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A novel validated solution for lightning and surge protection of distribution transformers

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A B S T R A C T

This paper proposes an industrial solution (equipment) for lightning and surge protection of distribution transformers. The proposed protection equipment has been installed at 100 distribution transformers (sample) of the Public Power Corporation (PPC) of Greece. The article estimates the future transformer failures, considering two different cases: (a) transformer without the proposed protection system; and (b) transformer equipped with the proposed protection system. Three different methods are used to estimate the future transformer failures without the proposed protection system: Monte Carlo simulation, Poisson statistical distribution, and binomial statistical distribution. These three methods together with the c control chart method are also used in this paper, for the case of transformers equipped with the proposed protection system, to estimate the maximum allowable number of yearly transformer failures in order the proposed protection system to be considered as an effective protection means. Moreover, the article computes the satisfactory sample size of transformers in which the protection system has to be installed in order to be able to obtain statistically reliable results regarding the effectiveness of the proposed protection system. The results show that the proposed method is an excellent means for lightning and surge protection of distribution transformers, since zero transformer failures have been observed so far during the whole period of its operation (29 months), in contrast with 8.36 average lightning and surge related failures per year in the same sample of 100 transformers before the installation of the proposed protection equipment.

Introduction

Distribution transformers are among the most expensive and critical units in a power system [1,2]. Transformer failures are sometimes catastrophic and almost always include irreversible internal damage [3]. Consequently, it is very important to install protection systems to the transformers of an electric power system [4].

A method for discrimination between magnetic inrush current and internal fault current in transformer differential protection can be found in [5]. Insulation failure in transformer winding is detected by artificial neural network (ANN) and k-nearest neighbors [6]. A transformer fault diagnosis system is developed in [7], which is based on dissolved gases analysis by extracting fuzzy rules from Kohonen self-organizing maps. An ANN is used to predict incipient transformer faults [8]. Diagnosis criteria for detection of low-level short circuit faults in transformer windings are obtained by sweep frequency response analysis [9]. A percentage differential relaying method for the protection of power transformers based on transient signal analysis and discrete wavelet transform is proposed in [10]. Chaos theory and surge arrester device based on metal oxide varistor are used for ferroresonance suppression in power transformers [11].

The electrical and mechanical design considerations for a transformer include lightning and switching surge voltages [1,12]. Both of these surge voltages can cause serious damage to the distribution transformer [1]. Both lightning and switching surge voltages are large magnitude traveling waves, which travel at the speed of light. The distribution transformer is designed and manufactured with a user-specified basic impulse level (BIL) rating. The BIL rating determines the level of lightning and switching surge voltages that the transformer can withstand without damage [1].

The protection of distribution transformers from the low voltage side is an important subject that has triggered the interest of the electric utilities, the manufacturers of protection systems,

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and the international scientific community [13–16]. The work [13] describes the problem of failures of distribution transformers due to low-side surge phenomena and how it is being addressed by the industry. Some Brazilian electric companies (CEMIG, CEEE, COPEL, CEMAR, COELCE, LIGHT, CPFL Energy Group, DME Poços de Caldas and CELESC) suggest the application of low voltage lightning arresters as an efficient way to shield the transformer against overvoltages caused by surges of atmospheric discharges [17]. Studies from these electric companies point out the induced overvoltages as responsible for more than 55% of total transformers' failures [17].

This paper proposes an industrial solution (equipment) for lightning and surge protection of distribution transformers. The proposed protection equipment has been installed at 100 distribution transformers (sample) of the Public Power Corporation of Greece, at the specific substation locations of Lakonia shown in Table 1, providing excellent protection with zero transformer failures during the whole period of its operation so far, namely 29 months, from January 2012 when the equipment was installed till today (May 2014). Based on eleven-year statistics of failures of this sample collected before the installation of the protection equipment, the future transformer failures are estimated in this article, considering two different cases: (a) transformer without the proposed protection system and (b) transformer equipped with the proposed protection system. Three different methods are used to estimate the future transformer failures without the proposed protection system: Monte Carlo simulation, Poisson statistical distribution, and binomial statistical distribution. These three methods together with the *c* control chart method are also used in this paper, for the case of transformers equipped with the proposed protection system, to estimate the maximum allowable number of yearly transformer failures in order the proposed protection system to be considered as an effective protection means. Moreover, the article computes the satisfactory sample size of transformers in which the protection system has to be installed in order to be able to obtain statistically reliable results regarding the effectiveness of the proposed protection system. The results show that the proposed solution is an excellent means for lightning and surge protection of distribution transformers.

Proposed lightning and surge protection system

Rayvoss transformer protection system

The lightning and switching overvoltages and overcurrents that are developed at the conductors of an electrical installation constitute the most important cause for electrical equipment destruction. Additionally to the cost of repair and replacement of the destroyed equipment, there are also the consequences of the interruption of production processes and the loss of revenue for the enterprise. The protection from lightning and switching overvoltages and overcurrents is implemented with the installation of surge protection devices (SPDs).

Table 1
Locations of the 100 distribution transformers at which the proposed protection system has been installed.

