7.1.1. Generator step-up (GSU) transformer at the Salem No. 1 Nuclear Plant in Lower Alloways Creek, New Jersey

The GSUT was adversely affected by the solar storm in March 1989. It consists of three single-phase shell form transformers and is rated at 360 MVA, 500 kV grounded Y / 24 kV D. The effects observed during the storm included the following:

- 50 MVAr (14 % of the nameplate rating) increase in MVAr demand
- unacceptable levels of dissolved combustible gases in oil
- high noise levels

The units were removed from service a week later, and internal inspections were conducted.

Figure 1. Damaged transformer at the Salem Nuclear Plant. The insulation burned, and the 24 kV LV winding rated for 3000 A melted [1].

Internal inspection of all three phases revealed the following:

- charred winding series connections between two parallel low-voltage windings
- the degree of burning varied for different series connections
- phases A and C had burnt connections, but phase B was clean

This damage was inflicted because of the high levels of stray magnetic flux and circulating currents that were occurring outside the transformer core due to the half-cycle saturation. When these fluxes concentrate and impinge on regions of the transformer, such as windings and internal structural or tank members not expected to receive such exposure for normal operation, they can lead to almost immediate and severe hot-spot heating insults to exposed internal windings and structures of the transformer (Fig. 1).

Other similar shell-form transformers at this nuclear plant have experienced similar overheating, albeit to a lesser extent. One small impact of GIS may not be enough to damage the insulation, but it can accumulate over several insults before rejection. LPTs are made to order, so the risk of exposure depends on the configuration of the windings and the tank/support construction and is a function of time and magnitude of the incident GIC.

7.1.2. Salem No. 2 Nuclear Plant generator step-up transformer

On 19 September 1989, a GMD event caused significant GIC flows in the neutrals of the transformers located at the Salem substation. This event was suggested to have caused minor damage to one phase of Salem No. 2 Nuclear Plant GSU. The GSU had the same design as that of Salem No. 1 transformers. However, no details were provided in the published literature. This damaged phase of the GSU was replaced during a subsequent refuelling of Salem No. 2.

The peak temperature measurement on the exterior of the tank was 173 °C (internal hot-spot temperatures would have been even higher), and this happened approximately 1–2 minutes after the GIC peak

7.1.3. The autotransformer located by the Allegheny Power System (APS) at the Meadowbrook Substation in Virginia

A three-phase, seven-leg, core shell-form autotransformer, rated at 210/280/350 MVA, 500/138 kV, was affected by the March 1989 solar storm. The effects observed during the GMD included

- high noise levels,
- a significant increase in dissolved combustible gases in the oil,
- bands of discoloured tank paint at four locations,
- a 14 % increase in MVAr demand,
- an increase in harmonic current (THDi = 9.2 %),
- a significant increase in noise level (10–15 dB).

The transformer was removed from service, and a detailed internal inspection was performed, revealing no internal damage. Finite element analysis indicated that the wooden slats sandwiched between the outer periphery of the core and the tank walls blanketed these regions of the tank walls, which contributed to the heating and caused the discoloration of the external tank paint. Citing calculated results from Westinghouse and Allegheny, the temperature of the tank wall was estimated to have reached 400 °C at some locations of the transformer tank. Since there were no other signs of damage, the transformer was returned to service with monitoring of the GIC in the neutral and the temperature at the indicated heating points of the tank wall.

APS experienced an additional GMD event on 10 May 1992. Fig. 2 demonstrates the correlated rise of GIC with tank and oil temperature captured during the event. During the course of the storm, GIC flow in the neutral of the transformer reached a level of approximately 60 A DC (20 A per phase) in about 15 minutes, with a corresponding steady increase in temperature on the exterior of the tank (see Fig. 2). The peak temperature measurement on the exterior of the tank was 173 °C (internal hot-spot temperatures would have been even higher), and this happened approximately 1–2 minutes after the GIC peak. There weren't any significant changes with regard to the oil temperature.

