Determining Circuit Breaker Health Using a Novel Circuit Breaker Vibration Analysis Approach

By

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Introduction

All objects can be characterized by their response to physical stimuli. When struck by its clapper, a bell will ring with a certain fundamental frequency and numerous overtones (harmonics). The frequencies of the fundamental and the overtones are determined by the size and geometry of the bell as well as the material from which it is made.

Imperfections such as cracks will cause the bell to respond at different frequencies and/or different amplitudes. If the normal frequencies and amplitudes are known, it is theoretically possible to determine the type, size, and location of an imperfection.

These basic physical facts have led to the well proven scientific method of vibration analysis (VA), which is used extensively for determining existing or impending problems in rotating equipment such as motors or generators. Past attempts to use VA for circuit breakers have met with only limited acceptance, primarily because of the size and complexity of the test equipment, added expense, and the lack of good vibration signatures for comparison purposes.

This paper discusses a new VA method that is being used successfully for determining the mechanical condition (and thus the electrical performance) of circuit breakers. Using a marriage of compact and modern communications equipment, internet data transfer, and sophisticated Condition Base Maintenance Algorithms (CBMA), this new method offers a number of valuable features such as:

1) Extreme portability
2) Easy transmission of data to a central location
3) Capture of "first trip" data[1]
4) A basic "comparison" method of analysis based on a vibration envelope and/or a detailed mathematical analysis of results
5) Ability to perform testing during routine switching
6) Reduces the risk of human error (and thus safety) since it requires no modification or removal of the circuit breaker.

Field tests on circuit breakers have long provided diagnostic and prognostic data for the electrical components. Since the majority of circuit breaker failures are mechanical in nature, this new method helps to fill the toolbox of test methods available to field technicians.

[1] *First trip* is defined as the first time a circuit breaker opens after an extended time in service.

For the remainder of this paper, this new method of vibration analysis will be referred to as *CBVA*. This acronym is a simple three letter contraction of *C*ircuit *B*reaker *V*ibration *A*nalyzer or *C*ircuit *B*reaker *V*ibration *A*nalysis.

What Advantages Does This New Test Tool Offer

The CBVA provides a homogeneous, single-signature graph in three dimensions. The graph can be analyzed for quantitative information concerning the breaker operation and condition. The following points illustrate why the CBVA is a *must do* test.

First Trip Data

Consider the following facts:

- Circuit breakers are mechanical devices, and depend upon proper lubrication to operate correctly.
- Many circuit breakers stay in service with no operations for years or even tens of years.
- NFPA 70E-2012 Article 210.5 requires that, “protective devices shall be properly maintained to adequately withstand and interrupt available fault current.” An information note immediately below Article 210.5 states that, “failure to properly maintain protective devices can have an adverse effect on the arc flash hazard analysis incident energy values.”

The three facts taken together define the importance of a breaker’s *first trip* operation because studies performed during the last fifty years have shown that fully 50% of unmaintained circuit breakers will fail to operate properly after being in service for a period of five years or longer. An excellent paper by Neitzel and Neeson[i] provides excellent background on this.

In the past, the first thing that was done when preparing to perform maintenance on a circuit breaker was to open the breaker and then start the maintenance, thus losing any information about the initial trip. With this new technique, the trip information can be captured when the breaker is first opened – providing invaluable information as to the efficacy of the on-going maintenance plan.

Simple spot check testing

One of the complicating factors of maintenance efforts is the need to have a shutdown before any maintenance can be performed. CBVA allows a quick vibration check during routine switching operations; furthermore, since the test involves simply attaching the test device and operating the breaker, maintenance personnel can be easily trained to perform the test quickly and safely.

Overall mechanical condition

Time-travel analyses (TTA) in conjunction with thorough visual-mechanical inspections (VMI) provide a wealth of information as to the mechanical condition of the breaker. A good vibration analysis of the circuit breaker will provide most of the information that the TTA and VMI yield together.

This is not to say that equipment owners and service providers should stop TTA or VMI in favor of performing vibration analysis. Any good maintenance and testing regimen should include all three because CBVA can be performed multiple times between normal maintenance cycles at little or no additional cost. Using all three provides a much more comprehensive picture of a breaker's mechanical condition. .

Breaker timing

During operation the vibration signature peaks at the moment of trip, the moment of spring charging, and the moment of close. As will be shown later in the paper, a careful analysis of the signature can be used to determine trip time and close time. The CBVA trip time signature displays the vibration events from mechanism motion and Mechanism stop. Thus it captures the entire time not just the time that the contacts open or close.

Safety

Safety is enhanced in at least two ways:

- By using remote operating mechanisms, the test can be performed when the technician is well outside the arc-flash boundary.
- When a breaker is being racked, there is a much higher probably of failure than when it is just sitting. This new test does not require that the breaker be racked.

Why Do Circuit Breakers Vibrate

Fundamentals of vibration

When any real object is subjected to physical stress, the object will tend to deform. If the stress is great enough, the object's deformation may be partially or totally permanent. Consider the dent in your fender when that post "jumped out" and struck it. The stress (force) of the impact was so great that it permanently deformed the fender.

If the force of the impact is small enough, the fender will deform, but then it will "spring" back into shape leaving little or no permanent damage. This is because virtually all materials have some degree of *elasticity*.[2] As long as the deformation does not cross the threshold of elasticity, the material will spring back into shape.

All physical objects in motion have the property of *inertia*.[3] So after the object springs back into shape, it tends to go past the un-deformed state to another deformed position. The object will do this several

[2] The quality or state of being flexible : flexibility, bendability, ductility, elasticity, flexibleness, give, limberness, malleability, plasticity, pliancy, resilience, suppleness. – *Excerpted from* ***American Heritage Talking Dictionary*** *Copyright © 1997 The Learning Company, Inc. All Rights Reserved.*
[3] The tendency of an object to stay in motion unless it is acted on by an external force.

times until the back-and-forth oscillations are reduced to zero by the natural *damping*[4] effect. This leaves the object in its original shape.

