A Step Closer Toward Maintenance-Free Gear

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***Abstract*—A difficult-to-predict electrical failure is the continuity failure. Pressure junctions are common problem sources for continuity failures. Available tools to search for pressure-junction problems include low-resistance testing, temperature monitoring using physical contact between sensor and heated part, pyrometer temperature monitoring, infrared photography, and visual inspection. While each method is effective, each of these methods has one or more disadvantages. This paper will describe a breakthrough patented method of directly calculating conductor and pressure-junction impedance, resistance, and reactance using the noisy harmonic-laden switching-transient-laced (in other words, normal) load current flowing through an electrical distribution system. This technique then provides the solution to the problem of how to detect a conductor-path-impedance change of only a few tens of micro-ohms using conventional protective and metering devices without the need to de-energize the equipment or without the need to inject currents.**

***Index Terms*—Arc flash, continuous, glowing contact, junction-resistance calculation, loosening connection, online.**

I. Introduction

ELECTRICAL equipment failures can be broadly divided into two types: insulation and continuity failures.

The former occurs when current flows when and where it should not. This paper will not discuss the former. A common example of the latter is an unexpected interruption or possibly even an arc Flash event if initiated by a loosening connection [1]–[7]. Available tools to search for the failing pressure connections include low-resistance ohmmeter (Ductor) testing, temperature monitoring using physical contact between sensor and heated part, pyrometer temperature monitoring, infrared photography, and visual inspection. While each method is effective, each of these methods has one or more disadvantages.

A somewhat more ideal solution would be one that is able to continuously measure the impedance of all circuit conductors, calculate the X/R ratio of those conductors, and solve for the resistance per phase of each conductor using relaying and metering already needed by, and in place on, the equipment. This resistance could then be trended over time and even compared between phases, looking for any individual phase trending away from the average over time.

Manuscript received June 16, 2010; accepted September 29, 2010. Date of publication January 6, 2011; date of current version March 18, 2011. Paper 2010-PCIC-263, presented at the 2010 IEEE Petroleum and Chemical Industry Technical Conference, San Antonio, TX, September 20–22, and approved for publication in the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS by the Petroleum and Chemical Industry Committee of the IEEE Industry Applications Society.

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Digital Object Identifier 10.1109/TIA.2010.2103393

Any deviations from normal would be flagged for closer inspection during the earliest available time window. Furthermore, this more ideal embodiment would use ordinary load current and not require additional temperature sensors or current-injection equipment to be installed and maintained. Additionally, it would be preferable to have this functionality built into the existing protective relays, meters, circuit-breaker trip units, low- and medium-voltage adjustable frequency drives, motor overload relays, and any other power monitoring device already connected to the system. Finally, the system must have the sensitivity to detect a change of a few tens through a few hundreds of micro-ohms using the low-level noisy harmonic-laden switching-transient-laced load current that would be expected to be flowing through an electrical distribution system. If such a system could be designed, it could mean that, wherever these relays, meters, breakers, etc., were installed, changes in conductor impedance between any two or more of those devices could be detected.

For the typical junction that degrades over weeks and months, such a system would have the potential to identify that failing junction prior to its escalating past the loose or corroded junction stage and moving into a glowing junction and then into a plasma-cloud-generating junction. An arcing plasma-cloud-generating junction is particularly dangerous as the plasma cloud could grow until it enveloped a grounded or adjacent energized conductor, at which point the equipment could fail catastrophically [1], [8]. This would result in an outage or worse. If technology could detect the failure before it reached this stage, electrical equipment safety could be enhanced.

Such a technology now exists [9]. This paper will describe a breakthrough method of signal processing and analysis using the low-resolution time-skewed load current and voltage signals already available from A/D systems provided within typical electrical equipment. Those signals are used to calculate impedance, resistance, and reactance to three orders of magnitude higher resolution than the inherent resolution of the underlying A/D system on those metering devices. This technique detects a conductor-path-impedance change of only a few tens of micro-ohms using conventional protective and metering devices without the need to de-energize the equipment or without the need to inject currents. Potential benefits of this include the potential for an earlier warning of pending arc Flash event and reduction of maintenance expenses.