No	Location	Municipality	Regional administration
1	Areopoli	East Mani	Lakonia
2	Vathia	East Mani	Lakonia
3	Karies	Sparti	Lakonia
4	Kounos	East Mani	Lakonia
5	Lagia	East Mani	Lakonia
6	Richea	Monemvasia	Lakonia
7	Tsikkalia	East Mani	Lakonia

This article introduces Rayvoss, a new protection system specifically designed to provide lightning and surge protection for distribution transformers. The proposed Rayvoss protection system is based on Strikesorb surge protection module (Section Strikesorb surge protection module). It should be noted that Strikesorb is a general purpose surge protection module that is used worldwide in a wide range of applications including telecommunications, renewable energy, industrial, medical, residential and governmental sectors [18].

Strikesorb surge protection module

Protector requirements and features

The requirements for a reliable surge protector are the following:

- The protected equipment should never be exposed to damaging transients/surges regardless of the condition of the protector.
- The protector should operate in such a way as to preclude safety risks with regard to smoke, fire, and explosion without sacrificing any of its performance capabilities.
- The reliability and lifetime of the protector has to be greater than those of the equipment being protected.
- The protector should be able to continuously protect critical equipment under all abnormal line conditions and at all times.

These requirements mean that the protector should have the following features:

- No flammable material should be used in the protector. For example, no potting material.
- The protector must be physically robust in order to sustain high amounts of energy without disintegrating.
- The protector should not require any internal fusing in order to meet the UL-1449 safety standard.
- The protector should become a short circuit at its end of life.
- The protector should exhibit a life span of several years in a surge exposed environment without maintenance requirements.
- The protector should be able to dissipate absorbed transient/surge energy safely without undue heating.
- The protector should exhibit minimal internal dynamic resistance and minimal inductance.

The Strikesorb surge protection module shown in Fig. 1 is designed to meet the above requirements [19]. The Strikesorb technology is protected worldwide by several patents, e.g., [20,21]. Strikesorb uses a compressed distribution grade Metal Oxide Varistor (MOV). The innovative deployment of field proven, large diameter MOVs, allows Strikesorb modules to provide premium performance under extreme conditions. Independent test data confirm that a Strikesorb 40 module can withstand 140 kA strikes without degradation in performance characteristics. The Strikesorb 80 module can withstand strikes up to 200 kA thus, safeguarding critical electrical and electronic infrastructure against any potential threat. Detailed presentation of Strikesorb technology and comparison with conventional surge protection technologies can be found in [19].

Protector mechanical design features

Each Strikesorb protector (Fig. 1) is constructed with a single 40 mm or 80 mm distribution grade zinc oxide varistor that is housed inside a robust, hermetically sealed metal casing. No potting or other flammable materials are utilized by the protector or contained within the casing. The zinc oxide varistor is placed between two electrodes that exhibit high thermal capacity and

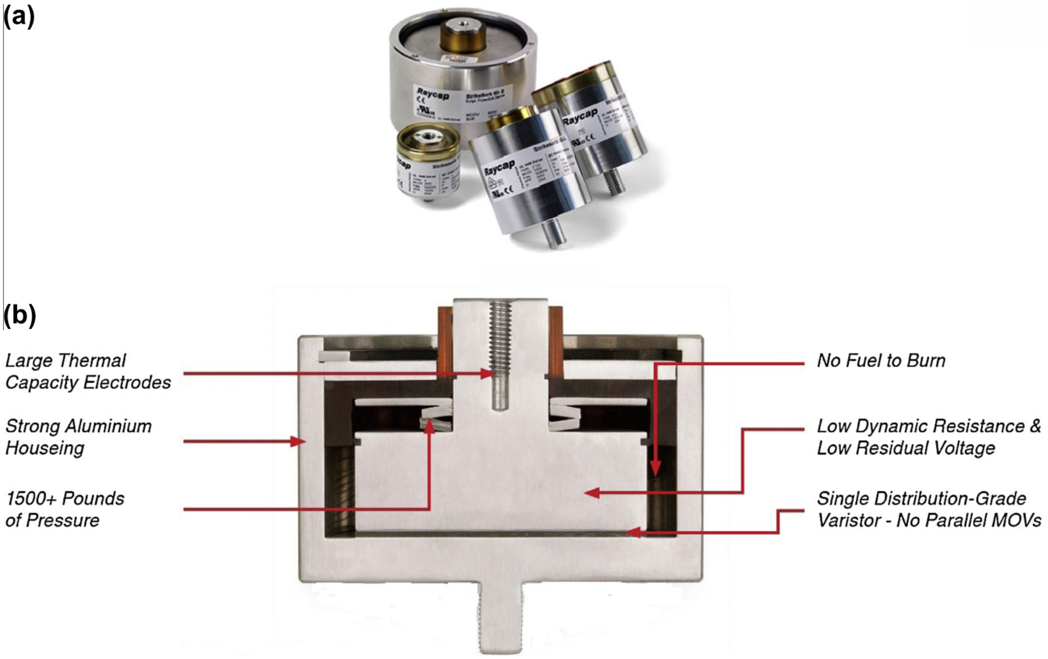


Fig. 1. (a) Four Strikesorb protection modules, (b) cut of a Strikesorb surge protection module designed to operate without fuses.