If the object has a large damping factor, the oscillations will taper off very quickly. The damping factor for any object is a function of its mass and geometry as well as the material of which it is made. Thus if the geometry of the object changes or if the object is changed or damaged in some way, its damping factor will change consequently changing the frequency and waveform of the vibrations.

A simple object, such as a tuning fork will have very pure vibration signature. That is, the oscillations will have few overtones and the waveform will tend to be more sinusoidal. This is why the sound that a vibrating tuning fork makes sounds so pure.

A more complex object with many different parts will tend to have a very complex vibration pattern. As a result, when the object is stressed, each individual part will contribute to the overall vibration waveform.

Circuit breaker vibration

A circuit breaker is a very complex mechanical mechanism. It has a huge variety parts including springs, lever arms, sheet metal, pivots, rubber stops, contacts, and many other such items. This means that the vibration signature of a circuit breaker will be very complex. Figure 1 shows such a vibration signature.

[4] The action of a substance or of an element in a mechanical or electrical device that gradually reduces the degree of oscillation, vibration, or signal intensity, or prevents it from increasing.

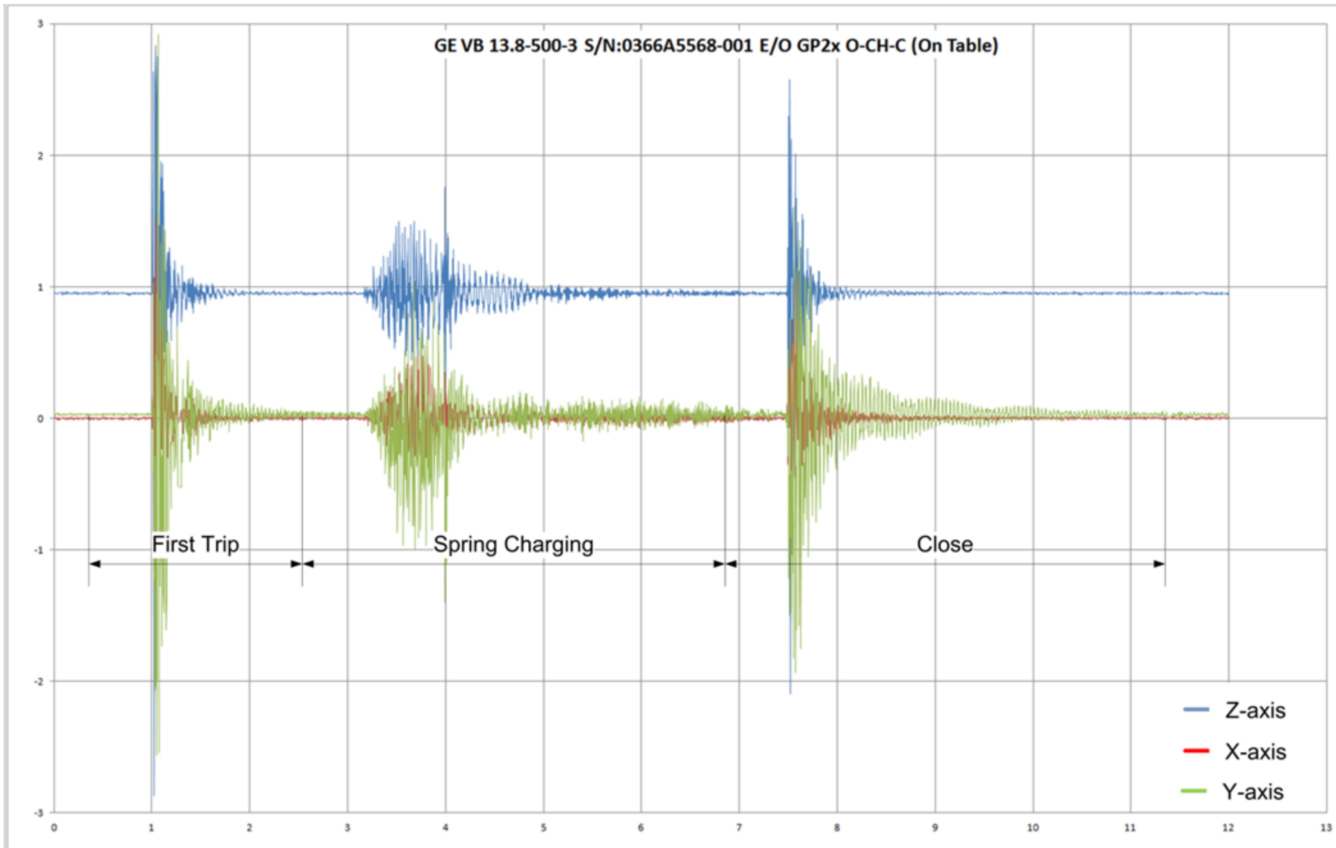

Figure 1 Three axis vibration signature for a circuit breaker *Courtesy of Group CBS Inc.)*

There are three different waveforms – one each for the x, y, and z axes. Note that the trace on each of the axes is similar but not identical to the others. This is because the breaker will not vibrate exactly the same in each of the three directions.

The Z axis is displaced by 1G from the other two. This is because the G axis is the vertical axis and is always subjected to the force of gravity – 9.8 m/sec^2 (32.2 ft/sec^2). The other two axes are horizontal; therefore, gravity has little effect on them.

Considering just one of the traces, you notice that there are three major segments. The first segment is the vibration signature created when the breaker trips, the second segment shows the vibration created when the charging mechanism resets the closing springs, and the third segment shows the vibration created when the breaker is reclosed.