II. Continuity Detection Methods Used Today

A. *Temperature Sensing (RTD/TC/Thermistor/Fiber)*

Since a conductor dissipates energy proportional to its resistance, monitoring the temperature as a function of the current

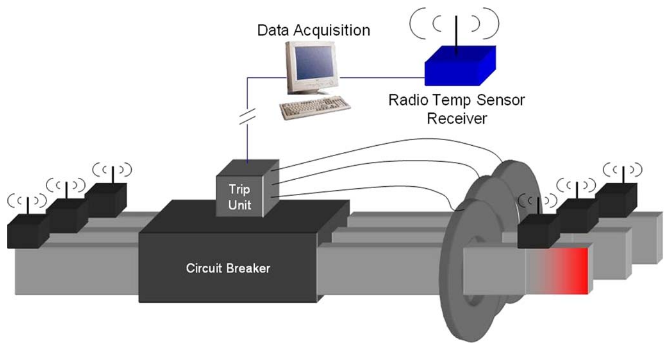

Fig. 1. Temperature sensing with current sensing compensation.

flowing gives an indication of resistance. It is very important to monitor current since energy dissipation is proportional to the square of the current, so even small differences in current can result in large energy dissipation differences. Direct-contact temperature sensing using resistance temperature detectors (RTDs), thermocouples (TCs), or thermistors directly measure the surface temperature of the object to which they are mounted (Fig. 1). Since they are in contact with energized conductors, electrical isolation, both channel to channel (differential mode) and channel to ground (common mode), becomes an issue. As the voltage of the conductors increases, fiber or radio communications may be employed to overcome the problem of ever higher A/D converter isolation voltage ratings. Using either fiber or radio requires powered electronics which increase the complexity and cost of the implementation. Also, since these are point-contact devices, care must be used in placing these near the points needing to be monitored in order that they capture the most accurate representation of the object's temperature. Since electrical conductors act as heat sinks to a hot spot, this nearby metal will wick away the high temperature, making positioning of the temperature detector all the more critical.

B. Temperature Sensing (Pyrometer)

Compared with the infrared (IR) photography method, a single infrared sensor can be aimed at a particular junction. As shown in Fig. 2, care must be taken to insure that the field of view of the sensor is limited, since the signal output will be the average of the temperatures of all objects within its field of view.

C. IR Photography

IR photography measures the intensity of emitted infrared energy, correlating the emitted energy across a field of view to a position within the field of view. Skilled analysts can review this thermal image and draw conclusions about the equipment viewed.

D. Temperature Sensing (Fiber DTS)

A fiber distributed temperature sensing (DTS) system uses fiber optic cable as a linear temperature sensor. As the temperature of the fiber changes, small physical changes to the quartz fiber result in changes to the light transmission characteristics. Using either optical time domain reflectometry or optical frequency domain reflectometry, these changes can be quantified and located along the cable length. This technology requires more sophisticated and costly processing compared with analog sensing from pyrometer or direct contact temperature sensing.

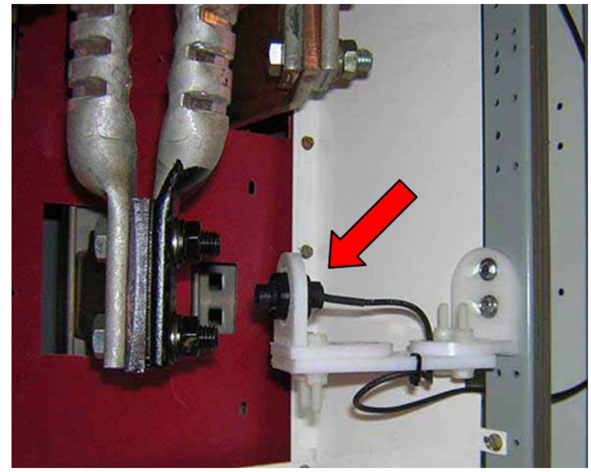

Fig. 2. Pyrometer pointed at pressure junction.

Note that regardless of the type of temperature sensing method employed, the temperature rise must be normalized to the magnitude of current flowing. Furthermore, this temperature must also be measured as the temperature rise above ambient, since higher ambient temperatures will raise the temperature of the conductor, which, in turn, increases the resistance which increases the losses further. It is important to understand why a temperature is rising. As shown in Fig. 3, an increase in conductor temperature can occur from either a change in resistance of the conductor or from a change in ambient temperature.

