The SDIPF reliability curve of old EHV power transformers

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

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

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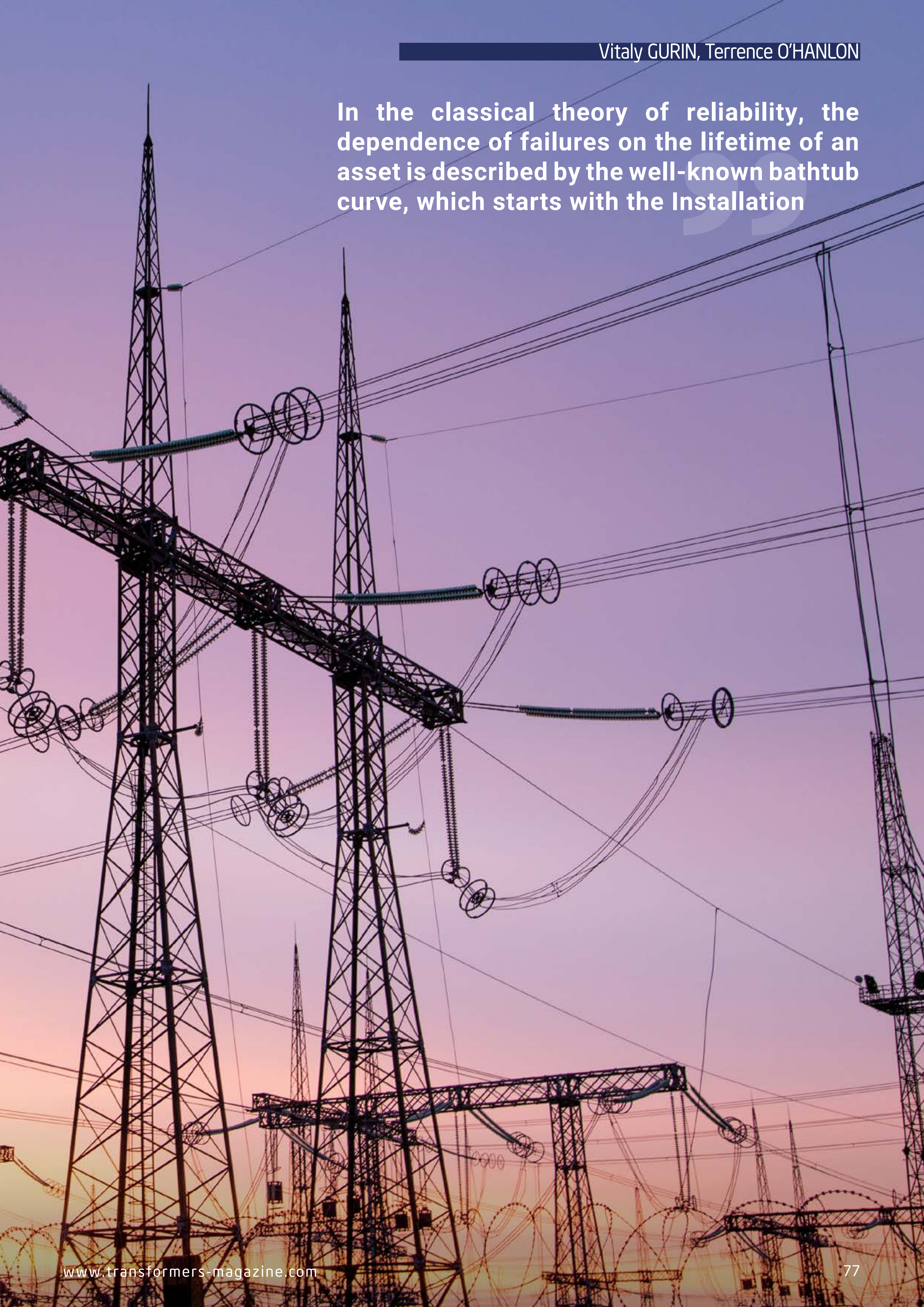
In the classical theory of reliability, the dependence of failures on the lifetime of an asset is described by the well-known bathtub curve, which starts with the Installation



Engineers dealing with new specifications should be aware that modern reliability concepts (the Asset Lifecycle theory) take into account earlier stages of transformer development than Installation

3. Bathtub curve and SDIPF curve

Failure is one of the basic concepts in the theory of reliability. In electrical engineering, the IEC 61508-4 definition applies (quote): «***failure*** *– the termination of the ability of a functional unit to perform a required function*». CIGRE, a major failure, was defined as any situation which required the transformer to be removed from service for a period longer than 7 days for investigation, remedial work or replacement [1]. The authors of the cited works objectively could not adhere to any of these definitions since they wrote before the formulation of these definitions, but this is not fundamental for our review.