conductivity characteristics. The disk is not rigidly placed between the electrodes, but held under a high pressure to overcome the Piezoelectric and Lorentz forces that occur during surge events. The heat generated within the zinc oxide varistor disk efficiently dissipates into the environment via its electrodes and into the connected bus bars/metalwork via the device casing. The high thermal conductivity of the materials used ensures that any temperature rise within the varistor is minimal. Strikesorb modules are designed to remove 1000 times more thermal energy than conventional SPD products. The lower temperature rise in the Strikesorb suppression component dramatically extends the product life expectancy and prevents the zinc oxide material ageing.

Protector electrical design features

Strikesorb is designed to accommodate minimal inductance connections while at the same time maximizing the capacitance of the varistor disk. Its design is characterized by coaxial symmetry that results in a device that exhibits minimal impedance characteristics and minimal response time.

Conventional varistors that utilize thin wire leads and even thinner electrodes are plagued by current ‘hogging’ phenomena resulting from their uneven current paths, as is shown in Fig. 2(a). Their surge current capacity decreases and they are prone to developing hot spots that ultimately cause them to fail as they are stressed by surge events. On the other hand, the thickness of the electrodes employed by Strikesorb ensures that the current conducted through the varistor is planar/parallel (uniform), as is shown in Fig. 2(b), consequently no current ‘hogging’ occurs.

In conventional MOV components, the lengths of the current paths that are employed by the individual current filaments vary considerably, leading to the following effects: current flowing towards the outer edge of the varistor is restricted due to more resistive current paths in that region. The transit time of the current traveling through the longer paths is higher. The MOV’s surge current capacity is reduced below the levels it should be able to support. Current conducted through the component is more intense between the connection pins, as it is unable to take advantage of the total volume of the varistor. As a consequence, higher clamping voltages are realized as the MOV deteriorates and until it ultimately fails. On the other hand, Strikesorb overcomes this deficiency by essentially equalizing all current conduction path lengths to allow evenly distributed current flow throughout the

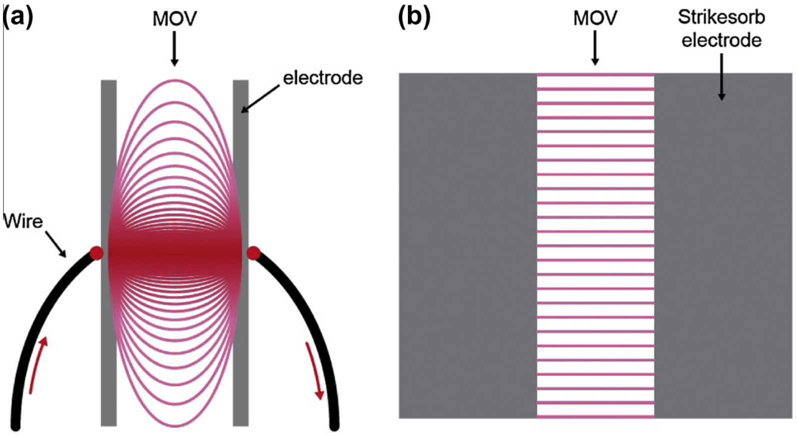


Fig. 2. (a) Current distribution in conventional varistor, (b) current distribution in Strikesorb module.

entire conductive surface area of its zinc oxide varistor. For all practical purposes, the Strikesorb's varistor conducts current evenly at all frequencies and utilizes the entire disk surface – volume during current conduction conditions.

Electrical verification testing

Reputable independent laboratories test reports indicate that Strikesorb verifies all its safety and performance claims. The testing has been conducted in accordance with established and broadly accepted international standards including, but not limited to, those defined by IEEEC62, IEC61643-1 (EN 61643-11), UL-1449 3rd edition and NEMA-LS1.

Strikesorb is currently the only UL Recognized SPD that has successfully gone through the complete revised testing procedure of the new UL-1449 3rd edition standard, including abnormal overvoltage testing at low and intermediate short circuit currents up to 1000 A rms for 7 h.

Field experience

Laboratory tests are essential to help assess a surge suppressor's performance capabilities under somewhat sterilized conditions. However, lab tests are not necessarily designed to provide an adequate means to compare the performance of different SPD products as they may be tested at different times and locations. The real measure of a successful suppression technology is its performance in real world applications. No claim is worth much unless it translates into better protection levels and maintenance free operation for the customers' equipment.

In order to prove their worthiness, Strikesorb modules were initially deployed in environments that were plagued by the worst possible power quality, worst case lightning scenarios and where conventional SPD products were unable to survive. This strategy resulted with a significant number of units being put into service throughout South America, Southeast Asia, and in notoriously troublesome locations in North America and Europe. Due to enormous success stories that were reported back from the field, Strikesorb modules were deployed on a much wider scale, with hundreds of thousands of protectors currently installed worldwide. After several installations worldwide, the field experience has proved that Strikesorb is able to withstand large amounts of surge energy while preserving its performance characteristics for several years and after multiple lightning and power surge events.