One solution to differentiating between changes in conductor temperature due to ambient temperature versus due to a change in conductor resistance is to compare all three phases and trend the difference in temperature between phases in addition to the absolute value of the temperature of each phase normalized to the current flow in each phase. Since resistance problems are uncommon, they almost always occur on one phase at a time. Fig. 4 shows examples of how measuring and trending the difference between three separate temperatures can detect a problem not caused from an increase in ambient temperature.

Assuming a change in ambient would affect all three phase conductors equally, the difference in temperature normalized to current would remain constant between each sensor during ambient temperature changes, but would not when the temperature change was due to a failing pressure connection on one phase. Again, current must be used to normalize the monitored temperature to avoid nuisance alarms from temperature variations due to changes in current flow. Measured normalization divisors are field determined since they are a function of the ability of the conductor to be cooled through conductor, convection, and/or radiation.

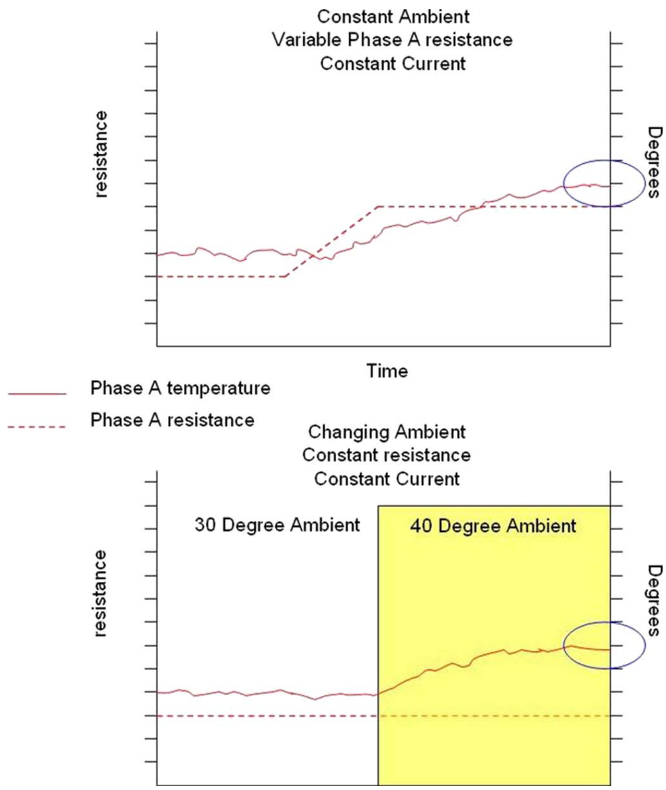

Fig. 3. Conductor temperature rise due to (a) change in resistance or (b) change in ambient.

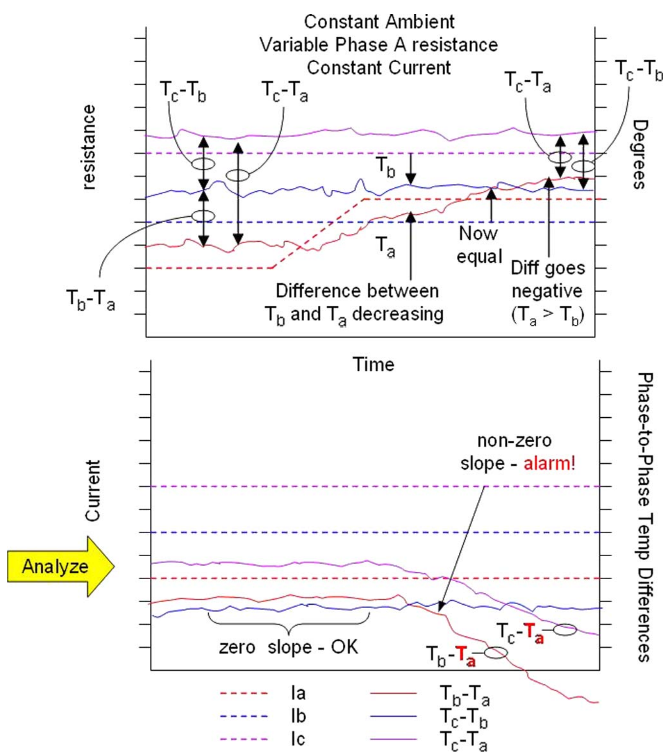

Fig. 4. Three-phase temperature analysis.

