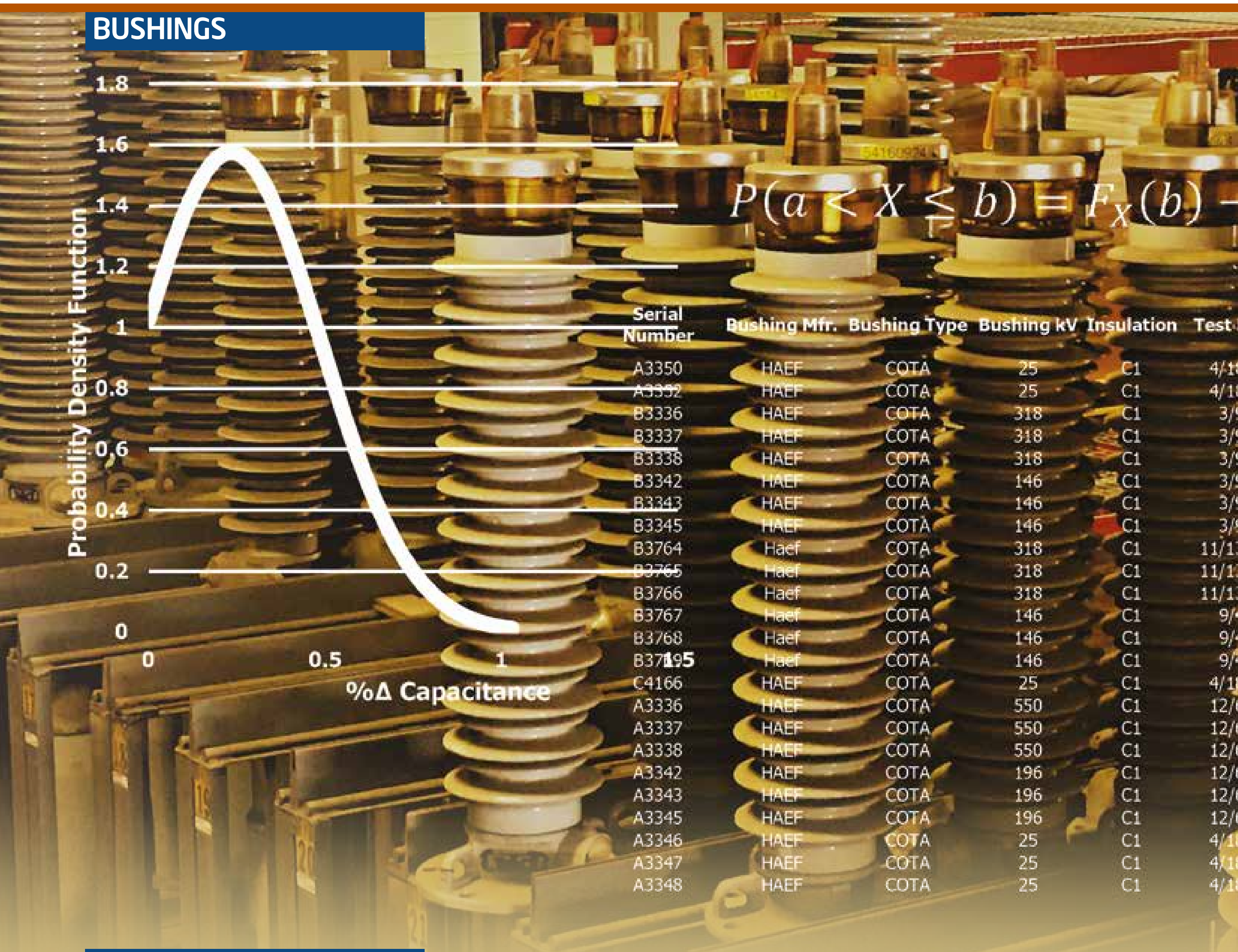

ABSTRACT

Use of statistics opens the door for enhancing bushing power factor / capacitance analysis. The tool, informed by a database with more than 6 million tests, tailors the diagnostic limits by determining what is statistically normal for a specific type, manufacturer, and voltage rating of a bushing. More precisely, it computes deviations of power factor and capacitance from a benchmark. It then determines the probability distribution that best fits the resulting dataset. Once the data is mathematically characterized, the mean and standard deviations are computed. In the end, the bushing in question is assessed based on how it statistically compares to the rest.

KEYWORDS

bushing, capacitance, data analysis, power factor, statistics

Refining bushing power factor and capacitance analysis through statistics

Diagnostic limits are tailored employing statistical norms for a specific type, manufacturer, and voltage rating of a bushing

Ronald D. HERNÁNDEZ, Mark F. LACHMAN

Typical approach for the diagnostic analysis of the high-voltage bushings uses power factor and capacitance measurements; obtained values are then compared with the benchmark data

1. Introduction

Power factor and capacitance are two types of tests employed in diagnostic analysis of high-voltage bushings. The former is mainly used to measure the dielectric losses of the bushing insulation, which are related to contamination and deterioration of the solid and liquid insulating materials. Meanwhile, the latter is used to detect physical problems such as shorted capacitance layers and oil leaks.