Description of the proposed protection system for distribution transformers

Fig. 3 shows the proposed transformer protection system being installed at a distribution transformer of PPC. The proposed protection system is installed parallel to the low voltage (LV) terminals of the transformer, according to the connection diagram of Fig. 4. Moreover, medium voltage (MV) surge arresters are installed at the MV terminals of the distribution transformer. Field experience has shown that if only MV surge arresters are installed, without Rayvoss protection (SPD at LV), then the peak of the overvoltage arising at or transferred to the LV side of the distribution transformer may exceed the corresponding insulation level. On the other hand, the simultaneous installation of MV surge arresters at the MV side and SPD (Rayvoss protection) at the LV side significantly reduces the LV side overvoltages.

The proposed protection system (Fig. 5) uses three Strikesorb 80 modules for the protection between the phases and the ground. These modules protect against overvoltages and overcurrents that appear in the three phases relative to the ground, which are caused either by lightning surges or by endogenous factors of the power supply system, e.g., switching surges.

Fig. 3. Rayvoss protection system being installed at a distribution transformer of PPC.

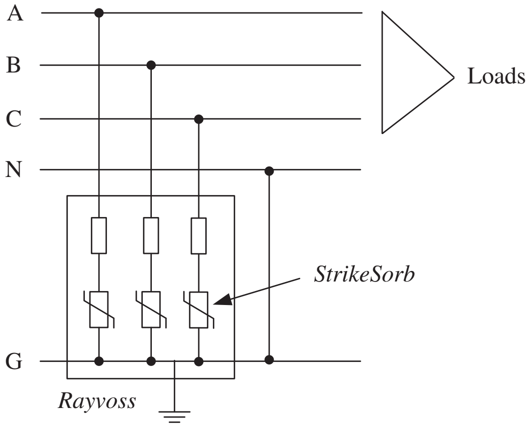


Fig. 4. Connection diagram of Rayvoss transformer protection system.

Fig. 5. Rayvoss transformer protection system.

Each Strikesorb 80 module offers 200 kA protection from direct lightning stroke current (waveform 8/20 according to NEMA LS-1) and 25 kA protection from indirect lightning stroke current (waveform 10/350 according to IEC 1643-1 class I).

The above modules, together with special type fuses (VSP) that can withstand lightning currents, are placed within an IP65 environmental protected metallic board with dimensions 400 × 400 × 200 mm.

The system has an electronic card with light emitting diodes indicating the operation mode as well as a remote monitoring system, which are installed within the metallic board.

Historical data of transformer failures

Table 2 shows the historical data of eleven years (2000 to 2010), for the failures due to lightning and switching surges of the 100 distribution transformers (sample), and Table 3 presents the statistics for the failures of Table 2. The high rate of failures due to lightning and switching surges (8.36 average transformer failures per year in the sample of 100 transformers during the eleven-year period of historical data) is a real challenge for any protection system; that is why, after agreement with PPC, the proposed protection system was decided to be installed in January 2012 at this sample of 100 transformers.

Among the 92 failures of Table 2, 75 failures are due to lightning surges and the rest 17 failures are due to switching surges. It should be noted that the selected sample of 100 transformers during the eleven year period faced in total 115 failures, out of which 92 failures are due to lightning and switching surges, while the rest 23 failures are due to other reasons (short circuits, overloads, internal transformer faults, and other causes). Consequently, lightning and switching surge related failures are quite significant as compared to other failures for the selected sample of 100 transformers. Moreover, the total average annual failures of the selected sample is 10.45%, which is very high, in comparison to the 1.93% total average annual transformer failures for the whole distribution network of PPC that currently has approximately 140,000 distribution transformers. The above statistical analysis shows that the selected sample of 100 transformers presents an exceptionally high rate of failures due to lightning and switching surges; consequently the lightning and switching surge protection of this specific sample of transformers is a real challenge for Rayvoss transformer protection system.

Failure estimation of transformers without the proposed protection system

In this section, with the help of the following three methods, namely, (1) Monte Carlo simulation, (2) Poisson statistical distribution, and (3) binomial statistical distribution, the failures of transformers without the proposed protection system are estimated. This analysis is very important, since it will estimate the number of future yearly failures on the sample of 100 distribution transformers in case they were not equipped with the proposed protection system, which is denoted as Case A in the following.

The Monte Carlo simulation method constitutes one of the most widespread methods of statistical sampling, due to its effectiveness and its general applicability. The Monte Carlo simulation is a category of computational algorithms that are based on repetitive random sampling for the calculation of the results [22]. The probabilistic standards of Poisson and binomial distribution are particularly useful for failures analysis [23] that is why they are used in this study.

More specifically, the analysis has been implemented as follows:

Table 3
Statistics of transformer yearly failures of Table 2.