E. Low-Resistance Ohmmeter

By injecting (or measuring existing) current flowing through a junction and dividing that value into the voltage drop across a junction, the equivalent impedance of the junction can be calculated. If direct current is used as the forcing function, the calculation results in resistance. Since resistance is what generates dissipation losses, using dc current injection simplifies the calculation. However, since dc currents result in the production of even-order harmonics on power systems, this is typically only done for very short periods of time on an energized system or on a de-energized system. Attempts to use ac current to infer resistance must compensate for reactance by extracting the underlying dc resistance from the measured ac impedance [10].

TABLE I
CONTINUITY TEST METHODS

Method	Disadvantage
IR Photography	Expensive, requires visibility of objects to be measured.
Non-Contact (Pyrometer)	As with IR photography, requires visibility of objects to be measured. Only measures items in field of view. Wide coverage requires multiple sensors. Requires I/O to gather temperature data.
Contact (RTD, T/C, etc.)	Only measures item contacted. Wide coverage requires multiple sensors. Possible isolation problems depending on I/O. Requires powered electronics which increase the complexity and cost of the implementation.
Fiber DTS	Expensive. Requires routing additional fiber over conductors
Low Resistance Ohmmeter	Difficult to perform on live system. Offline may require racking out device to test which could materially change results.

III. CONCERNS

Each of these methods, while popular and common, suffer from one or more disadvantages. These disadvantages are summarized in Table I.

The research that led to this invention began as an attempt to find a solution that addressed the disadvantages outlined in Table I. The thought was that if a method that leveraged the existing metering could be found, the incremental cost to monitor junction resistance would be very low. In other words, if the existing metering could provide the necessary sensitivity and accuracy, the only additional cost would be firmware or software. This firmware could be installed in the meter or an algorithm could be installed in a separate device that periodically extracted data from the meter and performed the resistance calculations.

Analysis, however, quickly showed the problem with using existing metering. The issue was that the difference between an acceptable junction resistance and an unacceptable junction resistance was very small [11]. This is due, in part, to a manufacturer's efforts to reduce the size and weight of their products while still maintaining acceptable temperature rise limits. Since testing standards place limits on the maximum allowable temperature of bus, conductors, lugs, contacts, and terminals, manufacturers have designed these conductors and pressure junctions with very low resistances. For example, the normal measured resistance between a 200-A lug and its underlying bus on a safety switch averaged in measurements of six devices around 14 $\mu\Omega$.

Even assuming your monitoring system only offered enough sensitivity to detect an increase of ten times nominal resistance (i.e., 140 $\mu\Omega$) on a circuit carrying 200 A, that would still result in a change in voltage drop across that lug of only 25 mV ($[140 - 14\ \mu\Omega] * 200$ A $= 25.2$ mV). While this is a small voltage change, remember that we are assuming that full rated current is flowing. Systems seldom operate continuously at their maximum rated current. Using a more realistic lower current would result in an even lower change in the voltage drop measured across these contacts. Using a nominal circuit loading of 35% of this 200-A rating (i.e., 70 A), the measured change in voltage drop from a good to a failing junction would vary by less than 9 mV ($[140 - 14\ \mu\Omega] * 70$ A $= 8.82$ mV). Since analog input circuitry must deal with noise, it would be wise to specify a resolution no less than one-half this value. In that case, the required resolution would be no more than 4 mV.

Since this safety switch had a maximum voltage rating of 600 V, a metering system that would be required to measure 600 V full scale would require a metering resolution of at least one part in 150 000 (600 V divided by 4 mV). This resolution would correspond to an A/D resolution of 18 b ($2^{17} < 150\,000 < 2^{18}$). A similar resolution would be necessary for the current measurement since a resolution of current measurement worse than this value would likewise result in uncertainty with the measured resistance. This would need to be done on a per-phase basis, and the up- and downstream readings would need to be time synchronized within a fraction of a cycle to insure that the up- and downstream measurements of voltage and current represented the same circuit conditions.