In the classical theory of reliability, the dependence of failures on the lifetime of an asset is described by the well-known bathtub curve (Fig. 1). It starts with ***Installation***. Commissioning such complex equipment as the PT is fraught with dangers. First, the PT could very well have left the factory with an internal defect that didn't show up until the transformer was stressed in transit. Cases of careless handling of cargo are not uncommon, especially on railways. Secondly, the installation process itself may include a sloppy moment or deviations from factory requirements. Finally, the PT is at great risk the moment it first turns on and experiences load conditions for the first time. The first part of the bathtub curve is called "*Infant Mortality*". For PT, it has a duration of 3-5 years; failures during this period, in addition to those listed above, are also due to shortcomings in production technology and poor quality control.

The second part of the curve is called *Normal Operation*, which has random failures. This period for LPTs of advanced manufacturers lasts at least 25–35 years with good maintenance, that is, actions to detect, prevent or mitigate the degradation of the transformer.

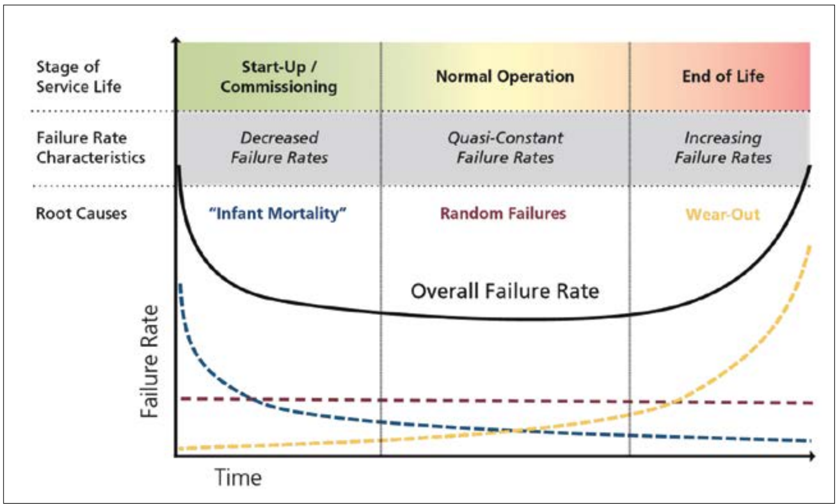


Figure 1. Bathtub curve

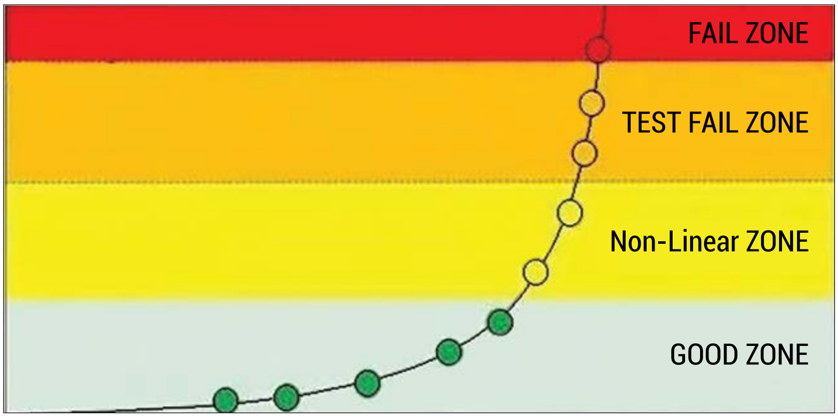


Figure 2. Zones of the third part of the bathtub curve

Concerning LPT, two types of maintenance are generally used. Time-directed maintenance tasks are traditional scheduled maintenance at certain points in time (for example, an annual DGA of a transformer) or according to the time of its operation (for example, after 10 thousand tap changes). More modern is Condition Based Maintenance (CBM) tasks, also known as Predictive Maintenance (PdM) tasks or Asset Condition Management (ACM). This maintenance provides significant cost savings and, at the same time, provides a more reliable assessment of the condition of the transformer. OEM maintenance manuals are sometimes designed to increase the consumption of manufacturer-supplied spare parts and consumables rather than the lowest maintenance cost in EPS.

