On-Line Diagnostics of High-Voltage Bushings and Current Transformers Using the Sum Current Method

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Abstract—Experience with the application of the sum current method to on-line diagnostics of high-voltage bushings and current transformers is presented. The method and analysis are described along with field experience obtained at fourteen substations, comprising 56 sets of (three) bushings and current transformers. The influences of temperature, humidity and changes in more than one bushing are discussed.

Index Terms—Bushing, capacitance, current transformer, on-line diagnostics, power factor, sum current method.

I. INTRODUCTION

HIGH-VOLTAGE bushings and current transformers are among the most vulnerable power system components. Subjected to high dielectric and thermal stresses, bushings are one of the leading causes of power transformer failures [1]. Free-standing current transformers continue to be a major concern to the utility industry [2]. In the past, the principle of the sum current method has been successfully applied to the on-line monitoring of these devices [3]. Today, microprocessor and communication technologies allow one to use this method in association with an expert system. The expert system, supported by comprehensive data collection, provides a critical bridge between on-line monitoring and on-line diagnostics.

The objective of on-line diagnostics is not to present the user with a voluminous amount of data requiring further analysis, but to inform him/her if any intervention is required. To be useful, on-line diagnostics should identify a wide array of problems in the incipient stage. Diagnostic methods must distinguish between changes that are “noise,” those of minor consequence, and those worthy of immediate attention. The diagnostic algorithms must learn from specific experiences and not depend on the user to establish thresholds or employ average values from other nominally similar apparatus.

This paper presents Doble’s initial experience with the application of the sum current method to on-line diagnostics of high-voltage bushings and current transformers. The method and analysis are described along with field experience obtained at fourteen substations, comprising 56 sets of (three) bushings and current transformers. These sets are equipped with the IN-SITE on-line diagnostic system at utilities around the world, and include voltage levels of 19.9, 34.5, 69, 115, 138, 230, 345, 400, and 500 kV.

II. METHOD DESCRIPTION

The basic principle of the sum current method, illustrated in Fig. 1(a), is based on the fact that in a three-phase system, if the system voltages are perfectly balanced and the bushings (or current transformers) are identical, the vector sum of the bushing currents will be zero (Fig. 1(b)). The bushing currents simply represent the leakage currents available at the capacitance or power factor taps of the bushings (Fig. 1(a)). In reality, bushings are never identical and system voltages are never perfectly balanced. As a result, the initial sum current will be small but finite and unique for each set of bushings. When one of the bushings deteriorates, its capacitance and/or power factor will change and, correspondingly, the sum current associated with the set will deviate from its initial value. Thus, the condition of the deteriorating bushing in the set can be determined by evaluating changes in the sum current.

In its simplest form the sum current method can be explained by considering two significant changes in the $C_1$ insulation of one of the bushings (phase A in Fig. 1(c) and (d)). Let the initial sum current be zero. The first change is purely resistive, i.e., only the in-phase component of the bushing current changes due to a change in the power factor of the bushing. This change results in the phasor $\Delta I_A^r = I_A^r - I_A^r$ (Fig. 1(c)). The change is in phase with the voltage phasor $V_A$ and it is equal to $I_A^r$. Starting again with a zero initial sum current, let the second change be purely capacitive, i.e., only the quadrature component of the bushing current changes (Fig. 1(d)). In this case, the change results in the phasor $\Delta I_A^q = I_A^q - I_A^q$. The change in current leads the voltage $V_A$ by $90^\circ$ and is equal to $I_A^q$.

In reality, bushing changes may be both resistive and compared with the sum current calculated using the nominal capacitive due to changes in power factor and capacitance system voltage and frequency, and the power factor and respectively. Therefore, if the changes are positive with respect to the initial values, the angle fo the sum current phasor will be located between the quadrature component of the bushing current phasor and the voltage phasor. This criterion permits easy identification of the suspect bushing using the phase angle of the sum current phasor.