This would be a burdensome requirement for a typical power quality meter. Many of these devices do not provide even 16 b of resolution (one part in approximately 64 000), with some as low as 10 b (one part in 1024), and only a few meters are able to time synchronize multiple separate meters to a fraction of a cycle.

Another problem discovered during testing was that these small changes in junction resistance can be masked by the ordinary changes in the resistance of the conductor itself as the temperature of those conductor changes [11]–[13]. The resistance of a metallic conductor is defined by

$$R = \frac{\rho l}{A} \tag{1}$$

where

- R resistance (ohms);
- ρ resistivity (ohm-meter or $\Omega \bullet$ m);
- L conductor length (meters);
- A conductor area (square meters).

Near room temperature, the electrical resistance of a metal such as copper or aluminum varies proportionally to the change in temperature. Standards organizations permit various temperature rises for electrical conductors, but a common value is a 50° C rise on a 40° C ambient. This would correspond to a temperature changing from 40° C to 90° C (or 313 K versus 363 K) or an increase in resistance of 16% as the conductor loading increased from no load to full load. While 16% is much less than the ten times increase we identified for our junction changing from a "good" to a "bad" condition, that 16% is distributed over a much larger conductor.

To convert this from a percentage into an ohmic value, a representative conductor size must be established. For a 200-A system, the assumption is made that current flows through a 6.35 mm (1/4 in) by 25.4 mm (1 in) copper bar with a cross-sectional area of 1.61×10^{-4} m^2 (0.25 in^2). If the total length of that copper bar between ends and impedance measuring points was 3.048 m (10 ft), then using a value of copper resistivity of $1.72 \times 10^{-8}\ \Omega \bullet$ m at 20° C [12] and using (2), we solve for the resistance of this bus as

$$R = \frac{\rho l}{A} = \frac{1.72 \cdot 10^{-8} \cdot 3.048}{1.61 \cdot 10^{-4}} = 325.6\ \mu\Omega. \tag{2}$$

An increase of 16% on 325.6 $\mu\Omega$ would be an increase of 52 $\mu\Omega$. 52 $\mu\Omega$ is 41% of the 126 $\mu\Omega$ change we would expect to see in our failing junction. This means that even expected changes to the temperature of our conductors that would occur during normal operation could mimic a substantial percentage of the resistance change of a failing pressure junction.

The solution to this problem turns out to be the same solution to the problem of how to ignore ambient temperature effects. Since a loosening connection is statistically more likely to occur on one conductor than equally on two or even three conductors, we use the plurality of data available from monitoring three separate phase-resistance values. As outlined in Fig. 4, if the calculated resistance normalized to current on all three phases increases proportionally, ambient temperature or current loading is increasing. That does not warrant an alarm. However, if one phase's calculated resistance normalized to current increased at a rate higher than the other two phases, then that is an indication of a problem.

However, all this analysis of the problem is of less use if we are unable to find a more reasonable solution that addresses the disadvantages outlined in Table I. Can we find an algorithm that can process the data available from existing metering devices to provide the needed resolution and accuracy to detect failing pressure connections? The eventual breakthrough came from understanding that the data provided by the existing A/D converter's monitoring voltage and current could be read in a new way and also by understanding the underlying physics of how the resistance of a conductor varies over time [9].

IV. Description of Invention

An explanation of the solution begins with a review of the method of calculating the impedance between two points in a distribution system. Ohm's Law ($E = IZ$) can be solved at any point along a conductor. With E (voltage) and I (current) as inputs, Z (impedance) can be solved. What does this Z represent? It represents the equivalent impedance seen by the source looking down at the load from that point. The impedance between any two points on a common bus can be found by subtracting two Z values calculated at the two points along

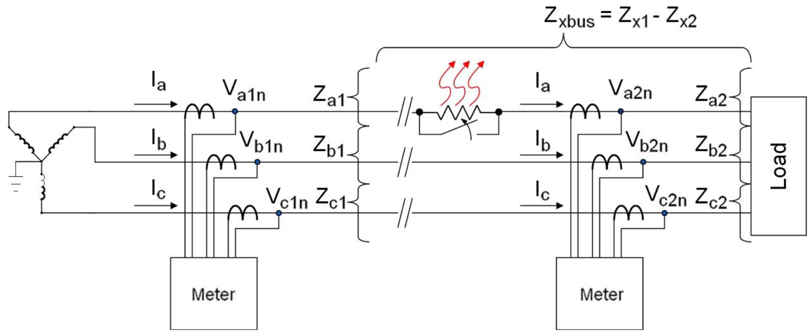

Fig. 5. Direct impedance measurement test setup with 500-$\mu\Omega$ resistance added to A-phase.