Poor maintenance sometimes occurs for STs that are less loaded than GSUTs, especially for distribution transformers. Maintenance improvement is a passive method of mitigating failures and can delay undesirable events to some extent. It is possible to optimize maintenance by offline diagnostics and online diagnostics (condition monitoring) of transformers. However, monitoring systems are by no means always economically justified because, from modern concepts, not any maintenance can radically affect the main causes of failures if the safety margins built into the transformer are insufficient.

The third part of the bathtub curve is called the *End of Life*. It has Wear-Out and increasing failures. The probability of failure increases as the condition of the asset deteriorates (see the four zones in Fig. 2). The service life ends when the wear failure rate reaches the orange zone. The transformer must be replaced until the red zone is reached. Otherwise, the consequences of his refusal can be catastrophic.

Engineers dealing with new specifications should be aware that modern reliability

O'Hanlon emphasizes that without Specify and Design, the "improvement" of reliability through maintenance that has prevailed over the past 40 years was a delusion

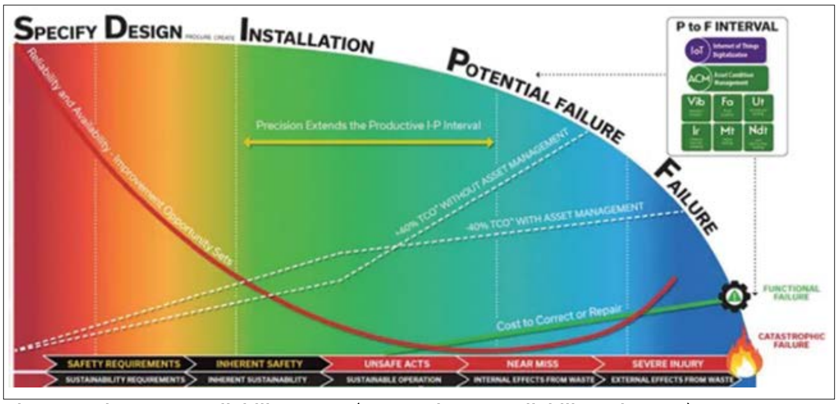


Figure 3. The SDIPF Reliability Curve (Source: https://reliabilityweb.com/)

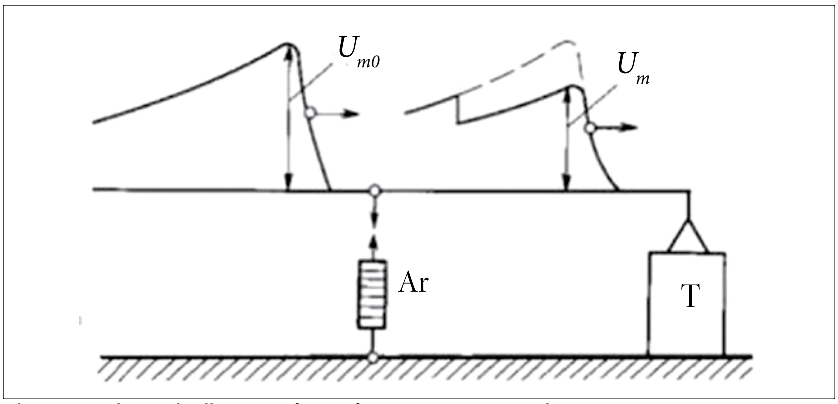


Figure 4. Schematic diagram of transformer surge protection

concepts (the Asset Lifecycle theory) take into account earlier stages of transformer development than ***Installation.*** An improvement on the bathtub curve is the SDIPF curve (Fig. 3) created by O'Hanlon. Find out more about Terrence O'Hanlon and his work in [2]. His work developing Uptime Elements Reliability Framework and Asset Management System as a Cultural Change Management Methodology has been used by thousands of organizations for the past ten years. The SDIPF Curve is a visualization that attempts to graphically "bend time" to the benefit of investing in and applying reliability efforts by showing a lifetime snapshot of the asset over time.