Number of transformers (constant sample size)	100
Total time period (years)	11
Total failures	92
Average value of failures per year, μ	8.36
Standard deviation of failures per year, σ	2.14
Average value of failures per year and per transformer, p_0	0.084
Standard deviation of failures per year and per transformer	0.021

1. The data for the Monte Carlo simulation are the following: the average value of failures per year ($\mu = 8.36$ from Table 3), the standard deviation of failures per year ($\sigma = 2.14$ from Table 3), the constant sample size (100 transformers from Table 3), and the number of simulation years (1000 years, which is a very common selection in order the Monte Carlo simulation to provide reliable results [22]). It is assumed that the transformer failures follow the normal distribution. The results of Monte Carlo simulation are presented in Table 4, Fig. 6, and the third column of Table 5.
2. The data for the Poisson distribution is the average value of failures per year ($\mu = 8.36$ from Table 3). The results of Poisson distribution are shown in the second column of Table 5.
3. The data for the binomial distribution is the average value of failures per year and per transformer ($p_0 = 0.084$ from Table 3) and the sample size (100 transformers from Table 3). The results of binomial distribution are shown in the fourth column of Table 5.

Fig. 7 presents a graphical comparison of the results (yearly failures probability) of the three methods (Monte Carlo simulation, Poisson distribution, and binomial distribution). In Fig. 7, the straight line parallel to the horizontal axis shows the 5% limit, which corresponds to the $a = 0.05$ significance level, or equivalently to the 95% statistical certainty [24]. As will be analyzed in Section 'Statistical hypothesis testing', by applying the statistical hypothesis testing [24], and using Table 5 and Fig. 7, the maximum number of failures will be computed, in order the proposed protection system to be considered that it constitutes an effective means for transformer protection with 95% statistical certainty.

Failure estimation of transformers equipped with the proposed protection system

Future yearly transformer failures

Statistical hypothesis testing

The answer to the question which is the number of yearly transformer failures in the sample of 100 transformers that indicates that the proposed protection constitutes an effective protection system, is based on the theory of statistical hypothesis testing [24]. More specifically, the hypotheses are the following:

$$H_0: \ p = p_0 = 0.084$$

and

$$H_A: \ p < p_0 = 0.084$$

Table 2
Yearly failures due to lightning and switching surges in the sample of 100 transformers before the installation of the proposed protection system.

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Failures	9	7	10	7	9	11	6	6	7	13	7

Table 4
Yearly transformer failures probability as computed by Monte Carlo simulation for Case A.

Failures	Probability (%)	Cumulative (%)
0	0.026	0.026
1	0.139	0.165
2	0.473	0.638
3	1.474	**2.112**
4	3.500	5.612
5	6.930	12.542
6	11.878	24.420
7	15.343	39.763
8	17.532	57.295
9	16.335	73.630
10	12.191	85.821
11	7.698	93.519
12	3.964	97.483
13	1.738	99.221
14	0.571	99.792
15	0.159	99.951
16	0.033	99.984
17	0.006	99.990
>17	0.010	100.000

The bold value shows the maximum number of failures for which the cumulative probability is less than the significance level of 5% as well as the corresponding cumulative probability.

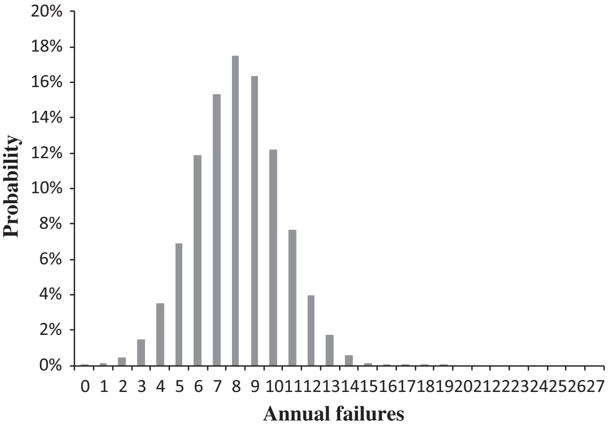


Fig. 6. Transformer failure probability computed by Monte Carlo simulation method for Case A (the sample of 100 transformers is not equipped with the proposed protection system).

Table 5
Transformer failure cumulative probability (%), as computed by Monte Carlo simulation, Poisson distribution and binomial distribution for Case A (without the proposed protection system).

Number of failures	Poisson	Monte Carlo	Binomial
0	0.023	0.026	0.011
1	0.219	0.165	0.115
2	1.037	0.638	0.605
3	**3.316**	**2.112**	**2.135**
4	8.079	5.612	5.677
5	16.044	12.542	12.173
6	27.141	24.420	22.003
7	40.394	39.763	34.622
8	54.243	57.295	48.654
9	67.107	73.630	62.379
10	77.862	85.821	74.336
11	86.036	93.519	83.706
12	91.730	97.483	90.365
13	95.392	99.221	94.687
14	97.578	99.792	97.263
15	98.797	99.951	98.680
16	99.434	99.984	99.403
17	99.747	99.990	99.747
>17	100.000	100.000	100.000

The bold value shows the maximum number of failures for which the cumulative probability is less than the significance level of 5% as well as the corresponding cumulative probability.