Historically, the limits employed in diagnostic analysis of high-voltage bushings rely on general rules. They include a comparison of test results with a benchmark value (e.g., the nameplate or the first measurement), the use of absolute limits, and trending of empirical data over time. This approach, while useful, has its limitations. It relies on similar or the same limits being applied across different types of bushings. For example, some manufacturers recommend that the power factor value corrected to 20 °C should not exceed the value of two or three times the benchmark. Meanwhile, a limit of power factor ≤ 0.5 % is given in IEEE Std C57.19.01™-2017 for oil-impregnated paper-insulated bushings. For capacitance, a 5 - 10 % increase / decrease in measured values over the benchmark value is used as an action limit by most users.

Doble's bushing statistical analysis tool is available in the web version of the Doble Test Assistant (DTAWeb) application, which uses statistics to open the door to a significant enhancement of the existing approach. The tool is used to tailor limits by determining what is statistically normal for a specific type, manufacturer, and voltage rating of a bushing. This is accomplished by having access to the Doble's database of more than 6 million tests. More precisely, the tool computes the deviations of power factor and capacitance from a benchmark value for a particular population of specific bushing types based on a DTAWeb query. It is followed by the determination of the probability distribution that best fits the selected test data. Once the data is characterized by probability, the limits can be applied by using common statistics. This includes deriving the mean, and standard deviation followed (if needed) by zooming in on the region(s) of higher data concentration where the latter depends on the shape of the best probability distribution. The tool also allows the determination of the probability (i.e., 'likelihood') for a given bushing type to have changes in power factor or capacitance falling within a certain range.

2. Basic concepts of probability and statistics

Before discussing the statistical treatment of the empirical (observed) data, it is instructive to revisit the basic probability and statistical concepts. This, in turn, allows for a meaningful interpretation of the observed data as presented in the case studies.

The variable under study here is the deviation of power factor / capacitance with respect to a benchmark value which can be considered a random variable of a continuous type

Our approach uses probability density function to find the probability of bushing's change in power factor or capacitance to fall into a particular range

2.1 Random variable

A variable whose values could assume any of the possible experimental outcomes of a random phenomenon is called a random variable. For instance, this variable could be the current of a random source or the gain in a game of chance [1]. In particular, the variable under study here - the deviation of power factor / capacitance with respect to a benchmark value - can be considered a random variable of a continuous type (i.e., its sample space has an uncountable infinite number of the sample points).

2.2 Probability distribution function and probability density function

The behaviour of a random variable is characterized by its probability distribution, that is, by the way, probabilities are distributed over the values it assumes.

A probability distribution function and a probability density function are two ways to characterize this distribution for a continuous random variable. Both of them are equivalent in the sense that the knowledge of either one completely statistically categorises the random variable [2] as in (1):

$$P(a<X\leq b) = F_X(b)-F_X(a) = \int_a^b f_X(x)dx \quad (1)$$

where $P(a<X\leq b)$ is the probability of the random variable *"X"* falling into the interval between *"a"* and *"b"*, with $F_X(x)$ and $f_X(x)$ representing the probability distribution function and probability density function of *"X"*, respectively.

Our approach uses probability density function to find the probability of bushing's change in power factor or capacitance to fall into a particular range. This probability is given by the *area under the curve* of the probability density function over the specified range.

2.3. Types of distribution

There are different types of continuous distribution that can be used to model the observed data produced by the DTAWeb query. Our application considers the following types: Gaussian, uniform, Gamma, exponential, chi-squared and Beta. For each, the probability density function and probability distribution function are available in the literature [1, 2].

A hypothesis testing procedure must be implemented in order to determine the distribution that best fits the observed data.

2.4 Chi-squared (χ^2) goodness-of-fit test

A statistical hypothesis is an assumption about the value of one or more parameters of a statistical model. Thus, hypothesis testing is the process of establishing the validity of a hypothesis. In the bushing statistical analysis tool, the hypothesis does not involve a specific parameter, but rather the probability distribution that best describes a population. The latter is produced by analysing a sample of data from that population. One of the most popular and most versatile tests for this purpose is the chi-squared ($\chi 2$) goodness-of-fit test.

Errors or risks are inherent in deciding whether a hypothesized distribution should be accepted or rejected based on a sample from the population. Tests for hypotheses testing are, therefore, generally compared in terms of the probabilities of errors that might be committed [2].

2.5 Measures of central tendency and dispersion

In order to facilitate the analysis of the data, it needs to be summarized numerically. To that end, we can employ two broad categories found in descriptive statistics. The first, measure of central tendency, describes the center point of the population with a single value. The second, a measure of dispersion, describes how far the individual data values have strayed from the center point.

The most common measure of the central tendency is the *mean (m)* or average, which is calculated by adding all values in the sample and then dividing the result by the number of observations. However, with the determination of the best probability distribution (i.e., the one that matches the sample data the best as a result of using hypothesis testing), it is possible to obtain a better estimation of the actual mean value corresponding to the whole population from where the sample was taken.