The SDIPF curve includes new stages of the asset life cycle, namely: ***Specify, Design*** and procure. O'Hanlon emphasizes that without Specify and Design, the "improvement" of reliability through maintenance that has prevailed over the past 40 years was a delusion. The new components provide much of the asset's internal reliability. After commissioning, the scope for improving internal reliability is extremely limited.

4. The essence of Specify in relation to power transformers

According to the literature, the following impacts on the operation of PT are important for our topic: electrical stresses on the insulation and extreme space weather.

4.1. Insulation coordination

During operation, the insulation of transformers is exposed to operating voltage and various types of overvoltage (lightning, switching, and quasi-stationary). Arresters are used to protect transformers from surges (starting a hundred years ago with lightning arresters, then surge arresters, and later metal-oxide surge arresters).

An overvoltage with amplitude U_{m0} propagates along the power line at almost the speed of light and, after the arrester, Ar is triggered, enters the transformer T with a reduced amplitude U_m (Fig. 4).

In the IEC standard [3], insulation coordination is defined as follows (*quote*): "Insulation co-ordination - selection of the dielectric strength of equipment concerning the operating voltages and overvoltage's which can appear on the system for which the equipment is intended and taking into account the service environment and the characteristics of the available preventing and protective devices".

By "dielectric strength" of the equipment, its rating or its standard insulation level is meant here. Furthermore, "standard insulation level" means the standard withstand voltages associated with the highest operating voltage U_m as recommended in the tables of this standard.

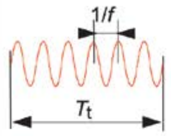
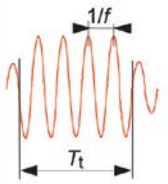
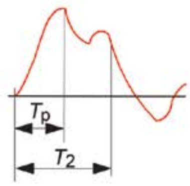
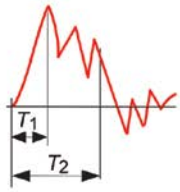
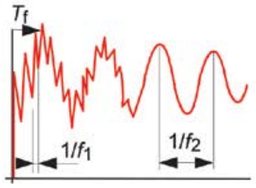
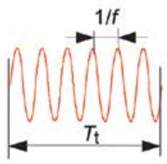
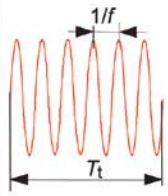
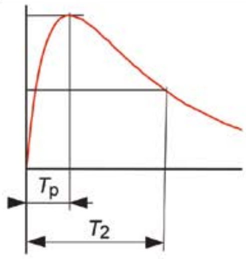
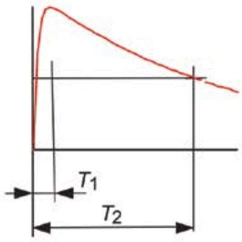
Ideally, insulation coordination should be based on comprehensive overvoltage data. According to [3] the voltages and the overvoltage's that stress the insulation shall be determined in amplitude, shape and duration by employing a system analysis which includes the selection and location of the overvoltage-preventing and limiting devices. For each class of voltages and overvoltages, this analysis shall then determine a representative voltage and overvoltage, taking into account the characteristics of the insulation concerning the different behaviour at the voltage or overvoltage shapes in the system and at the standard voltage shapes applied in a standard withstand voltage test as outlined in Table 1.

We emphasize that the classes and shapes of overvoltages, standard voltage shapes and standard withstand voltage tests listed in the standard are simplified in comparison with the variety of real effects on the PT's insulation, and this simplification is enhanced in the same order of enumeration. This is one of the possible causes of troubles of the PT in operation.

In the IEC standard, insulation levels are not strictly fixed, and for each voltage U_m there are several values of test voltages, from which the customer chooses one for his specification, depending on the characteristics of the applied protective devices.