The decreasing magnitude of the vibration in each segment is caused by the damping factor of the entire breaker mechanism. Any damage to the components, loose hardware, or failure of lubrication will cause the vibration signature to change. Given that this signature is a known good profile (KGP), any subsequent changes will show up as changes in the signature. With more research and experience analysis techniques will be able to identify the causes of those small changes.

Capturing motion and vibration in circuit breaker testing

Parameters

There are at least four different parameters that are used in analyzing the performance of a circuit breaker – vibration, travel distance (also called displacement or amplitude), travel velocity, and travel acceleration.

Travel distance (Displacement)

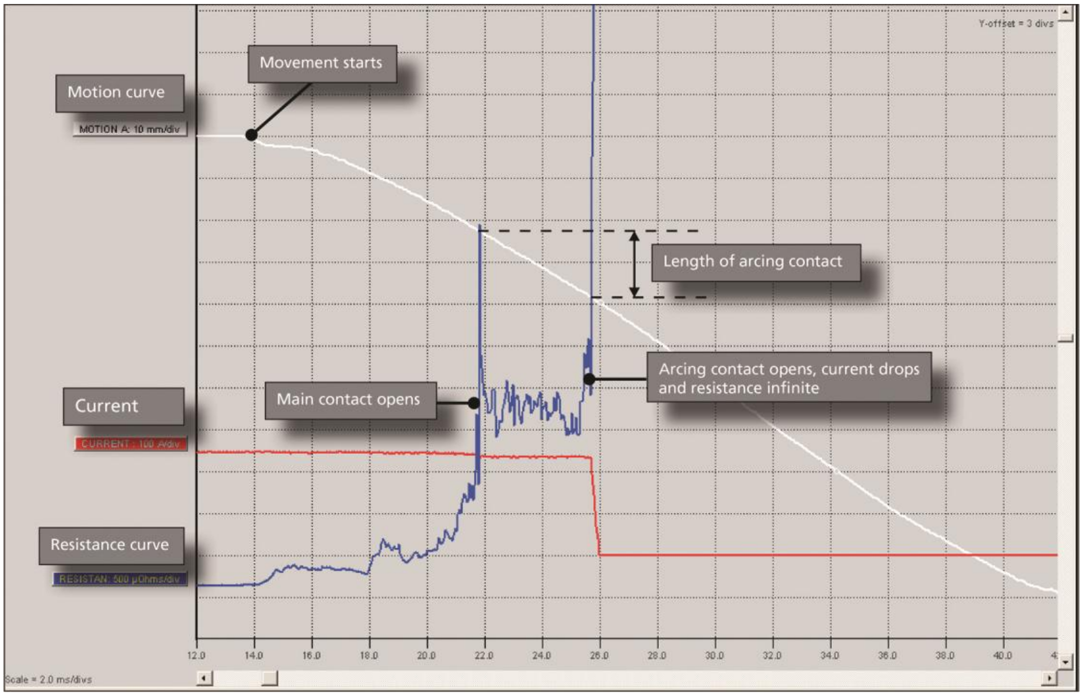

Figure 2 Time-travel curve for a circuit breaker ***(Courtesy of Megger, Inc. www.megger.com)***

Figure 3 A modern circuit breaker time-travel test set ***(Courtesy of Megger, Inc. www.megger.com)***

Figure 2 shows a time-travel curve taken for a breaker captured by the type of time-travel analyzer shown in Figure 3. The motion curve is taken by a transducer and fed into the test set. The test set plots the position of the contacts as the breaker moves from closed to open.

Once of the key pieces of information shown by the motion curve is found in its smoothness. There are no large jumps in the curve as the mechanism moves. This indicates that there is no binding anywhere in its travel.

Figure 4 shows drawing of another type of circuit breaker motion curve. In this example the breaker is first closed and then tripped. Note that at the end of the close cycle, the mechanism over-travels slightly. This is normal operation unless the over-travel exceeds a manufacturer specification or it differs significantly from the averages of previous tests.

The same phenomenon is seen in the trip motion curve. Note that there is some oscillation at the end of the trip stroke. This is also normal. Some over-travel on trip creates less stress on the operating mechanism.

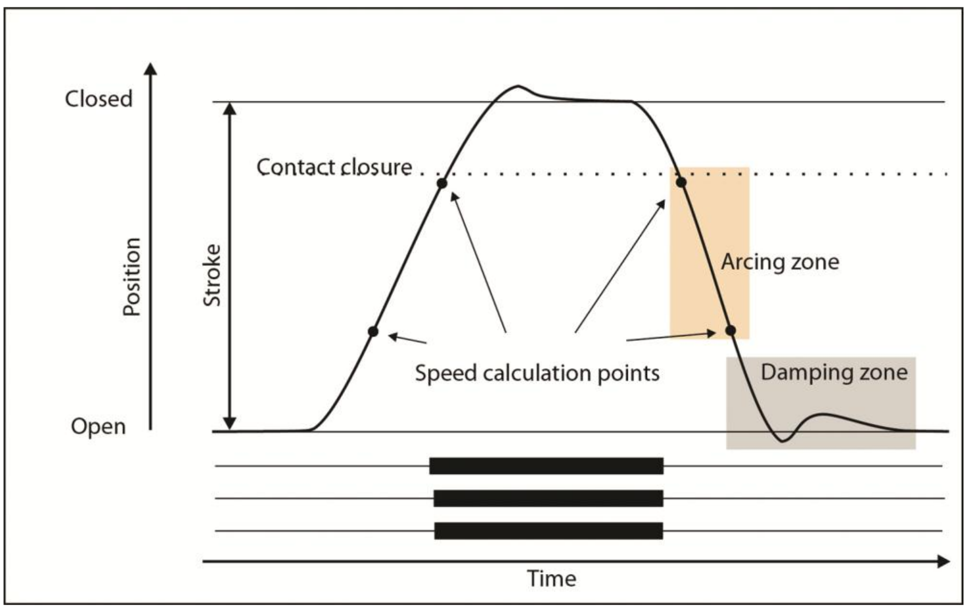

Figure 4 A close and trip motion curve (Courtesy of Megger, Inc. www.megger.com)

Travel velocity

The slope is relatively constant in the sections between the points labeled *Speed calculation points*. This means that the velocity remains constant between those points. The speed of the close or open operation can be calculated by taking the difference between the positions and dividing it by the time between those two positions.