7.1.4. Accidents at 11 other nuclear power plants

Kappenman wrote (quote): *"Other anecdotal evidence, post-March '89, suggested that many other important transformers in the network sustained damage that eventually precipitated failures. Because the U.S. transformer population as a whole is very large and non-homogeneous, it is difficult to fully recognize trends, though studies have confirmed compelling associations between transformer failures over a 25-year period and geomagnetic storm activity. Rather, a rash of failures in the small and more homogeneous population of nuclear plant GSU transformers (~100 units) in the U.S. suggested a compelling linkage to the March '89 storm and GIC exposure. Within 2 years after the March '89 exposure, 11 nuclear plants noted failures of the large GSU transformers, in addition to the Salem failure" [1].*

7.1.5. GSU transformer at the Zion Nuclear Plant (on the outskirts of Chicago)

The catastrophic accident during a moderate storm on 3 April 1994 was so severe that a transformer tank containing thousands of gallons of oil ruptured, causing a major fire in the factory yard, eventually involving control circuits and other sensitive systems. The fire also spread into the generator's hydrogen-cooled isobus inside the plant.

7.1.6. GSU transformers at the Braidwood Nuclear Plant (5 April 1994) and at the Powerton Coal Plant (15 April 1994)

The space weather conditions that gave rise to 3 April 1994 storm were associated with long-term and recurring

Within 2 years after the March '89 exposure, 11 nuclear plants noted failures of the large GSU transformers, in addition to the Salem failure

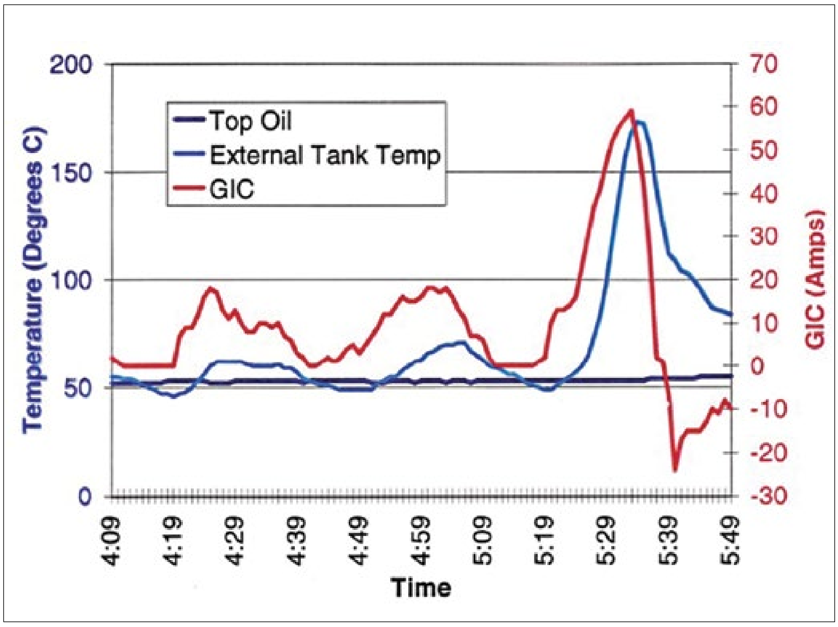


Figure 2. Autotransformer at the Meadowbrook Substation. GIC and transformer tank temperature for the 10 May 1992 geomagnetic storm [1].

> **Since 1989, a lot of work has been done in the scientific and technical communities of North America to investigate the behavior of power equipment during a GMD event and ensure the reliable operation of the EPS**

sources of solar activity occurring from early to mid-April. During this time period, major transformer failures occurred at Braidwood, Powerton and elsewhere to the north, south, east, and west of their location.

Kappenman points out that operators have resisted linking these failures with GIC, although the timing of these events may seem unusually random [1]. In many cases, it is very difficult to unambiguously determine the cause of a failure, given the unique design options of transformers and the completely unknown operational impacts on each transformer. In addition to the reasons discussed in chapter 6 and this chapter, there is a suggestion in the literature that static electricity could also cause a non-GIC failure (see Section 7.2.2, 7.3.4 below). In their report at CIGRE 2012 [3], the authors noted that, during the time since the superstorm of 1989, a number of these failures were studied and found to be caused by backfeed mode operation. In this mode of operation, the GSUTs are not sufficiently protected from switching and lightning surges, and the electrical damping in the electric circuit is very low, making it vulnerable to transient voltage magnification due to winding resonances.

7.1.7. IEEE Standard C57.163-2015

Since 1989, a lot of work has been done in the scientific and technical communities of North America to investigate the behavior of power equipment during a GMD event and ensure the reliable operation of the EPS.