The best probability distribution is characterized by the shape and scale parameters that define the curve. These, in turn, are used to calculate the measures of central tendency and dispersion associated with that type of distribution.

Now, by describing the population by a single mean value only, we lose information that could be useful. This is addressed through the measure of dispersion. One of the most common measurements of dispersion is the *standard deviation* (σ), which indicates how close or spread out the data points are with respect to the mean. The standard deviation is actually a more useful measure than the variance because it has the same units of measure as the original data.

With the determination of the best probability distribution, it is possible to obtain a better estimation of the actual mean value corresponding to the whole population from where the sample was taken

3. Power factor and capacitance deviations with respect to a benchmark

As stated, the bushing statistical analysis tool computes the deviations of power factor (ΔPF) and capacitance (ΔC) from a benchmark value. The benchmark, depending on the choices made, could be the first measurement (default option) or the nameplate value, if present in the database.

The deviations are calculated as in (2) and (3):

$$\Delta PF = |\%PF_{benchmark} - \%PF_i| \qquad (2)$$

$$\Delta C = (|C_{benchmark} - C_i| / C_{benchmark}) \times 100\,\%, \qquad (3)$$

where the subscripts "benchmark" and "i" correspond to the benchmark value and any given test value, respectively.

Here it is useful to recognize that "%" as a unit of measure carries a different significance for ΔPF and for ΔC. The ΔPF is an absolute value of the change where *PF* is already in "%", while ΔC is a change in "%" with respect to the benchmark. It should be noted that before applying (2) and (3), the raw data is subjected to a rigorous filtering process, reducing the presence of bias that could impact statistical conclusions. It includes getting rid of negative test results along with erroneous PF / capacitance and temperature values introduced by the users when uploading the data into DTAWeb.

The raw data is subjected to a rigorous filtering process, reducing the presence of bias that could impact statistical conclusions

4. Applying statistical analysis to bushing data

The following discussion offers examples of the tool's application.

4.1 Case study 1: Comparing bushings to the population as part of the asset management strategy

In seeking guidance in their asset management, the utility compared two Trench, 25 kV, type COTA bushings to similar bushings on their grid (same manufacturer, type, voltage), as well as to the entire Doble's database population.

After running the statistical analysis using the utility's database, the results, which include the C1 insulation power factor data - nameplate, 1st test, last test, ΔPF with respect to the 1st test - along with other calculated parameters, are shown in Table 1. Of particular interest is the last column *"Out StdDev Region"*, where the tool identifies the bushings with ΔPF that fall outside the standard deviation regions *($m+1\sigma$, $m+2\sigma$ and $m+3\sigma$)*. We have highlighted the two bushings the utility wanted to focus on: S/N 04F0213-17 has been identified to be outside the ΔPF region of $m+3\sigma = 0.2057\ \%$ (given its $\Delta PF = 0.24\ \%$), while S/N 08F0211-33 is outside the ΔPF region of $m+2\sigma = 0.1517\ \%$ (given its $\Delta PF = 0.17\ \%$). Statistical data informing statistical conclusions from Table 1 is shown in Fig. 1.

Table 1. Bushing statistical analysis for case study 1 using utility's database population (tabulated results extract)

Bushing S/N	NP PF [%]	1st PF [%]	Last PF [%]	ΔPF [%]	NP C [pF]	1st C [pF]	Last C [pF]	ΔC [%]	Out StdDev Region [%]
61794-41	0,32	0,21	0,44	0,23	1107	1112	1109	0,31	m+3σ (0.2057)
04F0213-19	0,25	0,25	0,46	0,21	421	423	422	0,37	m+3σ (0.2057)
04F0213-17	0,24	0,25	0,49	0,24	418	422	419	0,63	m+3σ (0.2057)
04F0213-20	0,24	0,26	0,55	0,29	421	425	422	0,70	m+3σ (0.2057)
04F0213-02	0,25	0,23	0,57	0,34	398	400	401	0,27	m+3σ (0.2057)
04F0213-03	0,25	0,24	0,58	0,34	404	406	404	0,46	m+3σ (0.2057)
04F0213-01	0,25	0,24	0,46	0,22	395	398	396	0,44	m+3σ (0.2057)
04F0213-04	0,25	0,24	0,48	0,24	402	404	404	0,01	m+3σ (0.2057)
08F0211-33	0,20	0,26	0,43	0,17	394	399	398	0,20	m+2σ (0.1517)
05F0211-06	0,26	0,26	0,44	0,18	429	432	431	0,22	m+2σ (0.1517)
04F0213-08	0,25	0,25	0,42	0,17	405	408	410	0,52	m+2σ (0.1517)
05F0211-07	0,25	0,27	0,42	0,15	431	434	433	0,34	m+1σ (0.0978)
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