In the USSR, a slightly different definition of insulation coordination was used: *"Insulation coordination of electrical equipment is the mutual coordination of the values of acting voltages (overvoltages), the electrical characteristics*

Table 1. Classes and shapes of overvoltages, Standard voltage shapes and Standard withstand voltage tests [3]

Class	Low frequency		Transient		
	Continuous	Temporary	Slow-front	Fast-front	Very-fast-front
Voltage or over-voltage shapes					
Range of voltage or over-voltage shapes	f = 50 Hz or 60 Hz T_t ≥3 600s	10 Hz < f < 500 Hz 0,02 s ≤ T_t ≤ 3 600 s	20 µs < T_p ≤ 5 000 µs T_2 ≤ 20 ms	0,1 µs < T_1 ≤ 20 µs T_2 ≤ 300 µs	T_f ≤ 100 ns 0,3 MHz < f_1 < 100 MHz 30 kHz < f_2 < 300 kHz
Standard voltage shapes	 f = 50 Hz or 60 Hz T_t [a]	 48 Hz ≤ f ≤ 62 Hz T_t = 60 s	 T_p = 250 µs T_2 = 2 500 µs	 T_1 = 1,2 µs T_2 = 50 µs	a
Standard withstand voltage test	a	Short-duration power frequency test	Switching impulse test	Lightning impulse test	a

[a] To be specified by the relevant apparatus committees.

We emphasize that the classes and shapes of overvoltages, standard voltage shapes and standard withstand voltage tests listed in the standard are simplified in comparison with the variety of real effects on the PT's insulation

of protective equipment and equipment insulation, which ensures reliable operation and high efficiency of electrical installations" [4]. In contrast to the IEC, words in italics are significant in this definition. This means that in the Soviet interpretation of insulation coordination, they tried to take into account, in addition to the costs of limiting overvoltages to one level or another, also losses caused by interruptions in power supply and the cost of repairing / replacing damaged electrical equipment. Therefore, in the USSR, the insulation levels for each nominal EPS voltage were strictly specified and were a mandatory norm, which is typical for a totalitarian state.

For non-self-healing internal insulation "HV line terminal - earth" of transformers until the early 1960s, the following types were used:

- short-duration AC voltage (ACSD) test,
- lightning impulse (LI) test,
- chopped lightning impulse (LIC) test.

Then a decade later new types of tests were introduced:

- long-duration induced AC voltage (ACLD) test with PD norma, and
- switching impulse (SI) test.

At the same time, in the IEC and IEEE standards for transformers of 330 kV and higher, the ACSD value was sharply reduced, i.e., the ACSD test has actually been cancelled [3, 5]. However, in GOST, the ACSD test was retained without reducing its value.

Note: In the US, LI is called BIL (basic lightning impulse insulation level: A specific insulation level expressed in kilovolts of the crest value of a standard lightning impulse) and SI – BSL (basic switching impulse insulation level: A specific insulation level expressed in kilovolts of the crest value of a standard switching impulse) [6]. The word “basic” in these definitions emphasizes the fact that LI and SI usually define the main clearances in a transformer. The ratio of the transformer insulation strength at SI to the strength at LI in American practice is assumed to be 0.83 (this is typical for oil), and according to [7], it is in the range of 0.9–1.0 (this is typical for oil-impregnated solid insulation).

The insulation coordination criterion is the margin between the maximum overvoltage expected at the transformer in its location and the values of the factory test voltages. This margin determines a safety factor that should not be less than an adequate value based on experience. Until now, there are no theories of insulation breakdown of transformers, and this experience is accumulated by “trial and error”. Our review reflects the thorny path of accumulating this experience.

Thus, ***Specify*** for power transformers should be understood as insulation test voltages related to certain test conditions. The Specify determines the level of reliability of the insulation of the transformer and the EPS as a whole.

4.2. Extreme space weather

Fluxes of protons and electrons from the solar corona affect the entire life of humanity (Fig. 5). A major threat from abnormal space weather to critical infrastructure is the effect of geomagnetic disturbances (GMD) on the power grid [8, 9, 10, etc.].

