



Comparative Characterization of Parallel Distribution Sensors Under Field Conditions

Final Project Report

Power Systems Engineering Research Center

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Final Project Report

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Executive Summary

Electric utilities have an increasing number of technology options to enhance the performance and reliability of distribution systems. Electrical current and voltage measurements are foundational to many of these technologies. The type and quality of measurements vary by application. Conservation voltage reduction, for example, requires accurate feeder voltage magnitudes. Power-quality instruments require accurate spectral content of feeder voltages. Applications such as Distribution Fault Anticipation technology require accurate, high-fidelity, steady-state and transient current and voltage signals with substantial bandwidth and dynamic range.

Conventional current and potential transformers (CTs and PTs) are the de facto standards for sensing feeder currents and voltages. Although these conventional instrument transformers have their limitations, use has proven them to be suitable for a wide variety of purposes, including those outlined in the preceding paragraph. However, acquisition and installation costs for conventional CTs and PTs may constitute a limiting factor in the widespread application of technologies.

The accuracy of any measurement or control system is limited by fidelity of the measurement system and by the transfer characteristics of the sensors used to provide inputs to that system. Even a hypothetical monitoring device with perfect fidelity would produce inaccurate results if the signals at its input terminals were inaccurate. This seems obvious when stated, but it would be easy for a utility engineer to simply assume that sensors accurately represent reality, without questioning the validity of that assumption.

Under this PSERC project, researchers consulted with advisor utilities to determine commonly used varieties of alternative sensors. After reaching consensus on sensor selection, researchers installed a three-phase set of each selected model alongside a three-phase set of conventional CTs and PTs on an in-service, 12.47-kV distribution feeder. Over an extended period of time, the outputs of these devices were monitored with high-fidelity data-recording devices. These devices recorded multiple steady-state and transient electrical signals, including several overcurrent faults.

Waveforms recorded simultaneously from the multiple sensors were analyzed in the time and frequency domains. Analysis focused on relative characterization of the sensors, using the conventional CT and PT signals as the benchmark. In general, voltage waveforms from the alternative sensors were similar to those of PTs, but current waveforms from the alternative sensors differed substantially from their CT benchmark.

The generalized conclusion from this project is that utilities should not assume that any particular sensor has performance adequate for any particular function, without first carefully studying the requirements of the function and the performance of the sensors under consideration. In some cases, a sensor's published specifications may be inadequate for making an informed decision. In such cases, the utility would be well served to commission or otherwise obtain the results of tests that truly represent the types of signals to be encountered in the application for which they desire to use the sensor.

The electric utility industry continues to have need for economical current and voltage sensors with transfer characteristics suitable for power-quality measurements, fault-anticipation requirements, and other advanced applications, to enable improvements in service quality and reliability. Various manufacturers are known to be working on new types of sensors, some based on optical principles. As those sensing technologies mature, there will be a need for future work to quantify and validate their true performance in the field, and also to evaluate their survivability, longevity, and life-cycle costs. Specifically, statistically valid evaluation of the characteristics of new sensors, measured against conventional CTs/PTs and against laboratory standards, is a logical next step.

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1. Introduction

Today's utility has at its disposal monitoring and control technologies unimaginable a decade ago. On a distribution system, multiple technologies are available to monitor, analyze, and perhaps act upon measurements of feeder currents and voltages. For example, a power-quality (PQ) meter measures and reports on voltage characteristics and anomalies, and an overcurrent relay measures currents and acts to trip a breaker when a fault causes abnormally high current for a sufficient period of time. Conservation voltage reduction, which currently holds substantial industry interest, intentionally sets line voltages closer to the lower end of allowable limits, which implies the need to monitor RMS voltages for sustained excursions below allowable bounds. Distribution Fault Anticipation (DFA) technology, developed at Texas A&M University, measures feeder currents and voltages to detect electrical signatures that indicate line apparatus is nearing the point of failure, thereby enabling utility personnel to take proactive steps to fix problems and avoid or mitigate component failure and outages. Multiple utilities also are aggressively evaluating methods for distribution fault location, each based on measurements of currents and/or voltages during faults. Each of these technologies holds promise for improving system reliability and efficiency, particularly if its application is not limited to the substation.