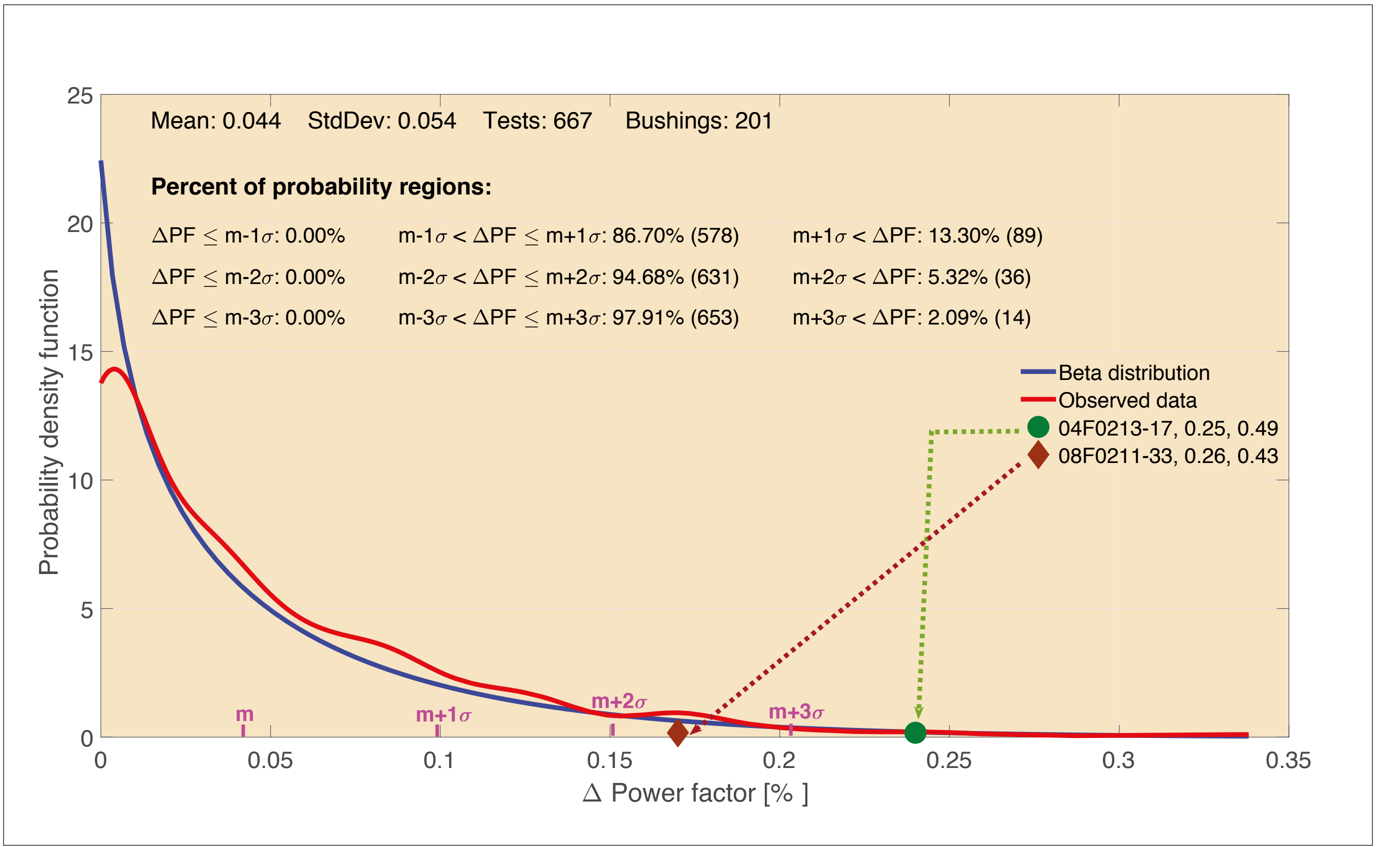

Figure 1. Bushing statistical analysis for case study 1 using utility's database population (*ΔPF*)

There is a case that illustrates how a potential bushing failure could have been flagged should the tool had been used earlier to analyze this utility's population of bushings

The figure shows the probability density function for *ΔPF* of the C1 insulation for the family of bushings of interest. The red curve corresponds to the selected sample (observed) data, while the blue curve corresponds to the beta distribution. This distribution has been found by the tool as the best fit for the data under review. The two bushings of interest have been identified (note the green circle and brown diamond markers along X-axis) as well as listed with their serial number and the 1st and last test results (note legends on the right). Clearly, the identified bushings, even though they might meet traditional limits (e.g., PF ≤ 0.5 %), deserve attention given their deviation from the bulk of the population. This is especially relevant for bushing S/N 04F0213-17, which is outside the region of $m+3\sigma$ where the probability of exceeding this value (i.e., $m+3\sigma < \Delta PF$) is 2.09 %, representing only 14 data points out of 667 (Fig. 1).