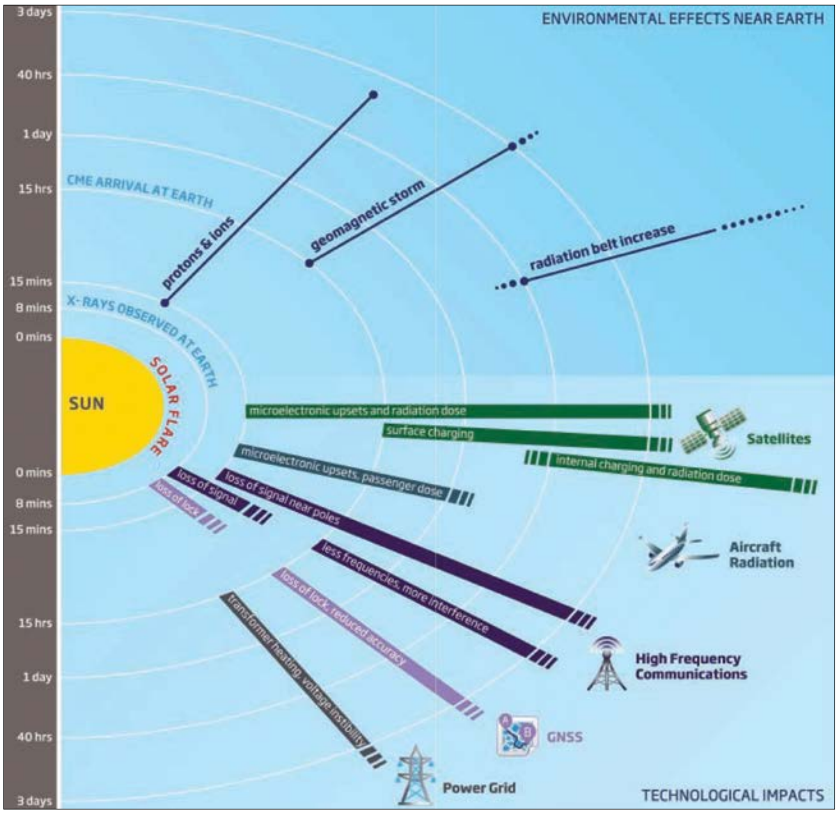


Figure 5. A summary of space weather effects on near-Earth and Earth

Rapid variations (from a few seconds to several tens of minutes) of the Earth’s geomagnetic field cause an induced geoelectric field on its surface. This field, in turn, induces electrical currents in the electrical network, which changes with a frequency much lower than the network’s operating frequency of 50–60 Hz. These quasi-permanent geomagnetically induced currents of 0.01–0.5 Hz (GICs) are superimposed on the alternating current (AC) carried over the power lines and destabilized the voltage in the EPS (Fig. 6).

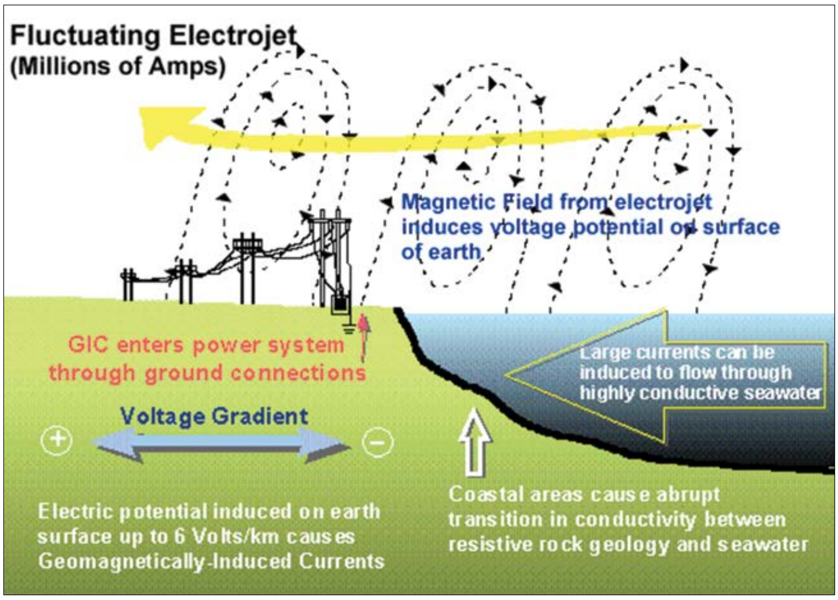


Figure 6. An illustration showing the phenomena of GIC

A major threat from abnormal space weather to critical infrastructure is the effect of geomagnetic disturbances (GMD) on the power grid

The resulting unbalance and voltage surges along the wires are redirected to PTs, which require a certain amplitude and frequency of voltage to work properly. The GIC biases the symmetrical AC in the transformer windings (Fig. 7). This bias drives the magnetic core of the transformer into half-wave saturation. Under saturation conditions, transformers consume more reactive power (MVAr) than under normal conditions. If the increase in reactive power demand becomes too great, voltage collapse can occur, leading to local or even national blackouts.