This velocity information is compared to a manufacturer's specification and/or the average of previous tests. Any deviation could indicate some sort of problem, such as weakened springs or friction.

Travel acceleration

The slopes of the curves in Figure 2 and Figure 4 change throughout the operating cycle. Since a change of slope indicates a change in velocity, these parts of the curve represent acceleration or deceleration.

Changes in slope are expected; however, if the change occurs in a part of the curve where there should be no change, a problem is indicated.

Vibration

The final parameter, and the main one of interest for this paper, is vibration. Figure 1 shows a vibration signature taken with the CBVA. The vibration analysis creates a signature that is a comprehensive view of the condition of the entire breaker. As Figure 5 shows, it can even be used to calculate contact parting (or closing) time by observing the distance between the first to major vibration excursions.

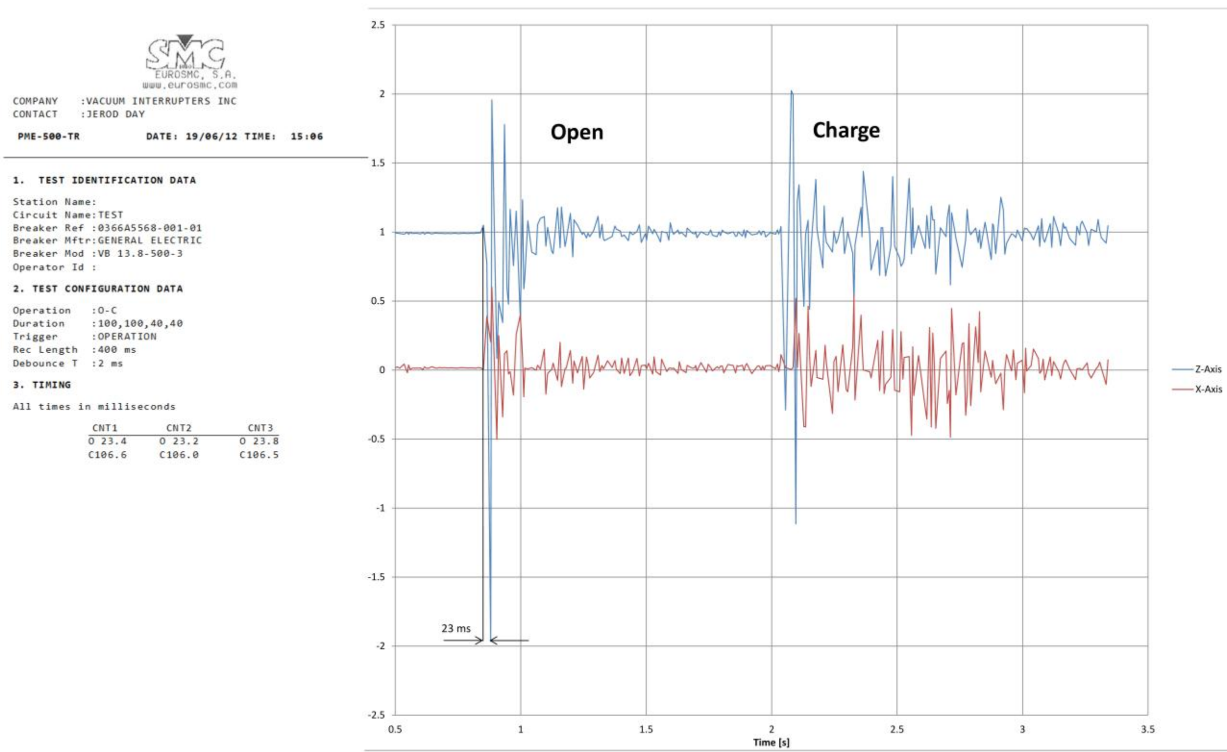

Figure 5 CBVA Tripping and Charging Signature Compared to Time-travel Data (Courtesy of Group CBS Inc.)