The same analysis was performed with the entire Doble's database population (Table 2 and Fig. 2). As expected, the total number of tests is higher (1,839 versus 667). There is also a change in both the mean and standard deviation values. As a result, the two bushings of interest have moved from their previous probability region positions. Bushing S/N 04F0213-17 is now identified outside the *ΔPF* region of $m+2\sigma$ where the probability of exceeding this value (i.e., $m+2\sigma < \Delta PF$) is 4.69 %, representing 87 data points out of 1,839 (Fig. 2). It demonstrates the impact the sample size has on the results of statistical analysis.

The analysis tool provided further guidance by identifying the three additional bushings outside the $m+3\sigma$ region (first three bushings in Table 2), where the probability of exceeding this value (i.e., $m+3\sigma < \Delta PF$) is 2.40 %, representing 45 data points out of 1,839 in the entire Doble's database population (Fig. 2).

4.2 Case study 2: Investigating bushing failure

The case illustrates how a potential bushing failure could have been flagged should the tool had been used earlier to analyze this utility's population of bushings. Another bushing failure investigation using the tool can be found in [3].

The tool identifies the bushings with *ΔPF* or *ΔC* that fall outside the standard deviation regions (*m+1σ, m+2σ and m+3σ*)

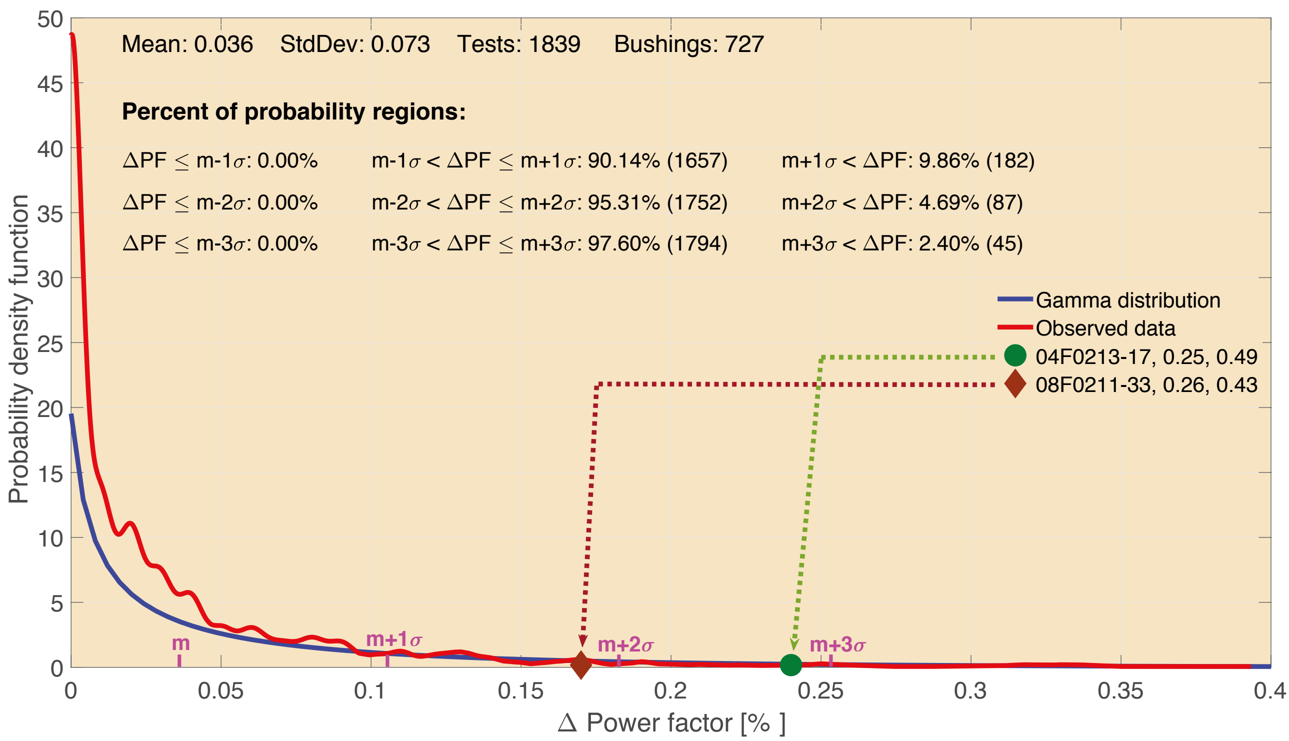

Figure 2. Bushing statistical analysis for case study 1 using entire Doble's database population (*ΔPF*)

Table 2. Bushing statistical analysis for case study 1 using entire Doble's database population (tabulated results extract)