Girgis and Vedante from the Power Transformer Division of ABB Inc. located in St. Louis, Missouri, have made a great contribution in the area of the effects of GIC/DC on power transformers. They developed a methodology to evaluate both the impact of GIC and the GIC capability of transformer designs [4]. The GIC capability of a transformer is defined as the combination of load current and magnitude of GIC that the transformer would operate at without exceeding the loss of life of the transformer insulation beyond what is allowed by industry standards.

Article [5] gives an example of determining the GIC capability of a 750 MVA, 765/345/35.5 kV, 1-phase autotransformer.

Girgis and Vedante are the co-authors of the standard for establishing power transformer capability while under geomagnetic disturbances [6].

7.2. Failure of 765 kV transformers in AEP

American Electric Power (AEP) has the second-largest EHV EPS in North America. Its EHV 345–765 kV transmission has a length of more than 13 thousand km, including a 3400 km-long 765 kV transmission. The New York City Power Authority (NYPA) has a total of 219 km of 765 kV lines. AEP and NYPA operate asynchronously from 735 kV Hydro-Québec and are only connected to the Hydro-Québec through a few DC connection points.

Most AEP transformers were installed 50–80 years ago, and by the mid-1970s–80s, it became clear that EHV transformers had a significantly higher operating failure rate than lower-voltage units, with 765 kV transformers having the highest rate.

Further on, we will consider the failures of 765 kV transformers in more detail and the opinions of the authors of the articles on the causes of these failures. As of 1990, the AEP 765 kV transmission system consisted of 91 circuit breakers, 24 CSUTs, 72 autotransformers, and 84 shunt reactors, all with single-phase designs.

Let us consider the available information about the failures of 765 kV transformers and the opinions of the authors of the articles about the causes of these failures.

7.2.1. Four failures of large EHV ATs in 1974

In [7], four failures of large EHV ATs on the AEP system are described. The failures were initiated by flashovers in the no-load tap changer during system faults. Investigations and tests attribute the flashovers to part-winding resonance. Test data is presented for various terminal conditions and wave shapes corresponding to system transient conditions. The relationship of these tests to ANSI standard dielectric tests is discussed. Corrective measures for existing transformers include arresters tied to an internal crossover connection and capacitor banks connected to the delta tertiary windings.

McElroy, one of the co-authors of article [7], provides a more detailed explanation on the following pages of the same journal [8], stating that the failures of these four ATs were a direct and immediate consequence of transmission line faults as far as 547 km (340 miles) away. The related system transient behaviour is analyzed, and the transformer response to these transients is presented on a quantitative basis. It has been demonstrated, with regard to these transformers, that the ANSI standard dielectric surges offer an inadequate test of winding insulation remote from the terminals, where significant winding resonance is known to occur. The extent of these test limitations to other transformers is discussed.

7.2.2. The single-phase 500 MVA, 765/345 kV autotransformers in 1985

In November 1985, this transformer failed during insulation testing. The point of failure was from the high-voltage winding to the neutral lead. In December 1985, an identical transformer failed violently and caught fire after 7.5 h of service at no load.

> **The GSU transformer failure at Rockport created a unique and complex problem because the only spare transformer available for installation was a design with which AEP had previously experienced problems**

The failure was, again, from the high-voltage winding to the neutral lead. It is surmised that these two transformers failed due to static electrification [9].

7.3.3. The GSU transformer at the Rockport Plant

Article [10] describes extensive engineering studies carried out at the AEP Service Corporation to determine the feasibility of operating a 1300 MW generating unit with an unbalanced GSU transformer bank. These studies served as a basis for plans developed to restart AEP's Rockport Plant, following the failure of a phase three GSU transformer on 17 December 1985, with two remaining single-phase GSU transformers and a dissimilar spare transformer. The GSU transformer failure at Rockport created a unique and complex problem because the only spare transformer available for installation was of a design with which AEP had previously experienced problems. The limitations of the spare transformer resulted in a highly unconventional operating mode for the Rockport generating unit. The transformers failed, with the event occurring during quiescent system conditions, presumably due to transients.

7.3.4. The single-phase, 500 MVA, 76S/26 kV GSUT

In January 1986, this generator step-up transformer failed in service while at minimum load. The failure occurred between a high-voltage series crossover and top leads at the neutral end of the windings. This failure is believed to have been possibly caused by static electrification [9].