Now, let the initial sum current be $I_A^q$ (Fig. 1(e)). If change $\Delta I_A$ occurs in Bushing A so that it changes the current through $C_1$ from $I_A^r$ to $I_A$, then the sum current changes from $I_A^q$ to $I_A^q$ (Fig. 1(f)). The change in the sum current $\Delta I_A$ is equal to $\Delta I_A$. Then, using $I_A^q$ as a reference, the phase angle (Fig. 1(g)) can be used to determine which bushing created the change. Also, the change in the quadrature component of the sum current $\Delta I_A^q$ can be used to calculate the change in capacitance, and...
the change in the in-phase component $\Delta I^R$ can be used to calculate the change in power factor. In Fig. 1(g) the angle between $I_A$ and $V_A$ is shown much smaller than it would normally be for a typical bushing (close to 90°) and the scale has been changed compared to Fig. 1(f) to show both the in-phase and the quadrature components of $\Delta I_S$.

It appears that a simple subtraction of vector $P_R$ from $P_S$ allows one to obtain the necessary diagnostic parameters, i.e. changes in power factor and capacitance. However, before this calculation can be performed, several questions must be answered:

- How are changes in the sum current, caused by bushing deterioration, distinguished from changes caused temperature, ambient humidity, or power system imbalances?
- How is $P_R$ calculated (first calculated phasor or an average phasor; if average—what subset of the data should be used etc.)?

These questions are answered in the following section.

III. ANALYSIS DESCRIPTION

This section gives a step-by-step overview of the diagnostic analysis, and shows how the measured data is processed to provide an alert to the user (if necessary) on the condition of the bushing. Data from on-line measurements is presented to illustrate some of the data processing steps.

A. Phasor Extraction

The process begins by extracting the fundamental (50 or 60 Hz) phasor from each sum current waveform. The phasors are measured with respect to a reference signal which is typically the leakage current available at the tap of one of the bushings on the voltage bus ($I_3$ in Fig. 1(g)).

B. Setup Verification

For a few initial recordings, the measured sum currents are compared with the sum current calculated using the nominal system voltage and frequency, and the power factor and capacitance values measured off-line. This comparison verifies, to an extent, whether the power factor and capacitance values used in the calculation correspond to the present condition of the bushings and whether the software and hardware are properly configured.

C. Learning Phase

The purpose of the learning phase is to determine the value of the initial sum current for each set of bushings on a given bus. This is accomplished by collecting data for a specified period of time and calculating the initial sum current as the average of a subset of the data collected. The subset is determined from a statistical analysis of the data which eliminates any outliers based on the standard deviation of the distribution.

D. Average Sum Current Calculation

After the learning phase, an average sum current is calculated for each recording using a moving window which includes only the valid phasors, i.e., those that passed the outlier test. If a phasor is accepted, it is included in the calculation of the average sum current. If the phasor is rejected, the previous average sum current is used. The resulting average sum current is used for all further analysis.

Fig. 2 presents a plot of the sum and the average sum current magnitudes obtained hourly from a set of 400-kV Current Transformers located at the La Eliana Substation operated by Red Electrica in Spain. The data spans a period of 10 weeks. The plot identifies daily fluctuations due to temperature, excursions caused by power system imbalances, the learning phase, the rejected phasors, and the average sum current.

A plot of the phasors in polar form shows that the averaged values of the valid sum current phasors form a much tighter
cloud than the raw sum current phasors (Fig. 3). Thus, elimination of power system imbalances through the use of statistical processing and reduction of “noise” by the application of averaging techniques results in a reasonably stable parameter, i.e., the average sum current. The implicit assumption of the averaging technique is that most of the targeted deterioration processes have a time constant longer than that associated with the filter and, as a result, the average sum current is expected to remain responsive to adverse changes in the bushing’s condition. This assumption however, requires further confirmation through experience with deteriorating bushings.

E. Significant Change Detection

Those effects with a time constant comparable to or greater than that of the filter will result in a change by a long-term imbalance in the system voltages, the effect will show up in the average sum current of every bushings set on the bus. This is used to discriminate between significant changes in the condition of the bushings and imbalances in the power system voltages [4].

F. Trend Analysis

When a significant change in the condition of the bushings is detected, the difference between the initial sum current and the latest average sum current is determined. The resulting phasor is used to identify the suspect bushing in each set and associated changes in power factor and capacitance. This information is then used to calculate parameters which help diagnose the condition of the bushings. The parameters are the changes in capacitance and power factor, their rate of change (first derivative with respect to time), and their acceleration or deceleration (second derivative with respect to time). These parameters are calculated using the coefficients of a quadratic function which represents the time evolution of the capacitance and power factor of the suspect bushings. The coefficients are the result of a least-squares fit performed over a moving window of data.