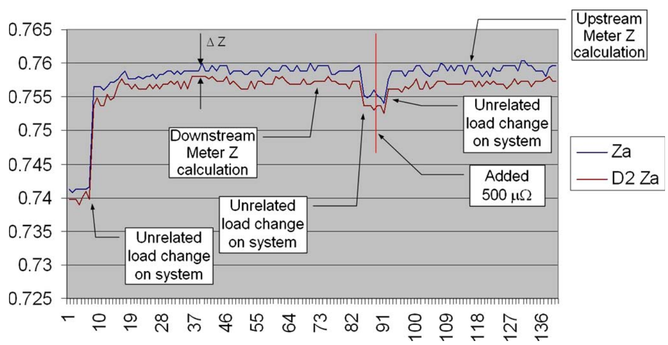

Fig. 6. Raw impedance.

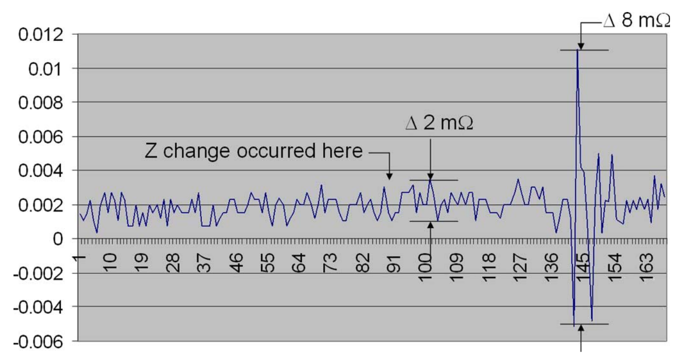

Fig. 7. Noisy ΔZ.

the same conductor. The impedance of the bus between any two metering devices is shown in Fig. 5 and can be calculated using

$$Z_{a\_\text{bus}} = Z_{a1} - Z_{a2} = \frac{V_{a1n}}{I_a} - \frac{V_{a2n}}{I_a} \tag{3}$$

$$Z_{b\_\text{bus}} = Z_{b1} - Z_{b2} = \frac{V_{b1n}}{I_b} - \frac{V_{b2n}}{I_b} \tag{4}$$

$$Z_{c\_\text{bus}} = Z_{c1} - Z_{c2} = \frac{V_{c1n}}{I_c} - \frac{V_{c2n}}{I_c}. \tag{5}$$

The resultant ΔZ, Z_{x_bus} is noisy, masking small changes in impedance. For example, in the circuit shown in Fig. 5, a 500-$\mu\Omega$ known resistance was added to the circuit.

In this experiment, the rms voltage upstream and downstream from that added resistance, as well as current, were sampled on all three phases at essentially the same time (within 20 ms of each other). Values for up- and downstream impedance were calculated and shown in Fig. 6. The space between the lines represents the impedance between those two metered locations along the A-phase, called ΔZ_a. The left axis units are in ohms times 100 (e.g., 0.76 is 76 Ω). On this particular test circuit, the applied voltage was 208Y/120 and the current was approximately 1.58 A. 120 V divided by 1.58 A is approximately 75 to 76 Ω. The impedance of the conductors between the two metering points was approximately 2 mΩ (2000 $\mu\Omega$) prior to the addition of the 500-$\mu\Omega$ addition. In this test, 500 $\mu\Omega$ represents a 25% increase in ΔZ.

At $t = 85$, the 500 $\mu\Omega$ was switched into the circuit. Notice that it is very difficult to see any change in the spacing between the two lines (ΔZ_a) after the additional resistance was added. In an attempt to see the values more clearly, Fig. 7 only shows the difference between the two Z values (ΔZ_a).