7.3.5. Works by Kogan and Wagenaar [11, 12]

Kogan and Wagenaar from AEP, together with the co-authors, reflect the user's point of view on the reliability of the considered transformers as of 1988–90. They point out that the manufacturers of the first 765 kV transformers (the mid-1960s), in an effort to ensure their reliability, laid insulation that exceeded the requirements of the AEP specification. For example, the specification indicated an 1800 kV BIL, but the manufacturers created transformers that could withstand voltages of 1925 kV, 2050 kV, or even higher. Over some time, the manufacturers stopped this practice due to the economic pressure of the declining transformer market. Therefore, the new 765 kV transformers put into operation after 1976 have much lower insulation strength margins.

Kogan and Wagenaar from AEP, together with the co-authors, reflect the user's point of view on the reliability of the considered transformers as of 1988–90

A review of failure statistics for the 765 kV GSUTs resulted in the following observations [12]:

1) The 765 kV CSUTs fail at a considerably higher rate (2.3 %/year) than the 345 kV GSUTs (0.7 %/year).
2) All eight GSUT failures were attributed to dielectric causes. No evidence of mechanical, chemical, or thermal degradation of the insulation was found.
3) The majority of the failures occurred in the total absence of any system disturbance, such as severe weather, elevated system voltage line switching, or faults.
4) Five GSUTs failed within their first year of operation. Some failures occurred within months, days, or even hours of initial energization.
5) Three failures occurred while the CSUT was energized from the 765 kV system with the generator disconnected, i.e., the back-feed condition.

A particularly problematic situation has developed with 765/345 kV 500 MVA autotransformers. In a sample of 72 pieces, 54 failures occurred (several ATs were damaged again after repair). The locations or types of failures are shown in Fig. 3.

To improve the reliability of 765 kV transformers, AEP increased the insulation level in the new specification by 13–15 % compared to the requirements

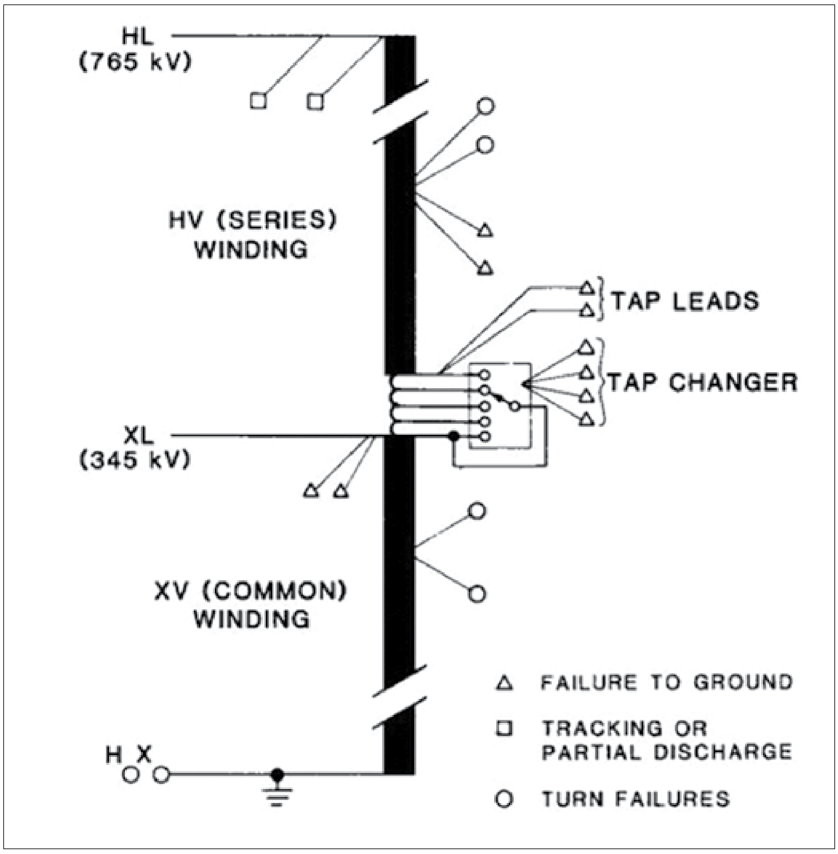


Figure 3. Approximate locations or types of failures for 765/345 kV, 500 MVA autotransformers [11]

> **The specifications should require new transformers to withstand geomagnetic disturbances, whereas particular care should be taken with five-limb cores, single-phase units, and shell-type transformers**

To improve the reliability of 765 kV transformers, AEP increased the insulation level in the new specification by 13–15 % compared to the requirements of the previous one (Table 1), and a higher level of collaboration with manufacturers was adopted.