Given the calculated parameters, the following questions can be answered:

1) What is the capacitance and power factor values of the suspect bushings?
2) Are the capacitance and power factor values stable or changing?
3) If changing, are they increasing or decreasing, and at what rate?
4) If changing, is the change slowing down?

The formalism for answering these questions is given in Fig. 4. Just as for the average sum current calculation, the issue of the moving window selection is directly related to the gestation time of the failure modes and is subject to further research.

G. Rules and Alerts

The least-squares calculations yield a set of features needed be implemented with any mathematical software package by the rule engine to perform the final analysis. The “IF-THEN” rules use a set of qualifiers that assume discrete values based on the value of the associated feature. An alone example of a rule that triggers a high priority alert is presented in Fig. 5.

The rules are designed to respond with alerts if the changes in the bushing insulation follow one of five failure modes. These failure modes represent the current understanding of how the capacitance and power factor of a bushing behave as it deteriorates. The power factor associated with the failure modes is shown in Fig. 6 (not to scale).

IV. FIELD OBSERVATIONS

A. Calculated Versus Measured Sum Current

Up to now, our experience with the 56 bushing and current transformer sets equipped with the INSITE on-line diagnostic system has shown various degrees of agreement between the measured (on-line) and the calculated sum current phasors. The calculated phasor is determined using the 10-kV power factor and capacitance values of the C1 insulation measured off-line, and nominal power system frequency and voltage. The algorithm for this calculation is presented in [5] and can be implemented with any mathematical software package similar to Mathcad [6]. Fig. 7 is a polar plot showing both the measured data (clouds) and calculated phasors (stand-alone data points).
Fig. 5. Example of a rule and associated alert.

The hourly recordings were taken at the Boise Bench Substation operated by Idaho Power. The following three cases have been identified:

Case 1: Remarkably Good Agreement for Both the Phase Angle and the Magnitude. This case is typical for new busings or busings in good condition such as the Lapp, 138-kV Type POC bushings installed in Transformer T234. The calculated sum current phasor for this bushing set is within the cloud formed by the measured phasors. These busings have the following 10-kV power factor and capacitance values: \( \alpha = 0.24\% \) and 411 pF, \( \beta = 0.25\% \) and 410 pF, \( \gamma = 0.23\% \) and 411 pF.

Case 2: Good Agreement for the Magnitude and Reasonable Agreement for the Phase Angle. This is the case with the General Electric 230-kV Type U bushings installed in Oil Circuit Breaker 215A. These bushings have the following 10-kV power factor and capacitance values: \( \alpha = 0.30\% \) and 445 pF, \( \beta = 0.33\% \) and 447 pF, \( \gamma = 0.23\% \) and 455 pF.

Case 3: Reasonable Agreement for the Magnitude and Poor Agreement for the Phase Angle. This is the case with General Electric 138-kV Type U bushings installed in Oil Circuit Breaker 106Z. It is stipulated that the disagreement in the phase angle can be attributed to carbon deposits on the outer lower porcelain or internal adverse voltage sensitive conditions in the busings which would become more evident at rated voltage. These busings have the following 10-kV power factor and capacitance values: \( \alpha = 0.29\% \) and 363 pF, \( \beta = 0.30\% \) and 362 pF, \( \gamma = 0.33\% \) and 361 pF.

A similar case is also present with the General Electric 138-kV Type U bushings installed in Transformer T232. These busings have the following 10-kV power factor and capacitance values: \( \alpha = 0.73\% \) and 404 pF, \( \beta = 0.90\% \) and 397 pF, \( \gamma = 1.08\% \) and 401 pF. The high power factor value of these busings indicates insulation deterioration. Therefore, the disagreement between the measured and calculated values could be due to the power factor tip-up caused by the higher rated voltage and temperature. Also, the cloud of the sum current phasors has a noticeably different shape. This data is discussed further in the paper.

The bushing algorithm takes advantage of the comparison between the calculated and the measured sum current values to verify the setup (see Section III-B). However, a comparison between the two phasors can also be used as an additional diagnostic tool. Just as in Case 3 outlined above, the comparison may reveal the presence of abnormalities in the bushing’s insulation such as deposits on the surface of the inner porcelain or of the outer lower porcelain (such as in oil circuit breakers), as well as voltage or temperature sensitive conditions when they are not detected during off-line testing. Further study is required to determine the criterion that would identify each of the above conditions at the level of deterioration significant enough to justify user intervention.