As with Fig. 6, a step increase in impedance was added at $t = 85$. Unfortunately, it is still very difficult to see any change. Furthermore, regularly occurring transient impedance deviations that are four to eight times larger than the added impedance occur. How could a 500-$\mu\Omega$ change be detected when measured impedances appear to be varying by 2000 to 8000 $\mu\Omega$ (2–8 mΩ)?

This is where the understanding of the metering and underlying physics of the conductor was used to solve the problem. First, we know that with the metering devices chosen, it was impossible to read both up- and downstream voltage and currents at precisely the same time. The result of this timing "jitter" is that one meter reads one set of data for one particular state of the load, while the second meter reads another set of data occurring at a slightly different time. Because this jitter occurs as the result of some repeatable event, the jitter can be considered somewhat random. In other words, the likelihood of one meter reading a higher value is about the same as the likelihood of that meter reading a lower value. The noise caused by the timing jitter can be represented by a probability density function (PDF) with an approximate normal or Gaussian distribution. This PDF is then processed to obtain the most likely value of impedance for any meter at any particular time.

Unfortunately, we have another problem, as discussed in Section III. The resolution of our metering device would need to resolve very small changes as only small changes in voltage drop are expected as a result of a failing pressure junction. In this experiment, the 1.58 A injected across that additional 500 $\mu\Omega$ resulted in only an additional 790-μV (0.79-mV or 0.00079-V) voltage drop.

The problem is that the meter chosen to monitor this experiment was a ten-year old midrange power-quality meter. This meter featured a 1-b resolution of 120 mV (0.12 V) on the PT inputs and 2.5 mA (0.0025 A) on the CT inputs. That means that a minimum of a 120-mV change would be needed before that meter detected even a 1-b difference. In this experiment, we needed to detect a 790-μV change or only 0.658% of this meter's 1-b A/D resolution.

This would explain why Fig. 7 was so noisy. We would need to have a system that was 151 times more sensitive (1/0.00658) compared with what we had in order to measure this small of a change. The A/D input would not be expected to detect such a small change. Even though our instrumentation was reporting a very noisy impedance calculation, our understanding of the underlying physics would tell us that the actual resistance of the bus is not changing that fast. What is happening instead is the cumulative effect of quantization error and time jitter. Quantization error occurs because we have insufficient resolution in our A/D to represent the voltage or current. Time jitter occurs because our load was changing as a result of harmonics and transients and we cannot obtain two measurements at precisely the same time. However, as we mentioned earlier, the quantization error, likewise, is subject to the same random Gaussian noise where an error signal above the actual value is just as likely as an error below. However, what was discovered was that the conventional method of filtering a Gaussian PDF using a median (average) value did not provide the correct value. This was because root-mean-square calculations square the sampled value and a deviation above the actual value would have a more pronounced effect than an error below. Instead, we employed the mode or the most common value as our output of the PDF. While any method could have been used to calculate the mode, in order to reduce the processing and memory requirements of the algorithm, the filtering algorithm operated as follows.

1) At startup, calculate the impedance Z and store.
2) Repeat Z calculation next sample time, comparing the most recent Z_n with $Z_{\rm roll}$.
   a) If $Z_n > Z_{\rm roll}$, then reduce $Z_{\rm roll}$ by $Z_{\rm roll} * g$.
   b) If $Z_n < Z_{\rm roll}$, then increase $Z_{\rm roll}$ by $Z_{\rm roll} * g$

where

Z_n most recent Z calculation;
$Z_{\rm roll}$ rolling mode calculation of Z;
g gain (user-selected value $0 < g < 1$).

While this provided a filtered value of Z, another issue was that simply dividing voltage drop by current would result in impedance Z, not resistance R. It is resistance that causes heating, not reactance. A change in load power factor could change the calculated impedance Z, but may have little to do with losses across a pressure junction other than to change in the magnitude of current. It was therefore necessary to process our raw data to convert impedance into resistance. Using the same method we used to deal with timing jitter, we examined the most common (mode) phase angle (ϕ) between the current and voltage waveforms and saved this value. From the calculated Z and ϕ values, we solved for R and X.