In addition to the existing standards, in order to more adequately encompass the conditions encountered by transformers during operation, new tests have been introduced in the new specification: 1.2/4200 µs switching impulse; testing of chopped LI with open circuit winding LV; induced voltage test with oil pumps running, and applied voltage at partial discharge limits.

The manufacturer's design is highly dependent on the customer's specification, so the manufacturers had to revise the entire design of the transformers, including the core and the mechanical and cooling structures, in addition to the new winding and insulation designs. In addition, the manufacturers have been forced to make the procedures for installing, operating, and maintaining transformers more stringent.

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

Peacock, D.W., *Factors Influencing Large Power Transformer Reliability*, Westinghouse Transmission and Distribution Technology Form, 1980, Westinghouse Co.

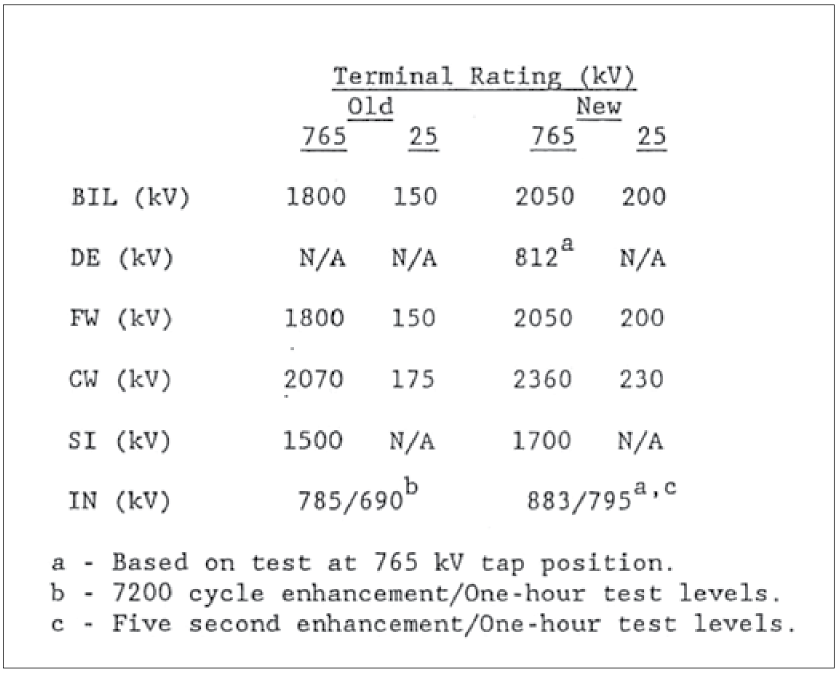
Conclusions to chapter 7

1. Of the hundred GSUTs at US nuclear power plants, about 1/5 were damaged. In the AEP network of 765 kV, 8 out of 24 GRUTs failed, and 54 failures of 500 MVA, 765/345 kV autotransformers (out of 72) occurred.

   There is a difference between the reliability of the first 765 kV transformers and those introduced after 1976. The latter have a much higher failure rate and pronounced infant mortality.
2. Various reasons are given as reasons for failures: extreme space weather, transmission line faults, backfeed mode operation, part-winding resonance, and static electricity.

   At the same time, almost all authors agree that the safety margins of transformers are insufficient, and that it is necessary to change the existing insulation co-ordination method towards stricter requirements for factory insulation tests.
3. To improve the reliability of 765 kV transformers, AEP increased the insulation level in the new specification by 13–15 % compared to the requirements of the previous one (Table 1), introduced new types of factory tests and adopted a higher level of interaction with manufacturers.
4. An important takeaway for engineers working with the new specifications is that Specify's deficiencies have been a major cause of 765 kV transformer failures in the US. The higher ***Specify*** standards in the new AEP specification required changes in ***Design***, manufacturing, and ***Installation***. The specifications should require new transformers to withstand geomagnetic disturbances. Particular care should be taken with five-limb cores, single-phase units, and shell-type transformers.