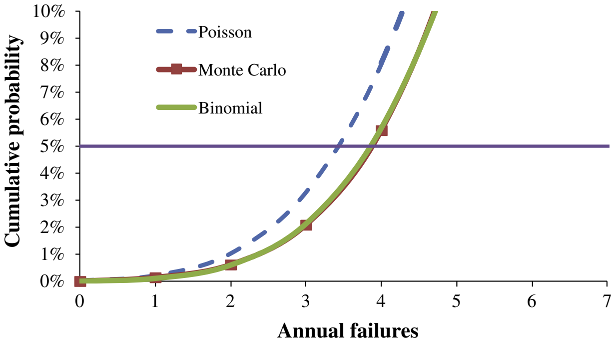


Fig. 7. Transformer failure cumulative probability computed by Monte Carlo simulation, Poisson distribution and binomial distribution for Case A (without the proposed protection system).

where p is the average value of failures per year and per transformer equipped with the proposed protection, while p_0 is the average value of failures per year and per transformer without the proposed protection ($p_0 = 0.084$ has been computed in Table 3).

The zero hypothesis H_0 declares that the proposed protection does not offer significant protection, with 95% statistical certainty (or equivalent with significance level $a = 0.05$). This happens because the zero hypothesis H_0 considers that the average value of transformer failures, either with the proposed protection, or without the proposed protection, remains the same. The alternative hypothesis H_A declares that the proposed protection is significant, with 95% statistical certainty.

According to the theory of statistical hypothesis testing, the zero hypothesis H_0 is rejected, namely the hypothesis that the proposed protection does not offer significant protection is rejected, for that number of failures for which the failure cumulative probability is less than 5% (significance level $a = 0.05$).

It is concluded from Table 5 that, for the Monte Carlo simulation method, the cumulative probability for the yearly failures to be from 0 to 3 is 2.112% (which is smaller than the significance level of 5%), while the cumulative probability for the yearly failures to be from 0 to 4 is 5.612% (which is greater than the significance level of 5%), so the conclusion is that when the yearly failures are from 0 to 3, the zero hypothesis H_0 is rejected, consequently the complementary (alternative) hypothesis H_A is accepted, which means that the proposed protection is significant.

Similarly, from Table 5, the following conclusions are drawn:

1. According to the binomial distribution, if the yearly failures are from 0 to 3, then the proposed protection is significant, because for number of failures from 0 to 3, the cumulative probability of the binomial distribution (2.135%) is less than the significance level of 5%.
2. According to the Poisson distribution, if the yearly failures are from 0 to 3, then the proposed protection is significant, because for number of failures from 0 to 3, the cumulative probability of the Poisson distribution (3.316%) is less than 5%.

Consequently, the three different methods (Monte Carlo simulation, binomial distribution, and Poisson distribution) provide the same conclusion: if the yearly lightning and surge related failures are from 0 to 3, then the proposed protection is significant.

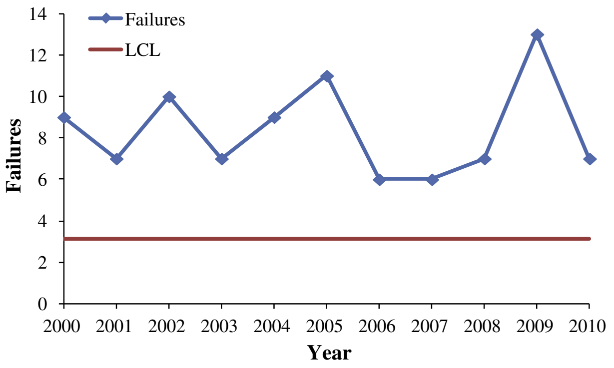


Fig. 8. *c* Control chart for the yearly transformer failures for Case A (without the proposed protection system).

c control chart

In order to compare the results and validate the conclusions, additionally to the three methods (Monte Carlo simulation, binomial distribution, and Poisson distribution) of Section 'Statistical hypothesis testing', one more method, namely the *c* control chart, is also used to determine the number of yearly failures for the proposed protection system to be considered as an effective protection means. The *c* control chart is widely used in the industry to monitor the number of defective products and processes [23,25].

In the *c* control chart, the lower control limit (*LCL*) is computed by [23,25]:

$$LCL = \mu - t_{0.05;10} \cdot \sqrt{\mu} \Rightarrow LCL = 8.36 - 1.812 \cdot \sqrt{8.36} \Rightarrow LCL = 3.12$$

where $\mu = 8.36$ is the average number of failures per year without protection (Table 3), and $t_{0.05;10} = 1.812$ is the value of the Student distribution for 0.05 probability (namely 95% cumulative probability) and 10 degrees of freedom, where the number of degrees of freedom is equal to the number of years for which there are failure data (11 years) minus one.

Fig. 8 shows the *c* control chart for the yearly transformer failures. According to the theory of the *c* control chart, it is concluded from Fig. 8 that if the yearly transformer failures are less than the lower control limit ($LCL = 3.12$), namely if the yearly lightning and surge related failures are from 0 to 3, then the proposed protection is significant.