The accelerometer

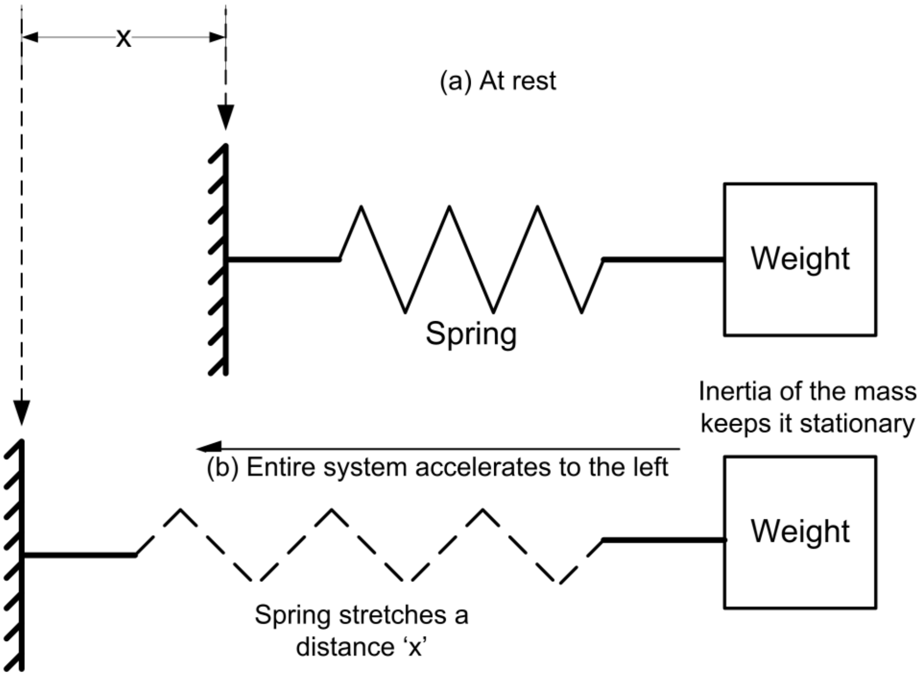

Figure 6 A Simple Accelerometer

Figure 6 shows a diagram of a simple accelerometer. When the system is stationary, as shown in 6(a), the spring is in its relaxed position. When the system accelerates to the left, 6(b), the inertia of the MASS tends to hold it in place. This means that the spring will stretch. How far it will stretch is dependent on the mass of the weight (*m*), the spring constant (*k*), and the acceleration (*a*).

To analyze this, we start with Hookes law which states:

$F = -kx$ (Eq 1)

Where:

F is the force applied to the spring

k is spring constant

x is the distance the spring stretches

Since the mass[5] and the applied acceleration are known Newton's second law can be used to determine the force.

$F = ma$ (Eq 2)

Since the two forces are equal we can write

$ma = -kx$ (Eq 2)

[5] Here we are assuming that the mass of the spring and all other components are negligible compared to the weight's mass.

Solving for *a* gives

$$a = -\frac{kx}{m} \qquad \text{(Eq 3)}$$

Since *k* and *x* are known, we can calculate the applied acceleration.

Accelerometers used in modern more sophisticated equipment are built on a silicon chip just like any integrated circuit. They do not use weights and springs; rather, they rely on sophisticated techniques that are beyond the scope of this article. Furthermore they may be sensitive to motion in 1, 2, or 3 directions. The acceleration is usually calculated using a small onboard microprocessor and printed out graphically as shown in Figures 1 and 5.

The new approach

Since the performance of vibration analysis depends on an accelerometer, the question is . . . . .

Where can I find an accelerometer?

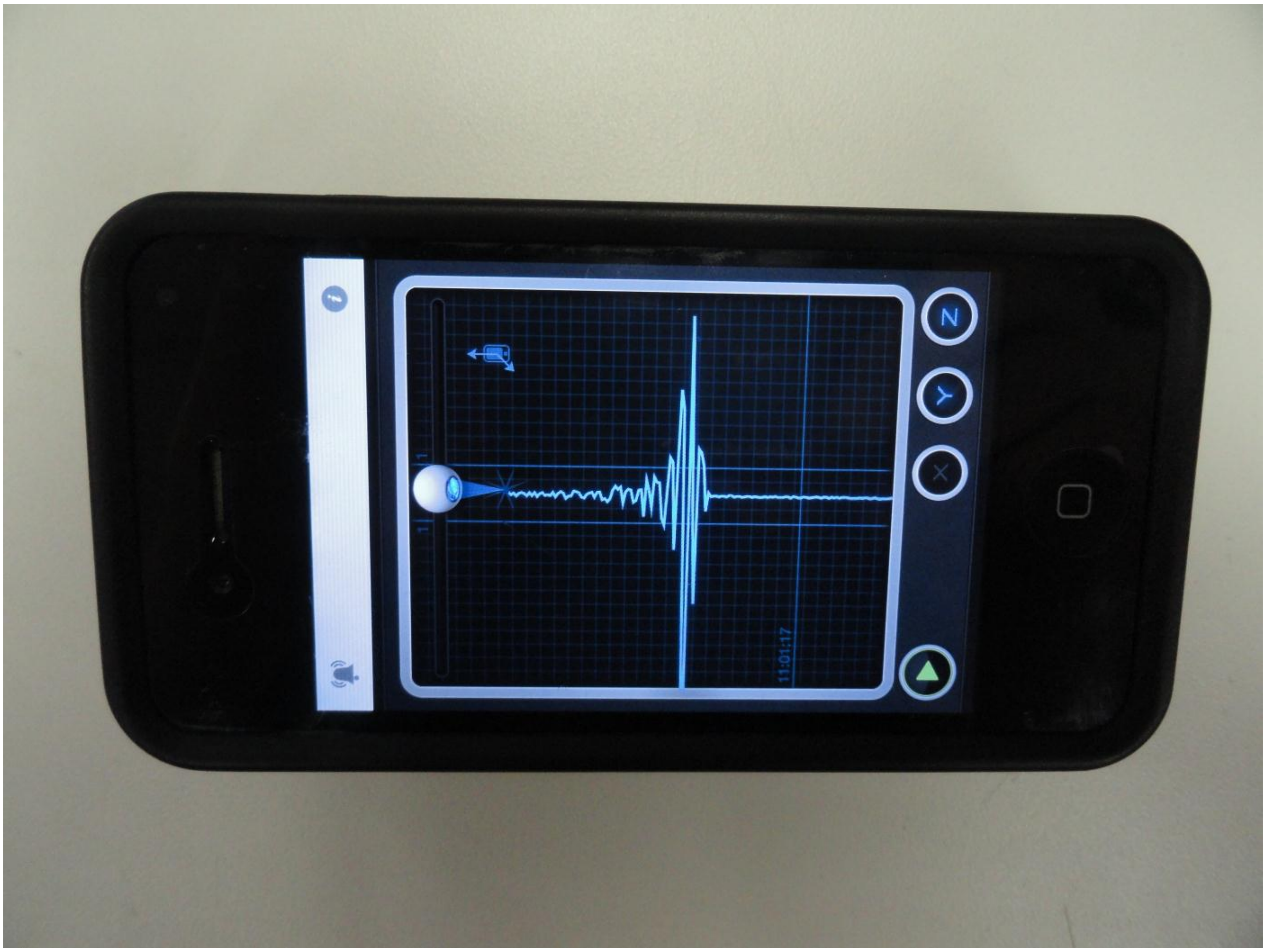

Figure 7 The *iDevice*, an Accelerometer in Your Pocket (Courtesy of Group CBS Inc.)