Table 1. BIL and factory test levels for old/new AEP 25/765 kV GSUT specification [12]



	Terminal Rating (kV)			
	Old		New	
	765	25	765	25
BIL (kV)	1800	150	2050	200
DE (kV)	N/A	N/A	812[a]	N/A
FW (kV)	1800	150	2050	200
CW (kV)	2070	175	2360	230
SI (kV)	1500	N/A	1700	N/A
IN (kV)	785/690[b]		883/795[a,c]	

a - Based on test at 765 kV tap position.
b - 7200 cycle enhancement/One-hour test levels.
c - Five second enhancement/One-hour test levels.

8. Reasons for the reliability of Zaporizhzhya 750 kV transformers

As of 1990, there were several thousand 330–750 kV 100–1250 MVA transformers in operation in the USSR (more than 90 % were ZTZ transformers). In [13, 14], the operating experience of these transformers is analyzed. The specific damage of ZTZ transformers for the 1982–1990 period is given in Table 2. It is defined as the percentage of the number of transformers that failed during the year to the total number of transformers in operation in the year under consideration.

As follows from the table, the amount of damage to the main insulation is relatively small (less than 0.5%). Longitudinal insulation failures occurred, as a rule, in the first years of service (Table 3), and main insulation failures occurred, as a rule, after 10–15 years of operation.

Table 2. Failures of EHV ZTZ transformers for the 1982–1990 period (% per year) [13]

Location of failure	Un * kV	Working time **	Years								
			1982	1983	1984	1985	1986	1987	1988	1989	1990
Main insulation	330	7.2	0.44	0.28	0.27	0.26	0	0.12	0	0.22	0
	500	9.8	0	0	0.10	0.10	0	0	0.42	0	0.08
	750	1.6	0	0	0	0	0	0	0	0	0
Longitudinal insulation	330	7.2	0.44	0.28	0.13	0.13	0.12	0	0.12	0.11	0.11
	500	9.8	0.12	0.22	0	0	0.28	0.17	0.08	0	0.08
	750	1.6	0	0	0	0	0.56	0	0	0	0
All types of insulation	330 - 750	18.6	1.11	0.64	0.54	0.77	0.63	0.73	0.96	0.55	0.63

*) Rated voltage **) x 10^3 transformer-years

Damage to the main insulation is caused by a decrease in the dielectric strength of the insulation due to the violations of the operating conditions, insufficient repair quality (not in the factory), contamination by wear products of the oil pump bearings, moisture ingress due to the leakage through the seals of the bushings or the exhaust pipe membrane.

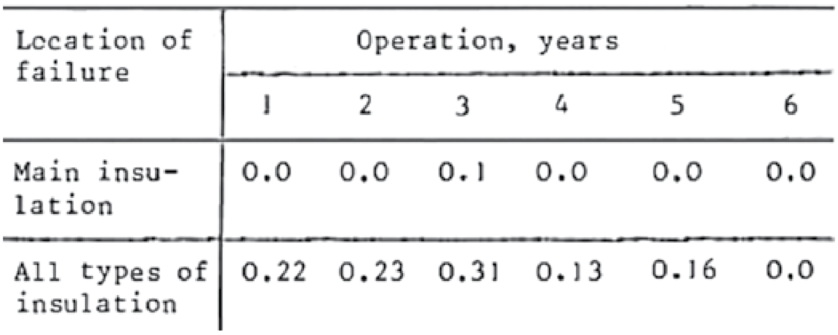
There were no failures of the main insulation on 750 kV transformers. The following circumstances ensured this achievement:

1. The designers of Zaporizhzhya transformers had more freedom in choosing insulation distances because the dimensions of the USSR railways were larger than that of their colleagues from the countries from which 735–765 kV transformers were supplied to North America (Table 4).

2. The insulation design of Zaporizhzhya transformers was previously tested on large-sized mock-ups during tests 10–15 % higher than the standard values before launching transformers into production.

As of 1990, there were several thousand 330–750 kV 100–1250 MVA transformers in operation in the USSR (more than 90 % were ZTZ transformers)

Table 3. The intensity of power transformers' failures for the first 6 years of service (%) [14]



Location of failure	Operation, years					
	1	2	3	4	5	6
Main insulation	0.0	0.0	0.1	0.0	0.0	0.0
All types of insulation	0.22	0.23	0.31	0.13	0.16	0.0

Table 4. Dimensions of the main railways of different countries

Size/m	Japan	Europe	USA	USSR
Width	3	3.15	3.25	3.75
Height	4.1	4.25	4.62	5.3

(Source: https://en.wikipedia.org/wiki/List_of_track_gauges)

ACSD can be included in the specification as a routine test with mandatory partial discharge measurements at 100 % test voltage in order to guarantee the reliability and durability of EHV and UHV transformers

3. Test voltages of Zaporizhzhya transformers are higher by 2–17 % than, for example, in transformers operating in AEP (see Table 5).