Synthesis

The results from Sections 'Statistical hypothesis testing' and '*c* control chart' are summarized in Table 6. The four different methods (Monte Carlo simulation, binomial distribution, Poisson distribution, and *c* control chart) provide the same conclusion: if the yearly lightning and surge related failures are from 0 to 3, then the proposed protection is significant with 95% statistical certainty.

Sample size

In the bibliography, there are different methods for the determination of the satisfactory sample size *n*, which, in the current study, expresses the minimum number of transformers at which the proposed protection system has to be installed in order to draw a statistically safe conclusion for the reliability of this protection system for desired risks *a* and β of the statistical hypothesis testing, where *a* is the probability of Type I (false positive) error and *β* is the probability of Type II (false negative) error [24]. In the following, two of the most representative sample size computation methods are applied.

Method 1

It is desirable to be able to detect a specific change in the actual new average value of the process under the proposed protection, from the estimated average value of $p_0 = 0.084$ (Table 3) without the proposed protection. Consequently, if it is desirable to determine the probability the control can identify a real change in the average value from $p_0 = 0.084$ to $p_1 = 0.03$ (always with risk $a = 0.05$, or equivalently with 95% statistical certainty), then for one-sided control and for the number of observations of 11 years, the sample size *n* is computed by [23,24]:

$$n \geqslant \frac{p_0 \cdot (1 - p_0) \cdot (t_{0.05;10})^2}{(p_0 - p_1)^2} \Rightarrow n \geqslant \frac{0.084 \cdot (1 - 0.084) \cdot (1.812)^2}{(0.084 - 0.03)^2}$$
$$\Rightarrow n \geqslant 86.6$$

where $p_0 = 0.084$ is the average value of failures per transformer and per year without protection (Table 3), $p_1 = 0.03$ is the desired average value of failures per transformer and per year with the proposed protection and $t_{0.05;10} = 1.812$ is the value of the Student distribution for 0.05 probability (namely 95% cumulative probability) and 10 degrees of freedom, where the number of degrees of freedom is equal to the number of years for which there are failure data (11 years) minus one.

The conclusion from the method 1 is that the minimum sample size is $n = 87$ transformers.

Method 2

According to this method [23,24], a sample size *n* is selected to ensure with 95% statistical certainty (namely with only 5% risk, i.e., $a = 0.05$) that if the average value of failures per year and per transformer with the proposed protection is $p_1 = 0.03$, then the control is selected to be able to detect correctly the effectiveness of the proposed protection in 70% of the cases, i.e., it is selected a reasonable risk *β* with value $\beta = 0.30$. The risk values of $a = 0.05$ and $\beta = 0.30$ are commonly used in the statistical sampling as very satisfactory for the study of failures of industrial equipment [23,24]. Based on the above data and requirements, and using the Minitab 16 software package [26], it is computed that the minimum sample size is $n = 103$ transformers, as can be seen from the results of Fig. 9.

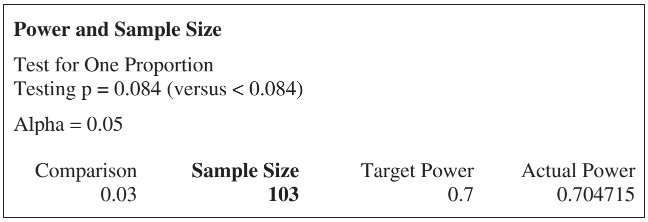
Duration of transformer monitoring

Using four different methods, it was concluded in Section 'Synthesis' that if the yearly lightning and surge related failures are from 0 to 3 in the sample of 100 transformers, then the proposed protection is significant.

In the question which is the conclusion if the yearly lightning and surge related failures are above three, the answer is given by

Table 6
Estimation of the number of yearly lightning and surge related failures for the proposed protection system to be considered as an effective protection means.

No	Method	Statistical certainty	Number of yearly transformer failures
1	Monte Carlo simulation	95%	From 0 to 3
2	*c* control chart	95%	From 0 to 3
3	Binomial distribution	95%	From 0 to 3
4	Poisson distribution	95%	From 0 to 3



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Power and Sample Size

Test for One Proportion
Testing p = 0.084 (versus < 0.084)