Bushing S/N	NP PF [%]	1st PF [%]	Last PF [%]	ΔPF [%]	NP C [pF]	1st C [pF]	Last C [pF]	ΔC [%]	Out StdDev Region [%]
04F0213-20	0,24	0,26	0,55	0,29	421	425	422	0,70	m+3σ (0.2544)
04F0213-02	0,25	0,23	0,57	0,34	398	400	401	0,27	m+3σ (0.2544)
04F0213-03	0,25	0,24	0,58	0,34	404	406	404	0,46	m+3σ(0.2544)
61794-41	0,32	0,21	0,44	0,23	1107	1112	1109	0,31	m+2σ (0.1815)
04F0213-17	0,24	0,25	0,49	0,24	418	422	419	0,63	m+2σ (0.1815)
04F0213-19	0,25	0,25	0,46	0,21	421	423	422	0,37	m+2σ (0.1815)
04F0213-01	0,25	0,24	0,46	0,22	395	398	396	0,44	m+2σ (0.1815)
04F0213-04	0,25	0,24	0,48	0,24	402	404	404	0,01	m+2σ (0.1815)
08F0211-33	0,20	0,26	0,43	0,17	394	399	398	0,20	m+1σ (0.1085)
05F0211-07	0,25	0,27	0,42	0,15	431	434	433	0,34	m+1σ (0.1085)
05F0211-06	0,26	0,26	0,44	0,18	429	432	431	0,22	m+1σ (0.1085)
04F0213-08	0,25	0,25	0,42	0,17	405	408	410	0,52	m+1σ (0.1085)
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Assigning significance to the placement of the data should be supported by examination of the shape of the probability distribution curve

A recent report by a utility described a catastrophic failure of an ABB, 69 kV, type O+C bushing S/N 3634XXXXXX. The event produced a fire resulting in a transformer failure (Fig.3). The statistical analysis was performed using the utility's population of bushings combined with that of their immediate neighbors.

The analysis was initially run for C1 insulation power factor data using the bushing's 1st test as a benchmark (i.e., $PF_{benchmark} = 0.22\ \%$) as shown in the highlighted row of Table 3. It was found that while the bushing's latest test, prior to the failure (i.e., $PF = 0.42\ \%$), was within traditional limits (e.g., $PF \leq 0.5\ \%$ and $PF < 2 \times PF_{benchmark}$), the tool has placed the bushing's ΔPF to be outside the region of $m+1\sigma$ as noted in the last column of Table 3.

It should be noted that, in general, when the data is placed outside the region of $m+1\sigma$, this does not necessarily suggest a reason for concern. Assigning significance to the placement of the data should be supported by examination of the shape of the probability distribution curve (Fig. 4).

It is observed that the bushing of interest (highlighted with the green dot on the graph) is located farther to the right with respect to the region with the concentration of ΔPF data (i.e., $0 - 0.15\ \%\ \Delta PF$). In other words, the bushing of interest is located in a region where the probability density function is very low with the probability of $\Delta PF > 0.15\ \%$ being only 3.08 %.

The ΔC analysis is similar to ΔPF in terms of the shape of the probability distribution curve (Fig. 5). It was performed for C1 insulation capacitance data using the bushing's 1st test as a benchmark (i.e., $C_{benchmark} = 266.6$ pF).

The results show that while the bushing's latest test, prior to the failure (i.e., $C = 270.97$ pF), met traditional limits (e.g., $|\Delta C| < 5\ \%$), its resulting $\Delta C = 1.64\ \%$ is located in a region where the probability density function is very low with the probability of $\Delta C > 1.5\ \%$ being only 2.46 %. The concentration of ΔC values is occurring in the region of $0 - 1.5\ \%\ \Delta C$.

Statistical tool can be employed for performing the comparison of bushing(s) under consideration to a population with the same type, voltage rating and manufacturer

Figure 3. Investigated ABB, 69 kV, type O+C bushing failure for case study 2

Table 3. Bushing statistical analysis for case study 2 using several utility databases (tabulated results extract)

Bushing S/N	NP PF [%]	1st PF [%]	Last PF [%]	ΔPF [%]	NP C [pF]	1st C [pF]	Last C [pF]	ΔC [%]	Out StdDev Region [%]
1ZUA1000065240	0,23	3,06	0,24	2,82	244	249	241	3,26	m+3σ (0.4231)
8C01241902	0,30	0,21	0,76	0,55	265	262	264	0,73	m+3σ (0.4231)
3092620293	0,26	0,26	1,13	0,87	262	259	260	0,46	m+3σ (0.4231)
0S02848109	0,30	0,28	1,07	0,79	277	277	275	0,56	m+3σ (0.4231)
1000058992	0,25	0,22	1,97	1,75	240	239	241	0,64	m+3σ (0.4231)
3092020393	0,30	1,69	0,58	1,12	263	263	265	0,94	m+3σ (0.4231)
3092020293	0,31	0,38	0,96	0,58	257	256	257	0,41	m+3σ (0.4231)
3092020193	0,27	0,38	0,94	0,56	267	266	261	1,88	m+3σ (0.4231)
1ZUA1000065236	0,24	2,73	0,24	2,49	242	247	239	3,23	m+3σ (0.4231)
1S03867924	0,28	0,24	0,59	0,35	266	262	262	0,08	m+2σ (0.2925)
1ZUA1000060875	0,25	0,64	0,26	0,38	313	522	521	0,08	m+2σ (0.2925)
3063010190	0,26	0,29	0,71	0,42	322	322	324	0,62	m+2σ (0.2925)
3634XXXXXX	0,22	0,22	0,42	0,20	267	267	271	1,64	m+1σ (0.1619)
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