The device

As it turns out, millions of people throughout the world are carrying an accelerometer in their pocket (Figure 7) – the ubiquitous *iDevice*.[6] [7] Did you ever wonder how an *iDevice* knows whether you are holding it horizontally or vertically or how the service tech knows if you have dropped when you take it in for service? It has a built-in, three-axis accelerometer. Any force applied to a mass causes the mass to acceleration. The force of gravity is no exception. The internal accelerometer in an *iDevice* is acted on by the force of gravity. If the *iDevice* is held vertically, the accelerometer senses the pull of gravity and orients the screen so it is displayed in portrait mode. If the *iDevice* is held horizontally, the accelerometer and its attendant software rotate the screen to a landscape view.

Other software applications use the accelerometer for other purposes. Many game apps ask the user to shake the device as an input response.

Does software exist to use the *iDevice* as a CBVA device?

There's an *app* for that

As you might expect, the use of an *iDevice* for a circuit breaker test device has involved a substantial amount of research and development – including development of an *iDevice* app named the CB*Analyzer*. ©™[8]

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[6] Throughout this paper the term *iDevice* shall mean iPhone®, iPad®, or iPod Touch®. All three are registered trademarks of Apple, Inc.
[7] Although all three iDevices can be used, size and weight make the iPad or the iPod Touch the obvious choices.
[8] CB*Analyzer* is Copyrighted and Trade Marked by CBS ArcSafe.

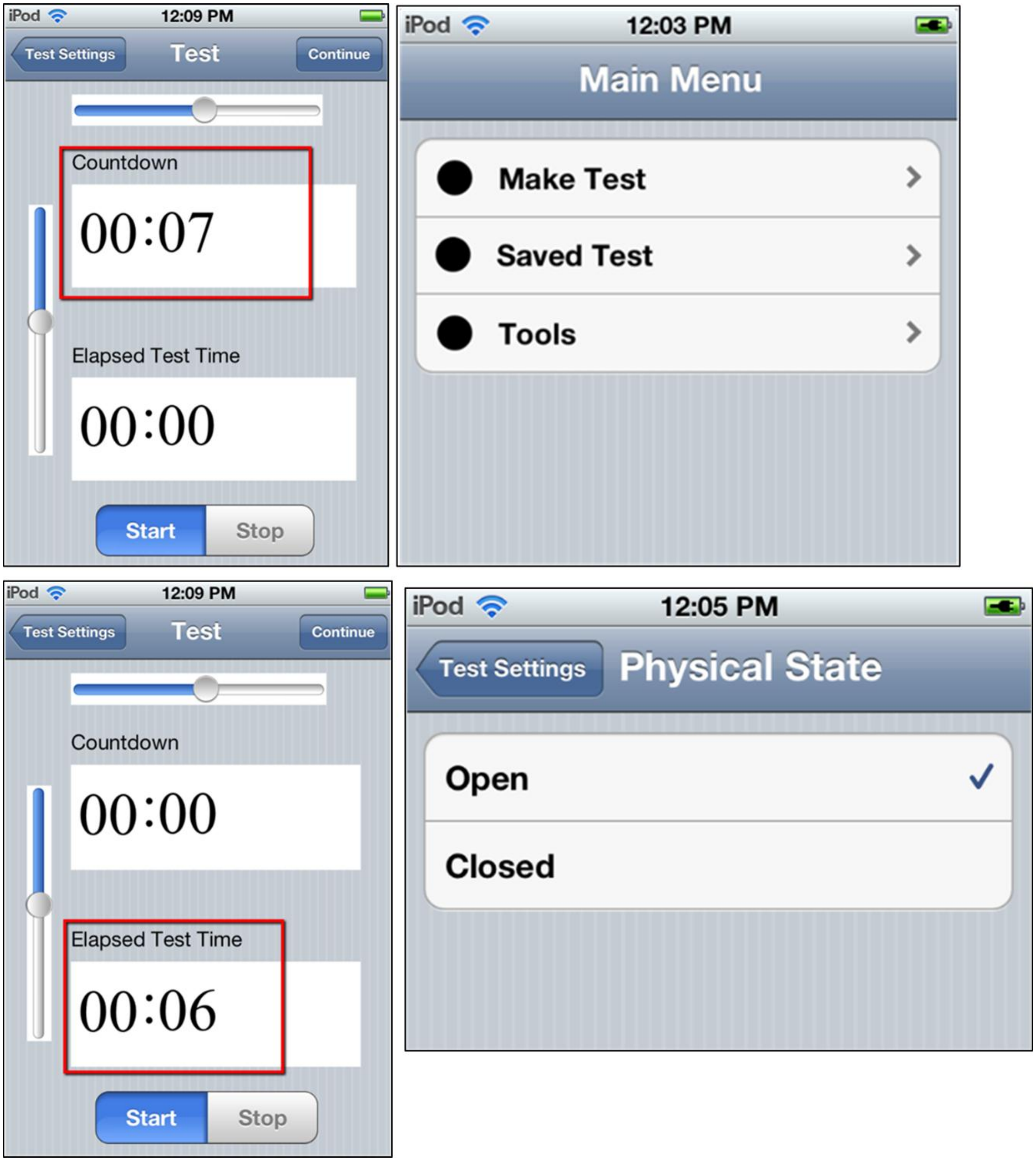

Figure 8 Screen shots of CB*Analyzer* (Courtesy of Group CBS Inc.)