For a monitoring device or system to perform its function properly, it is fundamental that it must obtain accurate representations of the electrical quantities of interest. The quality of electrical data is affected by two primary factors: 1) characteristics of sensors that connect to the power line to convert high-energy power-line currents or voltages into low-energy signals suitable for input into electronic systems and 2) characteristics of the device (e.g., meter) used to make measurements.

The standard sensing interface between the power system and control and monitoring devices has long been and continues to be provided by conventional current and potential transformers (CTs and PTs). CTs and PTs transform primary line currents and voltages to more manageable levels, typically $5A_{RMS}$ and $120V_{RMS}$. Such current and voltage levels historically provided suitable inputs for electromechanical devices, such as traditional protection relays and meters, where the signals themselves are required to provide the energy necessary to move electromagnetic components mechanically. Because of the ubiquitous placement of CTs and PTs in substations, they have remained the natural selection for sensing, even as relaying and metering have evolved into the digital age and other digital technologies have developed.

Given this background, conventional CTs and PTs represent the de facto standard for sensing. However, the cost of acquiring and installing conventional CTs and PTs is sometimes seen as a barrier to widespread deployment of new technologies. Therefore, utilities are exploring the use of multiple types of sensors based on alternative technologies that offer lower installation costs, and that have been shown to be effective for specific, targeted applications.

It is the authors' experience that utility practitioners tend to be well versed in the specifications for electronic data-acquisition devices. They are familiar with sample rates, dynamic range and resolution issues, quantization levels (i.e., number of bits) for analog-to-digital converters, etc, which are routinely provided by specification sheets from manufacturers of these devices. By contrast, less is often known about the specifications of the sensors that provide the input to the data-acquisition devices. This is particularly true for non-traditional types of sensors.

The sensitivity, linearity, frequency response, transient response, and other characteristics of alternative sensors generally are unknown, but important to predicting the suitability of these sensors for particular functions. As an illustration, Figure 1 shows distribution line current, as measured during the early stages of an incipient failure on that feeder. The current was measured from substation CTs and includes both normal feeder load current and the incipient fault current. The waveform shows significant harmonic content, but that in itself is not an indication of a developing problem. The incipient fault current adds to the load current an extra "pulse" of current that draws 22 peak amperes for a few milliseconds. This appears as a slight increase in the negative peak of the third cycle, which is circled in the figure. The remainder of the time period shows load current alone, which in this case happens to have heavy harmonic content. Proper characterization of the event requires signals that faithfully reproduce both the steady-state load current and the transient pulse of incipient fault current. The signals must properly represent both the magnitude of the pulse and its shape and phase relationship with other components, even in the presence of load current that may be significantly larger than the incipient fault current and that itself may have significant harmonic content.