Alpha = 0.05

  Comparison    Sample Size    Target Power    Actual Power
        0.03            103             0.7        0.704715
```

Fig. 9. Calculation of the appropriate sample size using Minitab 16 software.

applying the Monte Carlo simulation. More specifically, for more than three lightning and surge related failures in the year 2012 (the first year in which the proposed protection was installed), assumptions (scenarios) are created for the lightning and surge related failures of the year 2012 (namely 4, or 5, or 6, etc., failures), the average value and the standard deviation for the 12–year period are computed (eleven years of Table 2 plus the assumption for the failures of year 2012), and the Monte Carlo simulation method is applied. It should be noted that it is not fair for the proposed protection system, to mix the data of two different populations, i.e., the population without the proposed protection and the population equipped with the proposed protection. However, it was selected to mix these two populations, in order to estimate the duration that is necessary to monitor the transformer sample so as to be able to draw a statistically safe conclusion for the effectiveness of the proposed protection system.

More specifically, the Monte Carlo simulation method is applied as follows:

1. Lightning and surge related failure scenarios for the year 2012 are considered, namely yearly failures 4, 5, 6, etc.
2. For each failure scenario for the year 2012, this scenario is added to the data of Table 2, and the new average value and standard deviation for the yearly lightning and surge related failures are computed. For example, if the lightning and surge related failures of 2012 are 4, then, for the twelve years of the 100 transformers, the new average value is $\mu = 8.00$ lightning and surge related failures per year and the new standard deviation is $\sigma = 2.38$ lightning and surge related failures per year.
3. Using the new values for the average value and the standard deviation of yearly lightning and surge related failures, a Monte Carlo simulation is executed with 1000 simulation years and 100 transformers sample size. Next, the maximum number of lightning and surge related failures is computed, for which the cumulative probability of Monte Carlo simulation is less than 5% (risk $a = 0.05$), so the maximum number of yearly lightning and surge related failures is computed for which the proposed protection is effective.
4. The steps 2 and 3 are repeated for all the scenarios of step 1.

The application of this method computes the number of years to monitor the sample of 100 transformers in order to be able to decide for the effectiveness of the proposed protection system. The obtained results are shown in Table 7. It can be seen that if the year 2012, in the sample of 100 transformers, the lightning and surge related failures are from 0 to 3, then one monitoring year is enough to conclude that the proposed protection is efficient. Similarly, Table 7 shows that if the yearly lightning and surge related failures of 2012 are from 4 to 6 and the yearly lightning and surge related failures of 2013 are from 0 to 3, then two years of monitoring are enough to conclude that the proposed protection is efficient.

Synthesis

Based on the above study, the following conclusions are drawn:

1. The proposed protection is effective with 95% statistical certainty, if, in the sample of 100 transformers, the lightning and surge related failures are from zero to three. In this case, one year is needed to monitor the sample of 100 transformers to draw a statistically safe conclusion for the effectiveness of the proposed protection system.
2. The proposed protection is effective with 95% statistical certainty, if, in the sample of 100 transformers, the lightning and surge related failures of year 2012 (first year of installation of the protection equipment) are from four to six, and the lightning and surge related failures of year 2013 are from zero to three. In this case, two years are needed to monitor the sample of 100 transformers to draw a statistically safe conclusion for the effectiveness of the proposed protection system.
3. The sample size of 100 transformers permits with a 95% statistical certainty (risk $a = 0.05$) to estimate with a 70% probability (risk $\beta = 0.30$) that the proposed protection is effective if, after the application of the proposed protection, the new average value of yearly lightning and surge related failures in the sample of 100 transformers is 0.03 failures per transformer or equivalently three yearly failures in the sample of 100 transformers.
4. Twenty-nine (29) months after the installation of the proposed protection equipment on the sample of 100 transformers, there are zero lightning and surge related transformer failures during the whole 29–month period. Consequently, the proposed solution constitutes an excellent means for lightning and surge protection of distribution transformers.

Conclusions

This paper proposes an industrial solution for lightning and surge protection of distribution transformers. The proposed protection equipment has been installed at 100 distribution transformers (sample) of the Public Power Corporation of Greece. These 100 distribution transformers have been selected because a high rate of lightning and surge related failures was observed in this sample during an eleven-year period of historical data, which means that protecting this population of transformers is a real challenge for any protection system.

Based on eleven-year statistics of failures of this sample collected before the installation of the protection equipment, the future lightning and surge related transformer failures are estimated in this article, considering two different cases: (a) transformer without the proposed protection system and (b) transformer equipped with the proposed protection system. Three different methods are used to estimate the future lightning and

Table 7
Determination of the number of years to monitor the sample of 100 transformers in order to be able to decide for the effectiveness of the proposed protection system.

Failures in 2012	Failures in 2013	Monitoring years	Decision year	Proposed solution offers effective transformer protection?
0–3	–	1	End of 2012	Yes
4–6	0–3	2	End of 2013	Yes
>6	>3	>2	–	New study is needed

surge related transformer failures without the proposed protection system: Monte Carlo simulation, Poisson statistical distribution, and binomial statistical distribution. These three methods together with the *c* control chart method are also used in this paper, for the case of transformers equipped with the proposed protection system, to estimate the maximum allowable number of yearly lightning and surge related transformer failures in order the proposed protection system to be considered as an effective protection means. Moreover, the article computes the satisfactory sample size of transformers in which the protection system has to be installed in order to be able to obtain statistically reliable results regarding the effectiveness of the proposed protection system and the conclusion is that a sample size of 100 transformers is satisfactory.

The results show that the proposed solution is an excellent means for lightning and surge protection of distribution transformers. More specifically, the proposed protection provides excellent protection with zero lightning and surge related transformer failures during the whole period of its operation, namely 29 months, from January 2012 when the equipment was installed till today (May 2014). This has to be compared with the situation before the installation of the proposed protection system, where a high rate of lightning and surge related failures was observed; more specifically, 8.36 average lightning and surge related transformer failures per year in the sample of 100 transformers during an eleven-year period of historical data.

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