Fig. 8 shows the effect of a 3 % DC offset in the input voltage on the magnetizing current waveform. A five-fold increase in the peak magnetization current during the first half-cycle of the magnetization process is clearly visible.

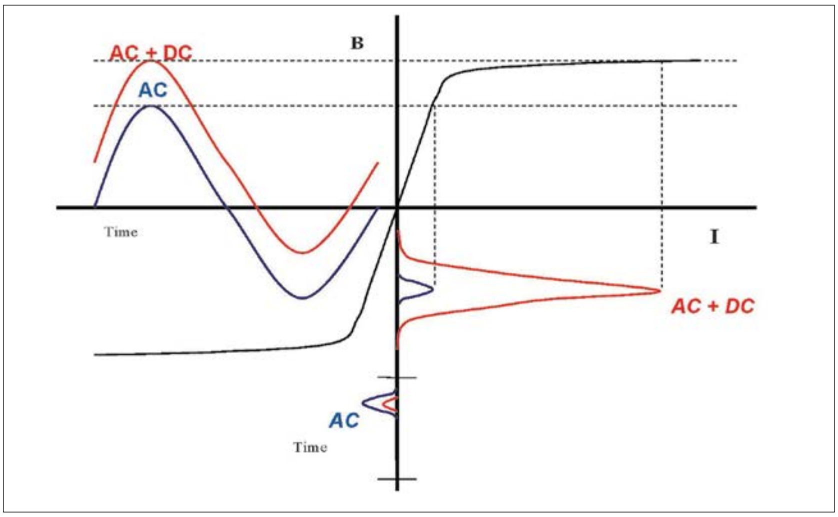


Figure 7. DC causes Part - Cycle, Semi - Saturation of the core (Source: [11])

Further, the saturated core of the transformer creates harmonics that are dangerous for the normal operation of the EPS (Fig. 8). 2nd order harmonics can erroneously operate a differential relay set to a low 2nd harmonic content to distinguish between inrush current and fault events. 3rd order harmonics can trigger relays with higher sensitivity to this / third harmonic, which also causes the power lines to shut down during the GIC event. Other harmonics may resonate with inductors and capacitances in the EPS located near the transformer. Resonance can cause dangerous overvoltages and affect the insulation integrity of the transformer windings.

As can be seen from Fig. 9, harmonics are 2–2.5 times larger in single-phase transformers. Namely, such transformers make up the vast majority of EPS: 735 kV in Hydro-Quebec and 765 kV in the USA.

The most serious effect of core saturation is when the main magnetic flux leaves the core. This can cause rapid heating in the transformer, gassing, operation of the Buchholz relay, shutdown of the transformer, and in the most severe cases, damage to the transformer. Even if no immediate damage is caused, half-cycle saturation of the bark can produce enough heat to dangerously heat the internal components of the transformer.

The largest and unprecedented operational impacts on the electrical grid occurred on 13 March 1989, when a severe geomagnetic storm hit the Earth due to a coronal mass ejection from the Sun.

The storm set off a chain of disruptions that, just 92 seconds later, resulted in the complete collapse of the entire Hydro-Quebec EPS. Such a rapid development of events has not given time to assess what is happening with EPS, not to mention any significant human intervention. Part of the equipment actually exploded, endangering the safety of personnel. Were damaged two 735 kV transformers at the LG4 station in the James Bay complex (check in chapter 6 to be published in one of the following Transformers Magazine issues), a 735 kV shunt reactor at Nemiscau (located midway between James Bay and Montreal) and the failure of a 735 kV lightning arrester. The collapse of the EPS left six million people and the rest of Quebec without power for several hours on a very cold night. Even though the outage lasted about nine hours in most places, it was dark in some places for several days. This geomagnetic storm caused about $13.2 million in damage to Hydro-Québec and tens of millions to the utility's customers.