Figure 8 is a montage of screen captures from CB*Analyzer*. Starting from the upper left and moving counterclockwise the shots show:

1. The screen that appears showing a countdown timer. When it reaches 0, the user initiates breaker operation.
2. The initial main menu that appears after the user has logged in.

3. A screen that allows the user to tell the app whether the breaker is closed or open before the test is initiated.
4. The screen that appears after the test cycle is completed. It shows the total elapsed time for the test.

The app is designed to take the user with little or no breaker service experience step-by-step through the entire process. Inexperienced maintenance personnel and highly experienced technicians alike will find the app very user friendly.

Application of the test device

The *iDevice* is attached to the circuit breaker magnetically using a special case designed for the purpose. Figure 9 shows the *iDevice* in position. The screen shows a test result of a trip operation. The screen scrolls from right to left during the test data acquisition process.

Figure 9 The *iDevice* attached to a DS-206 circuit breaker (Courtesy of Group CBS Inc.)

The location and orientation of the *iDevice* is important. First, since the circuit breaker is a complex assembly, the vibration signature will be different depending on where the *iDevice* is placed. Therefore it must be located in approximately the same location for the initial and all subsequent tests. The app asks the user to identify the breaker type that is being tested. It then allows the user to bring up a photograph showing the recommended location of *iDevice* placement.

Second, the *iDevice* must be level and oriented in the same manner every time. Research has shown that attaching it horizontally provides excellent results. It must also be attached in such a way that the navigation button of the *iDevice* is placed to the right for all tests. This keeps the x, y, and z axes in the same orientation for each test.

Note the horizontal and vertical slider bars in the upper left and lower right photos of Figure 9. These are not slider controls; rather, they are level indicators for the *iDevice* is. In placing the *iDevice* the tester will level it so that both indicators are in the center. When it is properly positioned, the Start button will turn dark blue to indicate that the test may proceed.

Capturing the VA signature

Actually performing the test is quite straightforward.

1. Position and orient the phone as previously described.
2. When the Start button turns blue, press it and a countdown from 10 begins
3. When the countdown reaches 0, the tester may initiate whatever test is being performed (trip, charge, close or any combination)
4. The *iDevice* senses the start of the test and begins recording the vibration signature.
5. After the test is finished, the tester presses the Stop button. The data is saved and sent to a database which analyzes the results. Note that if the tester is distracted and forgets to stop the test, the app will stop taking data after a short time period.

The signature data

Figure 1 and Figure 5 show the basic structure of two types of tests. The data itself is captured digitally by the app. Figure 10 shows a partial data list. The left column shows the time of the data capture after the event started. The next three columns list the acceleration of x, y, and z axes respectively. Note that the acceleration data is given in terms of *g* – the acceleration due to gravity.

Time (seconds)	X-axis (g)	Y-axis (g)	Z-axis (g)
0	0	0.026397516	0.948419301
0.0025	-0.001683502	0.031055901	0.951747088
0.005	0	0.034161491	0.951747088
0.0075	-0.001683502	0.035714286	0.953410982
0.01	0.001683502	0.034161491	0.948419301
0.0125	0.006734007	0.027950311	0.953410982
0.015	0.005050505	0.026397516	0.953410982
0.0175	0.008417508	0.02484472	0.955074875
0.020619	-0.001683502	0.031055901	0.951747088
0.023119	-0.003367003	0.035714286	0.953410982
0.025619	-0.005050505	0.029503106	0.946755408
0.028119	0	0.029503106	0.950083195
0.030619	-0.001683502	0.029503106	0.950083195
0.033119	0.001683502	0.034161491	0.950083195
0.035619	0.008417508	0.034161491	0.943427621
0.038119	0.005050505	0.034161491	0.946755408
0.040619	-0.01010101	0.037267081	0.948419301
0.043119	-0.013468013	0.035714286	0.951747088
0.045619	-0.005050505	0.026397516	0.951747088
0.048119	-0.003367003	0.02173913	0.953410982
0.050619	-0.001683502	0.029503106	0.958402662
0.053119	0	0.029503106	0.956738769
0.055619	-0.003367003	0.027950311	0.955074875
0.058119	-0.01010101	0.02484472	0.951747088
0.060619	-0.005050505	0.023291925	0.950083195

Figure 10 Partial data capture list (Courtesy of Group CBS Inc.)

After the data table is stored in the test device it is sent as a CSV file to an online website which receives it, interprets it, and graphs it using Microsoft EXCEL.®[9] If there is no internet service, the data will be cached and sent to the CBVA website when the iDevice comes in contact with a suitable network.

Analyzing the signature

Visual inspection

An experienced analyst can capture some information by simple inspection and comparison of current vibration signature graph versus a KGP. Such an inspection can identify obvious problems such as those

[9] EXCEL is a registered trademark of Microsoft

caused by a major mechanical problem. However research shows that a more sophisticated method will provide a wealth of information.

The visual inspection can be made by using the additional data or the trace showing an envelope (Figure 11).