4. ZTZ had more stringent acceptance tests:
   - ACSD was a routine test with mandatory PD measurement at 100 % voltage test; the majority of rejections for power transformers insulation take place during the ACSD test; the high "efficiency" of the ACSD test is explained by the fact that the value of its test voltage considerably exceeds the equivalent stress under the ACLD test determined by the voltage-time characteristic of the insulation [14]
   - the chopped lightning impulse had a zero-crossing factor greater than 0.3
   - the switching pulse had parameters close to the 250/2500 pulse for external insulation
5. ZTZ manufactured the first 750 kV transformer (210 MVA 750/500 kV autotransformer) in 1967. Afterwards, that one and similar transformers were tested for six years on a pilot 750 kV transmission Konakovo–Moscow. Only after that did serial production of transformers for the 750 kV industrial power transmission begin. By the way, a similar test for the 1150 kV transformers lasted 12 years.

Conclusion to chapter 8

The recommendation for specification developers is that, in addition to the IEC and IEEE standards, ACSD can be included in the specification as a routine test with mandatory partial discharge measurements at 100 % test voltage, as a more stringent tool for verifying workmanship and guarantees of reliability and durability of EHV and UHV transformers.

9. General conclusions

9.1. In the coming decades, the world will need to significantly increase its energy supply, including the creation of new EHV and UHV transformers, to meet the ever-increasing demand for electricity. On the other hand, half of the world's large power transformers in operation are over 30 years old and need to be replaced. The role of engineers with regard to the development of specifications for new transformers is to create a well-written specification to ensure the reliability and durability of new transformers, and it cannot be overestimated.

9.2. For the first time, an attempt was made to apply one of the sections of the modern reliability theory (the Asset Lifecycle theory) to explain the causes of peaks in the accident rate of UHV transformers in the 20th century (in the USSR in the 1960s; in North America in the 1980s). A historical review of these failures from the SDIPF Curve (Specify – Design – Installation – Potential failure – Failure) showed that the main causes of failures were shortcomings in ***Specify*** and ***Design***.

None of the specifications and standards adequately encompassed the conditions that transformers faced in operation, and the influence of the Sun on the reliability of transformers turned out to be a complete surprise.

9.3. This historical overview, as an invaluable collection of real experience, is intended primarily for specification developers in Asia, Africa, and Latin America, who have little or no familiarity with the negative experience of operating EHV transformers in the 20th century. It can also be useful to the developers of modern transformers in conditions where safety margins cannot be higher than half a century ago, but the reliability and durability should be comparable with the best examples of past generations.

9.4. The peak accident rate of ZTZ transformers almost 60 years ago was caused by the shortcomings of ***Design*** and ***Production***. The corrective measures taken ensured almost half a century of production of reliable and durable 330-750 kV transformers (more than 3300 pieces were manufactured in total) and the world's first 1150 kV transformers. The operation of the latter at a voltage of 1150 kV, unfortunately, was only 3–5 years; then, due to the collapse of the USSR, they continued to operate at a voltage of 500 kV. Zaporizhzhya 750 kV transformers turned out to be the most reliable among their 735–765 kV counterparts.

9.5. For the cases with a poor technical level of production at asset manufacturing plants, the SDIPF curve can be upgraded to the ***SDPIPF curve*** (Specify – Design – ***Procure/Production*** – Installation – Potential failure – Failure).

9.6. ***Specify's*** shortcomings regarding internal insulation requirements have been a major cause of 735 kV transformer failures in Canada. Impulse test voltage (BIL) has been and continues to be a top specification requirement.

9.7. ***Specify's*** shortcomings have been a major cause of 765 kV transformer failures in the US. The higher requirements in the new AEP specification required changes in ***Design***, manufacturing, and ***Installation***. The specifications should require new transformers to withstand geomagnetic disturbances.

Table 5. BIL and factory test levels for the GOST and old AEP specification

	Un	Um	BIL	LIC	SI	ACSD
GOST 20690-75	750	787	2100	2250	1550	800
AEP	765	800	1800	2070	1500	785
Ratio GOST/ AEP	-	-	1.17	1.09	1.03	1.02

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