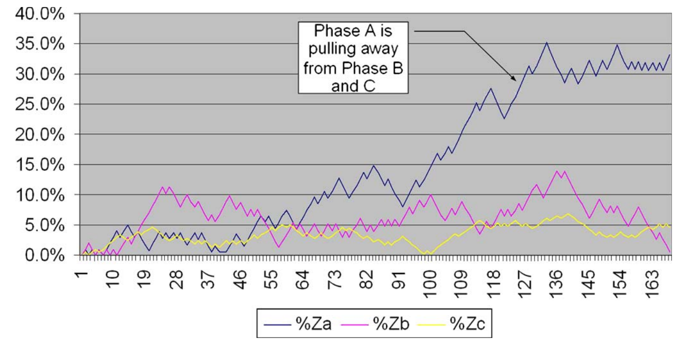

Fig. 8. Filtered output.

Note that depending on the location of the metering devices, the up- or downstream device may be separated by a transformer. Since a transformer reduces current and increases voltage proportional to the turns ratio and because impedance is equal to the voltage (which is increased by turns ratio) divided by current (which is decreasing as the turns ratio increases), the effective impedance viewed through a transformer is increased by the square of the turns ratio. This automatic transformer detection was included in the algorithm.

Another enhancement discovered and included in the patent filing was the recognition that, many times, knowing the exact value of resistance is not as important as knowing that the resistance value has increased relative to the other two phases. If we remove the requirement that we provide exact impedance or resistance, we can save processing time by removing the square-root calculation from the voltage and current rms calculation. This is also beneficial in that precision of the intermediate calculations is increased since no square root of the result is taken. By removing the square-root step, we are, in effect, displaying Z^2 since $V^2/I^2 = Z^2$, further increasing the sensitivity to small changes in impedance and resistance.

V. Results

Processing the data shown in Fig. 7 through the mode algorithm, the power factor algorithm, and removing the square root to calculate Z^2, we were able to extract a clear signature of the increased resistance on the A-phase conductor. In fact, it was only because of the particular gain value chosen in the mode algorithm that we limited the resolution to the value shown in Fig. 8. Once the changed value of impedance stabilizes at its new value, the impedance appears to dither at approximately $\pm 1\%$. In actuality, the inherent resolution of the algorithm is far greater. It was only because the gain value g was chosen to be high enough to obtain a fast-enough response to display the 500-$\mu\Omega$ step change within 30 samples of Z_n for this experiment. The user selects a gain g to balance sensitivity with response time (e.g., higher g: higher sensitivity, lower response time).

This surprising performance then begs the question, how can a system that should not have enough resolution be able to see signals changing several orders of magnitudes below the resolution of the measuring system? The answer can be understood by recalling that all our inputs (process variables) are from noisy real-world signals. Those signals produce a broad spectrum forcing a function that slews our signals across a wide A/D conversion range. The astonishing thing about this noise is that it allowed us to reprogram our A/D algorithm not to display the absolute value of the value being converted but rather to count the number of times each bit value was triggered. Those counts versus time were then placed into a PDF that, then, was fed into a mode algorithm. The most common value using the Z_{roll} times gain equation discussed earlier would extract the actual value of impedance. Further noise reduction occurred once the downstream and upstream values of impedance were subtracted since this tended to cancel out the effects of harmonics and load switching and transients, since these effects tended to produce the same noise signature in both calculations.

VI. Conclusion

Low-cost and relatively low-resolution metering devices can be mined for data, then converted into impedance, and processed further to compute pressure-junction resistance. Since pressure junctions tend to fail in isolation from similar junctions on adjacent phases, measuring the change in relative impedance between phases is an early warning of loosening connections. If left unattended, those loosening connections can progress into glowing junctions, then into plasma-producing arcing junctions, and finally into an arc Flash event. This invention will hopefully result in a much safer work environment. It also has the potential to increase uptime and distribution system reliability since it can detect hidden changes in conductor tightness. It may even reduce maintenance expense, since time-based infrascans are no longer necessary. Instead, infrascans could be scheduled on an as-needed basis if the system alerts that the impedance of a circuit element began to increase by a significant amount.

Acknowledgment

The author would like to thank R. Yanniello, F. Klancher, and R. Cox. All were instrumental in allowing this product development to proceed. R. Yanniello provided project funding. F. Klancher wrote the software routines to modify the power monitoring software to collect the needed data. R. Cox provided technical assistance on how to add this functionality to the current models of power meters.

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