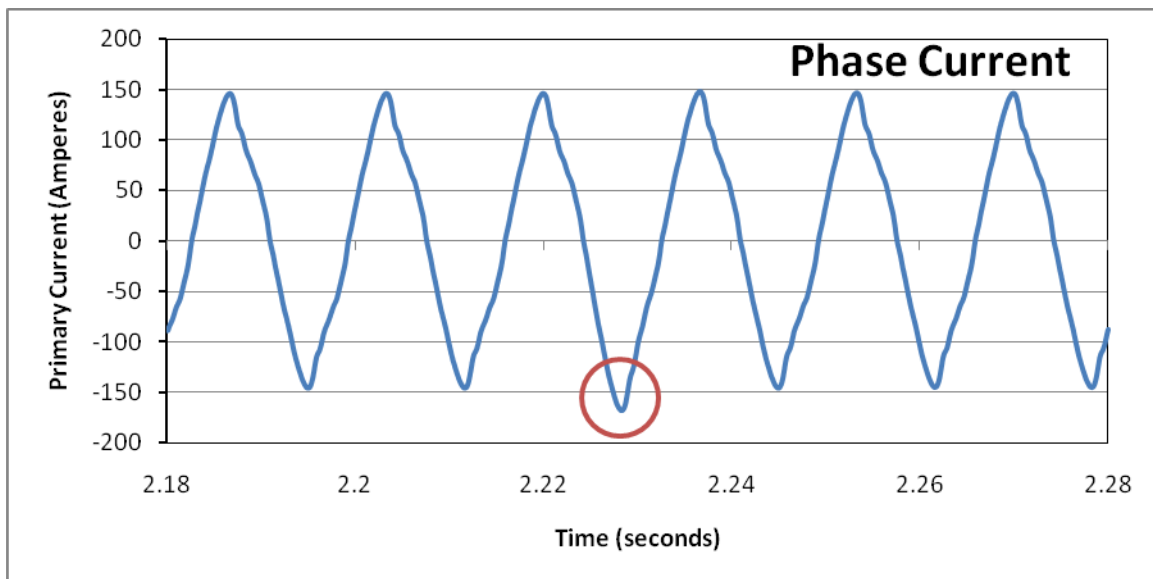


Figure 1: Recorded current waveform during subtle incipient failure condition

Some utilities have made assumptions about the suitability of particular sensors for particular applications and have begun deployment of lower-cost alternative sensors in advanced applications on their systems. However, some are encountering unexpected and

undesired results. Without accurate knowledge of the response of alternative sensors under both steady-state and transient conditions, unexpected results are impossible to understand or rectify. It is difficult or impossible to determine whether performance is because of flaws in the logic of the application in question, or alternatively because of fundamental limitations of the sensing characteristics of the sensors utilized.

When evaluating whether or how to deploy new technologies, utility practitioners face a difficult choice: 1) use conventional sensors, with known performance characteristics but relatively high installed cost, 2) assume that a given alternative sensor's performance is acceptable for the application at hand, or 3) abandon the effort. Therefore, the current project seeks to fill gaps in knowledge and understanding of the performance of alternative sensors. The outcome of this project is not intended to replicate testing and characterization of sensors according to traditional commercial standards, such as absolute accuracy or temperature dependency, because standard testing laboratories are adept at doing this and these characteristics are better known. Rather, the outcome of this project is the comparative characterization of the response of various sensors, particularly to harmonics, transients, and low-level variations, using conventional CTs and PTs as the basis for comparison.

2. Experimental Method

2.1 Sensor Selection and Acquisition

Researchers conducted multiple webcasts, teleconferences, individual emails and telephone contacts with industry participants. The purpose was to select candidate sensors for side-by-side evaluation with conventional CTs and PTs. Initially, each utility participant was asked to determine which types of sensors were being considered or used at that participant's utilities. The participant was asked to compile known information about the potential candidate sensors and present to the rest of the utility participants reasons that that sensor should be evaluated.

Because a significant number of utility companies were represented, it was assumed a significant number of different candidate sensors would be proposed to the group for consideration. However, it turned out that the utilities that submitted candidates for consideration were using or considering the same types of sensors. Therefore, it was relatively straightforward to select two types of current-and-voltage sensors for evaluation.

A third type of sensor was later added to the installation and evaluation. That sensor represents a relatively new technology, based on optical sensing of currents and voltages. Because the third type of sensor was of new design, its manufacturer was still in the process of debugging certain technical issues related to its electronics. As a result, insufficient data was obtained for inclusion in this report.

Southern Company loaned the project a three-phase set of each of the original two sensor candidates and later loaned the project a three-phase set of the optical sensors.

2.2 Monitoring Equipment

Researchers used a multi-channel recording device to monitor, trigger, and record waveforms. This device is based on the device researchers at Texas A&M routinely use in their Distribution Fault Anticipation (DFA) work. This device provided multiple advantages for this project, as compared to other commercially available devices:

- Synchronized sampling across multiple feeders
- Substantial storage capacity
- Wide dynamic range and small-signal resolution
- Fully automated data retrieval, archiving, etc.
- Front-end to accept standard, three-phase $5A_{RMS}$ current inputs and $120V_{RMS}$ PT inputs, plus ability to use modified front-end for low-energy inputs from alternative sensors
- Ability to withstand and measure wide range of currents, ranging from subtle signals on the order of one milliamp (CT secondary) to fault currents that produce up to 100 amps on the CT secondary leads (for one second).