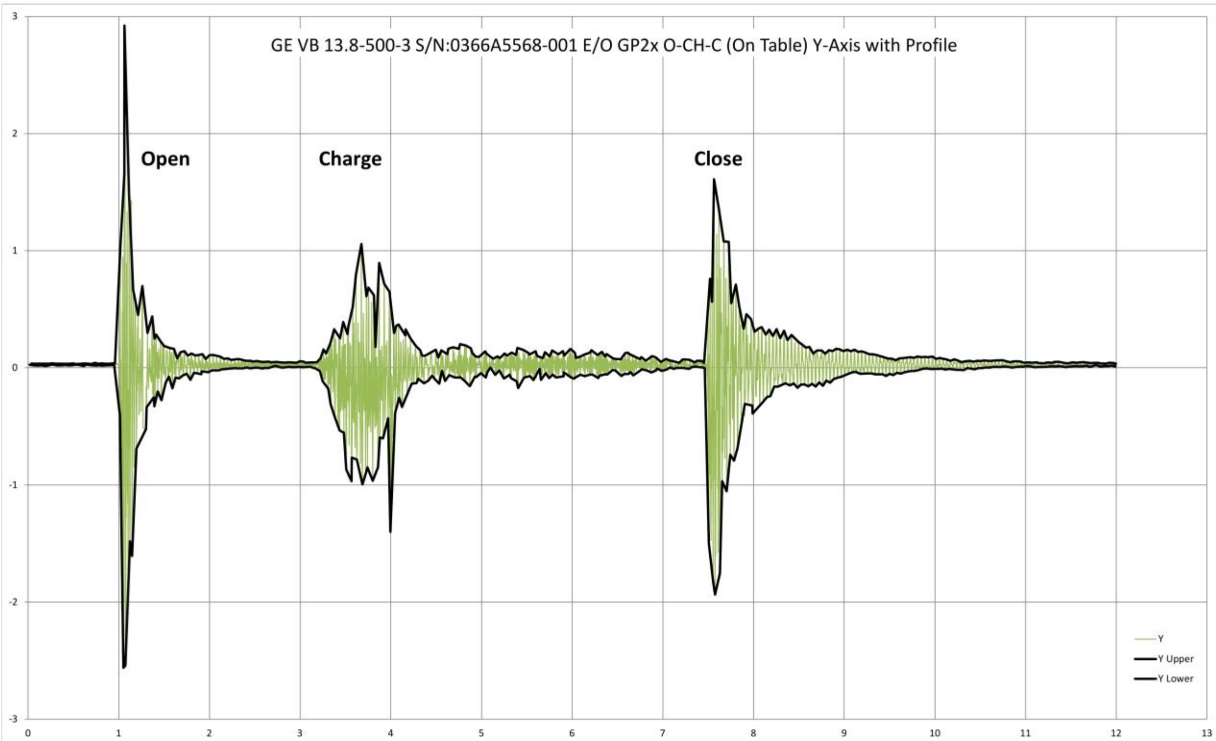

Figure 11 A vibration signature showing the calculated envelope Group CBS Inc.)

During the breaker operation, data can be sampled by the *iDevice* or iPod or other data acquisition devices used at rates from 100 Hz to 400 Hz depending on which version of the device is being used. Even the lowest rate is suitable for the purposes of CBVA.

To create the envelope curve, the peaks of the signature curve are captured and connected by a straight line.

Pattern recognition

Pattern recognition software (PRS) is employed feeding the raw data file to the CB*Analyzer*. The PRS captures the peaks and valleys of the data and compares it to a KGP. The PRS will identify differences from the KGP to such fine detail, that a problem can even be traced back to a worn or missing tooth in a gear, bad or failing lubrication, or even misalignment of mechanism parts.

CBMA

The PRS discussed above works excellently for many existing problems. Research is currently underway to use very powerful CBMAs to provide predictive information. While this particular research is in its infancy, the algorithms being used are proven in other applications, and it is expected that very good predictions will be possible.

Summary and Conclusion

Research has been underway on this new method for several years. Recent breakthroughs have allowed the project to progress into the development stage. At the time of this writing (late September, 2012) the beta release of the app is deployed. Several test sites are starting to use the app, with preliminary results being excellent.

The existing circuit breaker tests such a time-travel analysis yield excellent data. The cost and ease of implementation of this new approach to vibration analysis makes it very attractive to add to the arsenal of test tools. The CBVA approach using the *iDevice* offers the following:

1. Simplicity in application
2. Easily implemented during routine switching operations – easy spot checks
3. Provides quantitative data that can be analyzed, thus pinpointing problems
4. Although no pricing structure has even been investigated at the time of the writing, the cost of the test set itself (an *iDevice* or iPod Touch) is extremely low by the standards of other test equipment.
5. Easy “first trip” data collection
6. Since this is a non-invasive test, the chance of accidental damage to the breaker during maintenance is reduced
7. Web-based analysis tools allow almost instant condition report
8. Test result can also be used to time the open and close of the breaker contacts
9. Data stored for easy retrieval and future comparison against subsequent tests
10. Added safety since the test can be accomplished with the tester(s) located a safe distance away using remote switching devices
11. Easily established baseline data when breaker is first commissioned
12. Allows you to scan your breakers quickly and then focus reconditioning or heavy maintenance on only the breakers asking for help.
13. It is expected to be welcomed by insurance providers because of the ease of implementation and the quality of the results
14. Results can be qualitatively analyzed by visual inspection of the signature graphs or quantitatively analyzed using pattern recognition software and/or Condition Based Maintenance algorithms.

By the time that this paper appears in print (expected to be in February of 2013) a great deal of empirical data will have been gathered in the field. The authors believe that this new method will be of great value to the testing industry.

The conclusion – a simple new device for efficiently determining circuit breaker condition using CBVA has been developed to allow maintenance personnel the ability to focus attention on the breakers that need it the most.   The advantages for incorporating this new instrument into existing maintenance testing programs promises to be of great benefit.

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[i] Dennis Neitzel and Dan Neeson, *Preventive Maintenance and Reliabilityof Low-Voltage Overcurrent Protective Devices*, Pulp and Paper Industry Technical Conference, 2007, Conference Record, PP 164-169