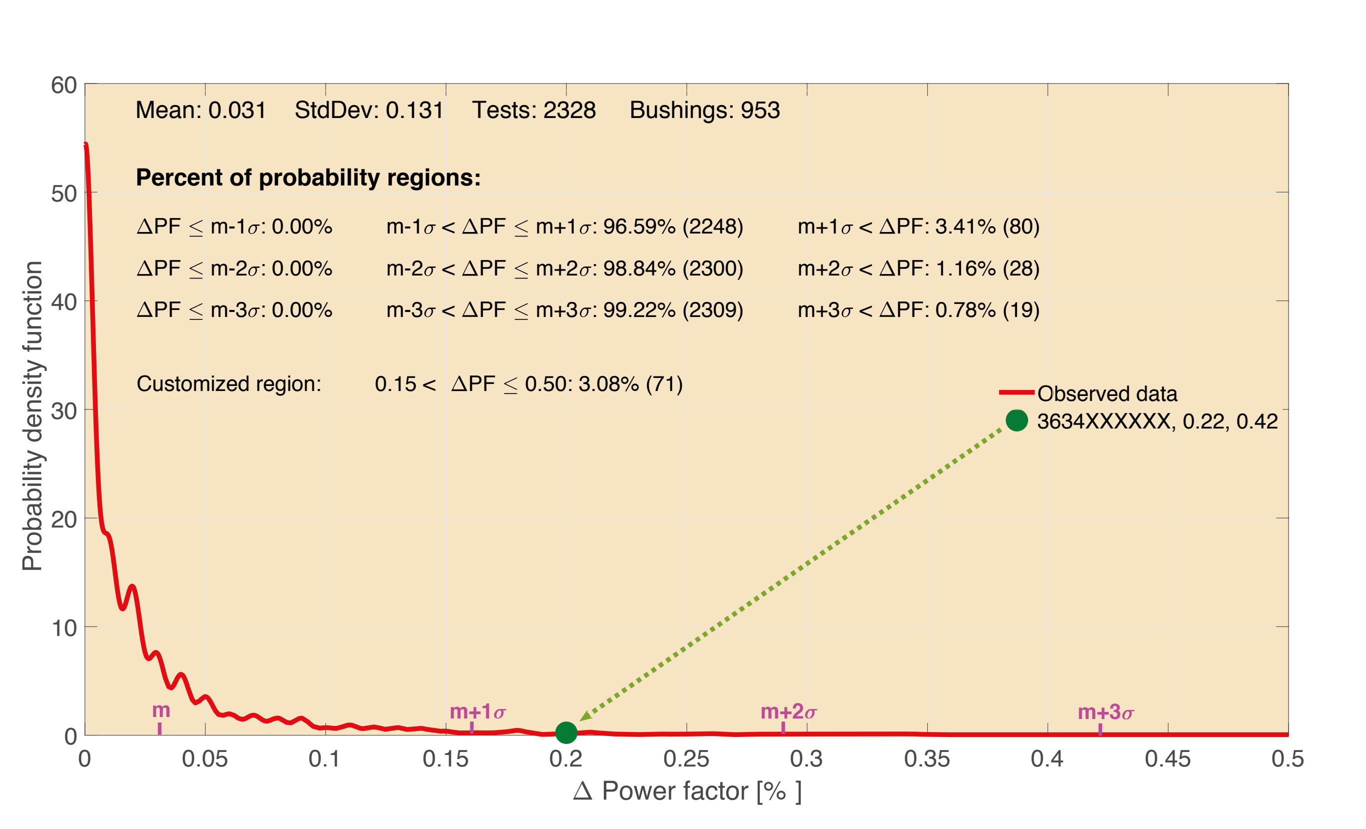

Figure 4. Bushing statistical analysis for case study 2 using several utility databases (*ΔPF*)