GMDs have also repeatedly caused LPT failures in the USA (check in chapter 7 to be published in one of the following Transformers Magazine issues), England, Sweden, South Africa, and New Zealand. The events of March 1989 came as a complete surprise to power engineers and transformer manufacturers.

Further, in chapters 5, 6 and 7, the collected data on the failures of UHV transformers in the USSR and North America in the 20th century will be presented and systematized for the benefit of engineers for the development of specifications for new transformers.

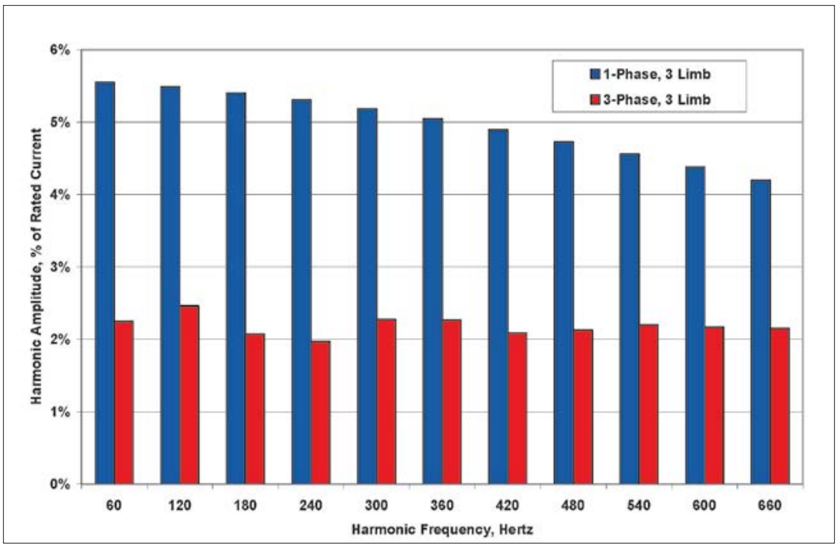


Figure 9. The harmonic spectrum of the magnetizing current of two transformers of different designs at the same direct current per phase (Source: [11])

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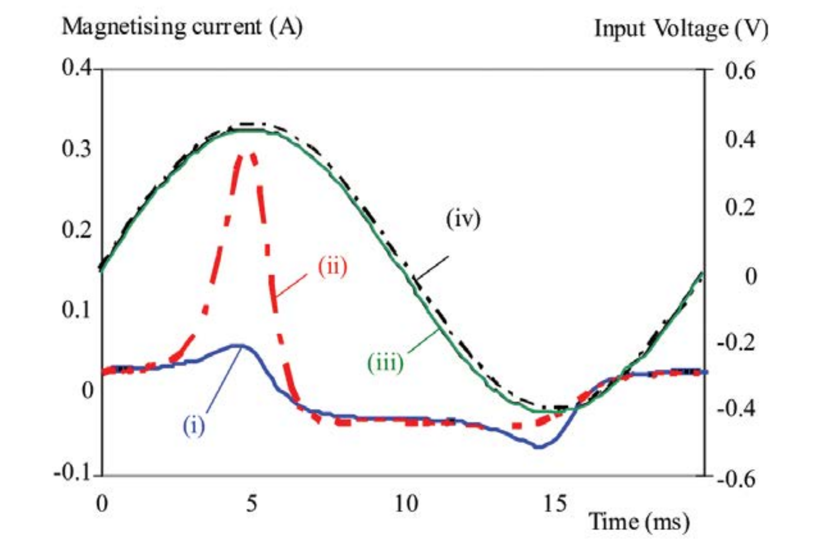

Figure 8. Effect of 3 % DC offset in the input voltage on the magnetizing current waveform (Bp=1.5 T). (Source: [12]); (i) – current under sine excitation, (ii) –current under excitation containing 3 % DC offset, (iii) – Vin sine, and (iv) – Vin with 3 % DC offset

The GIC biases the symmetrical AC in the transformer windings, which drives the magnetic core of the transformer into half-wave saturation

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.

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