B. Importance of the Latest Off-Line Measurements

The bushing algorithm uses the power factor and capacitance values measured off-line as a benchmark of the bushing’s condition prior to the commencement of on-line measurements. Therefore, in order to obtain accurate results, it is imperative that the off-line data be measured at the time of, or close to, commissioning of the on-line diagnostic system. If these values differ significantly from the bushing’s actual values, the measured sum current value will not agree with the calculated value and an alert will be issued. An example that illustrates this point is a set of 500-kV General Electric Type U bushings used for the
air-to-SF₆ entrance on Breaker 5028 at the Maury Substation operated by Tennessee Valley Authority. The software module determined that the measured sum current magnitude significantly exceeded the calculated value (Table I). Fig. 8 is a polar plot of hourly data for three bushings set on the 500-kV bus including the set 5028. The data shows that the sum current in the defective set is significantly higher than in the sets with good bushings.

The user was alerted that the off-line power factor and capacitance data did not reflect the present condition of the bushings. It was then realized that the off-line data was nearly 10 yrs old and off-line tests were immediately performed on these bushings. The new off-line data resulted in a good comparison with the measured sum current (Table II). The data also showed that two of the three bushings had significantly deteriorated and should be replaced immediately.

The user decided to leave those bushings in service relying on the capabilities of the diagnostic system. Six months later, off-line measurements of power factor and capacitance as well as dissolved gas analysis (DGA) were performed on the bushings. The tests revealed no significant changes in the capacitance and power factor values, in agreement with the results of the on-line diagnostic system. However, the DGA results (Table III) showed very large quantities of Acetylene (C₂H₂) and carbon monoxide (CO) for Bushings A and C (these gases could have been present in the bushings at the start of the six months). Based on the DGA results, large changes in capacitance and elevated power factor values, a decision was made to replace these bushings immediately. This case demonstrates one of the benefits of the diagnostic system: it allowed the user to keep the bushings in-service until an appropriate steps could be scheduled.

C. Off-Line Diagnostic Thresholds in the On-Line World

It is of interest to know whether changes in power factor and capacitance, known to be significant for off-line diagnostic measurements, can be detected on-line. One way to investigate this is to model the changes and observe whether the resulting changes in the calculated sum current can be detected by the system.

Fig. 9 is a polar plot of the sum current phasor from a set of General Electric 138-kV type U bushings. These bushings are installed in Transformer T234 at the Boise Bench Substation operated by Idaho Power. The measured date is superimposed on the sum current calculated for conditions when the power factor and capacitance of the bushing in phase A are changed independently. The power factor is changed in 0.5% increments while capacitance is kept constant at its nameplate value (locus of points along the 150° line) and the capacitance is changed by 1% (of the nameplate value) increments while power factor is kept at its nameplate value (locus of points along the 240° line).

As the plot indicates, the calculated sum current is already outside of the cloud of normal operation when the power factor changes by 0.5% or the capacitance changes by 1% of the nameplate value. This suggests that even the unfiltered data would allow the detection of changes in power factor and thresholds. A similar exercise can be performed for any set of bushings or current transformers with known power factor and capacitance values.

D. Failure Modes

Comprehensive on-line diagnostic techniques require an understanding of the sum current behavior under various failure mode conditions. While at the present time none of the 56 bushing and current transformer sets equipped with
the diagnostic system show signs of active deterioration, preliminary insights can be developed through modeling of the bushing failure modes. One of the most common modes is the short-circuiting of layers in the condenser core (line 4 in Fig. 6). For this failure mode, the sum current can be calculated using the algorithm presented in [5]. The algorithm describes the deterioration of one of the layers in one of the three bushings as a change in the value of the insulation resistance. The resistance changes from a high value (normal condition) to zero as the layer is short-circuited. Fig. 10 shows the behavior of some of the parameters as a function of time. The measured sum current and the calculated data are for Lapp 138-kV Type POC bushings (installed in Transformer T234, see Fig. 7) with 20 condenser layers and the following 10-kV power factor and capacitance values: $\varnothing A = 0.24\%$ and 411 pF, $\varnothing B = 0.25\%$ and 410 pF, $\varnothing C = 0.25\%$ and 411 pF. The failure mode is modeled for Bushing A. The most interesting observations are summarized in the following:

- While the short-circuited layer results in the permanent increase of capacitance, the power factor of the bushing returns to its previous value (Fig. 10(d) and (e)).
- The sum current phasor moves outside of the cloud of normal operation, thus indicating that these changes can be detected by on-line analysis (Fig. 10(g) and (h)).