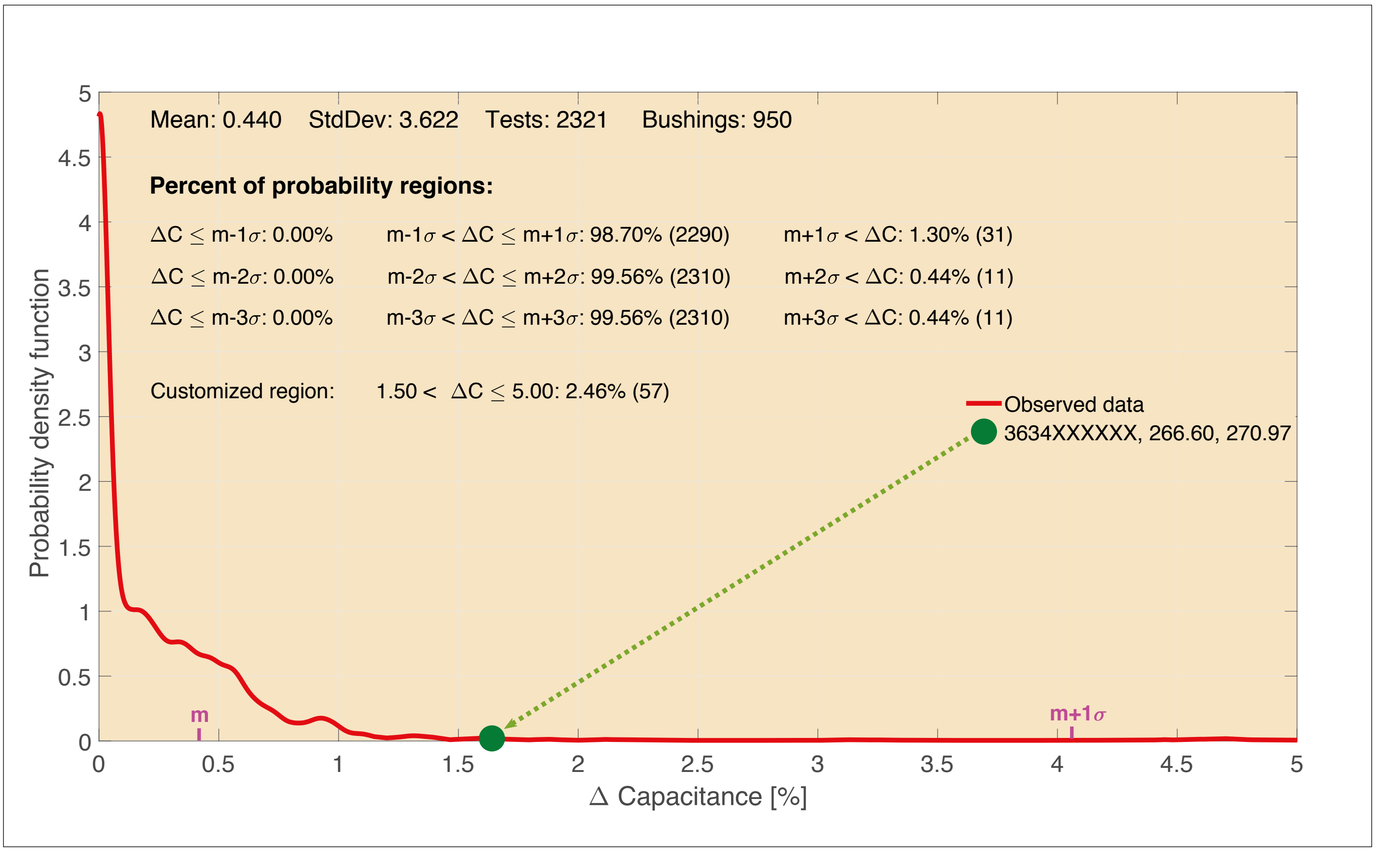

Figure 5. Bushing statistical analysis for case study 2 using several utility databases (*ΔC*)

Conclusion

In summary, a bushing statistical analysis tool has been developed. The available functionality can be employed for:

- Performing statistical comparison of bushing(s) under consideration to a population with the same type, voltage rating and manufacturer. This population can come from either utility's own or significantly larger power industry-wide database.
- Tailoring acceptable diagnostic limits for PF/C for a given bushing.
- Examining the probability of bushing exhibiting a given change in PF/C.
- Prioritizing asset management decisions by identifying bushings requiring urgent attention.
- Identifying bushing problems that otherwise may go undetected with the traditional approach to limit selections.
- Detecting trends associated with industry-wide bushing issues.

Bibliography

[1] A. Papoulis, S. U. Pillai, *Probability, Random Variables and Stochastic Processes*, 4th edition, McGraw-Hill, 2002

[2] T. T. Soong, *Fundamentals of Probability and Statistics for Engineers*, John Wiley & Sons, Ltd., 2004

[3] R. D. Hernandez, M. F. Lachman, E. J. Quintana, *Enhancing high-voltage bushing diagnostics through power factor / capacitance statistical analysis*, 86th International Conference of Doble Clients, Sec. BIIT-6, 2019

Authors

Ronald D. Hernández holds both Ph.D. and M.S. in EE from Northeastern University, Boston MA, USA, and B.S. in EE from the Technological University of Panama. He also holds a global MBA from IE Business School, Madrid, Spain. Dr. Hernández joined Doble Engineering Company in 2012 as Diagnostic Analysis Research Engineer. He has developed applications in the fields of moisture in insulation systems, dielectric frequency response and statistical analysis. Dr. Hernández is a member of the Electrical and Computer Engineering "Honor Society Eta Kappa Nu" and the IEEE Power & Energy Society. He is also a member of the IEEE Transformer Committee and is active in several working groups.

Mark F. Lachman, Ph.D., P.E., has been with the power industry for over 40 years. His experience includes development of off-line and on-line diagnostics as well as factory testing of power transformers. As Director of Diagnostic Analyses at Doble, he contributes to advancing interpretation of apparatus diagnostic data.