E. Effects of Temperature

It is well known from off-line diagnostic experience that the relationship between the power factor and the average temperature of the bushing is a good indication of bushing deterioration [7]. Fig. 11 shows this relationship for two General Electric 115-kV Type U bushings. The increase of the power factor with temperature (thermal tip-up) is associated with severe levels of deterioration and can be used as a diagnostic tool.

Controlling the temperature during off-line testing is difficult and this option is not always available to the tester. Similarly, on-line conditions offer an inherent temperature “driver,” i.e., load current and ambient conditions control the temperature of the bushing. These variables can be easily monitored and correlated with diagnostic parameters. This correlation is illustrated in Fig. 12 which shows seven days of top oil temperature plotted with sum current data from two sets of Type U bushings on the same transformer. The middle plot is for the high-side (230-kV) bushings with almost-as-new 10-kV power factor values of 0.30, 0.32 and 0.29%. The top plot is for the low-side (138-kV) bushings with elevated power factor values of 0.73, 0.90 and 1.08%.
The influence of temperature (lower plot) on the sum current is clearly evident, thus providing diagnostic confirmation for the deterioration detected by the 10-kV power factor values. The polar plot for this set (Unit T232 in Fig. 7) reveals an extended cloud shape, again reflecting the sensitivity of the sum current to temperature fluctuations. More data is required before this phenomenon can be incorporated in the diagnostic module of the bushing algorithm.

F. Effects of Humidity

Off-line experience has shown that high ambient humidity and deposits on the bushing’s outer surface can result in increased conductivity of the bushing’s surface. If electrostatic coupling from the bushing’s core surface to the bushing’s outer surface is significant (this path involves oil and porcelain), then the increase in the outer surface conductivity can influence the current available at the bushing’s tap and, subsequently, the sum current. The electrostatic coupling depends on the bushing’s design, voltage class and the extent of deterioration. Therefore, the effects of humidity will vary from set to set.

If all three bushings are affected in a similar manner, the effect of humidity and surface contamination on the sum current will be reduced by the sum of the bushing currents. Furthermore, these effects are further reduced through the use of statistical and averaging techniques. Though it can be postulated that the effects of humidity are identifiable through a careful analysis of the sum current waveforms, this hypothesis requires further study.

G. Simultaneous Bushing Deterioration

It is possible that two or three bushings in the same set can deteriorate at the same time. However, it is highly improbable that these bushings will deteriorate at the same rate. In any case, the algorithm identifies only one bushing: the bushing with current that dominates the sum current. This is the bushing that the expert system would recommend for replacement. Once the equipment is taken out of service, the user would normally test all three bushings before taking any action, thus assessing the condition of the remaining two bushings.

V. CONCLUSIONS

Our initial experience with the application of the sum current method to the on-line diagnostics of high-voltage bushings and current transformers has been presented. It is summarized in the following:

- Two 500-kV Type U bushings with very high capacitance and elevated power factor have been identified (during the setup verification) through a comparison of the measured and calculated sum current phasors, and kept in-service until an appropriate step could be scheduled. After a dissolved gas analysis confirmed the seriousness of the condition, the bushings were replaced. In one set of 138-kV Type U bushings, the sum current was temperature sensitive confirming the high 10-kV power factor values obtained for all three bushings.

VI. FUTURE WORK

Future studies will concentrate on the following issues:

- Extensive study of the influence of power system conditions on the sum current behavior.
- Use of more sophisticated statistical tools to distinguish between the bushing problems and external effects.
- Experimental laboratory study of the sum current behavior under various bushing failure modes.
- On-going study of the gestation time associated with various failure modes.
- Modeling of various failure modes using more sophisticated bushing and current transformer models.
• Development of temperature sensitivity criteria that would identify the level of deterioration required to justify an alert.
• Study of the influence of humidity and bushing surface conditions on the sum current behavior.
• Development of on-line diagnostics for bushings with potential devices.

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