- Wide range of configurable triggers for initiating waveform recording
- Internet connectivity to configure all settable parameters and to view real-time waveforms
- Familiarity of Texas A&M research personnel with device and associated software tools

As noted above, the standard DFA-based device accepts and records currents of $5A_{RMS}$ continuously and $100A_{RMS}$ for one second. The alternative sensors that were selected produce low-energy outputs. The voltage sensors provided low-energy voltage outputs that were scaled versions of line voltages, with a scaling factor of 10,000:1 (e.g., for the 7,200-volt line, the sensor output was a proportional waveform of nominally $0.72 V_{RMS}$). Current sensors also provided low-energy outputs that were scaled versions of the line current waveforms. The current conversion ratios of the two types of sensors were 60:1 and 100:1. This means that one type of alternative sensor produced a waveform with a one-volt magnitude for 60 amps of primary current, and the other produced a waveform with a one-voltage magnitude for 100 amps of primary current. The recording device provides for transformation ratios to be input into the device's configuration, so that waveforms are recorded and displayed in primary line volts and amps.

The low-energy modification resulted in an effective full-scale operating range on voltage channels of $0-2V_{RMS}$ and current channels of $0-135V_{RMS}$. With the selected sensors, this resulted in a range of $20,000 V_{RMS}$ for voltage channels on both sensors. The maximum current measurable was $8,100 A_{RMS}$ for the 60:1 sensor and $13,500A_{RMS}$ for the 100:1 sensor.

2.3 Substation Installation

Substation installation was graciously provided by Bryan Texas Utilities. Both types of alternative sensors were installed electrically in parallel with traditional CTs and PTs on a 7.2kV multi-grounded-wye, overhead primary feeder that serves several megawatts of a variety of load types, including residential, light commercial, and oil-field load. The selected feeder serves a rural area and has numerous miles of line exposure. The calculated maximum available fault current on the feeder is $4,617A_{RMS}$. Sensors were installed by utility personnel according to manufacturer instructions. They were then wired to data-collection devices as described on manufacturer datasheets. Sensor manufacturers were consulted where questions arose about proper installation techniques and wiring connections. After initial observations of waveforms indicated substantial difference between one sensor's outputs and those from conventional CTs, researchers consulted further with the manufacturer, to verify correct wiring. It became clear that it was important to establish proper grounding between sensor leads and the recorder inputs. Researchers also validated performance of the recording devices by comparing waveforms from those devices with those obtained from oscilloscopes.

3. Results

Researchers installed alternative sensors alongside traditional CTs and PTs for a period of six months. During this time, the data-collection devices recorded simultaneous waveforms from the parallel sensors at approximately 1,500 distinct times. The majority of these waveform recordings contain normal system transients like motors starting and capacitor switching operations. A few of the recordings contain power system faults. Some representative recordings, along with a few events of particular interest are discussed below.

The reader will note that this report refers to the alternative sensors as Alternative Sensor 1 and Alternative Sensor 2, without identifying specific manufacturers or specific models of sensors. This was a conscious decision made by the authors, and agreed to by PSERC leadership. This project did not have sufficient scope to obtain and test a statistically meaningful number of any particular model of sensor. As will be evident in the presentation and analysis of data, certain characteristics of the selected sensors would be inadequate for some applications. The authors draw generalized conclusions that apply widely, not just to the sensors selected for evaluation in this project.

3.1 Visual Waveform Analysis

3.1.1 Steady State

The most basic analysis that can be performed on a set of waveforms is a simple visual inspection of steady-state recordings. Figure 2 shows simultaneous current waveforms from all three sets of sensors. Even without detailed analysis, it is clear from visual inspection that the signal recorded by the Traditional CT contains appreciable harmonic content, although not an amount unusual for a typical distribution feeder. Visual inspection of waveforms from Alternative Sensor 1 shows that harmonic content is reduced in comparison to the Traditional CT output. Conversely, the output of Alternative Sensor 2 appears to amplify harmonic content.

Visual inspection of steady-state voltage waveforms suggests greater consistency between both alternative sensors and the Traditional PT. Figure 3 shows simultaneous cycles from all three sensors. Each alternative sensor voltage waveform closely resembles the PT output. Because feeder voltage waveforms contain significantly lower harmonic content than corresponding current waveforms, it is more difficult to make visual comparisons in the time domain regarding similarities and differences between the sensors. Numerical analysis of the frequency content of steady-state voltages will be presented in a later section.

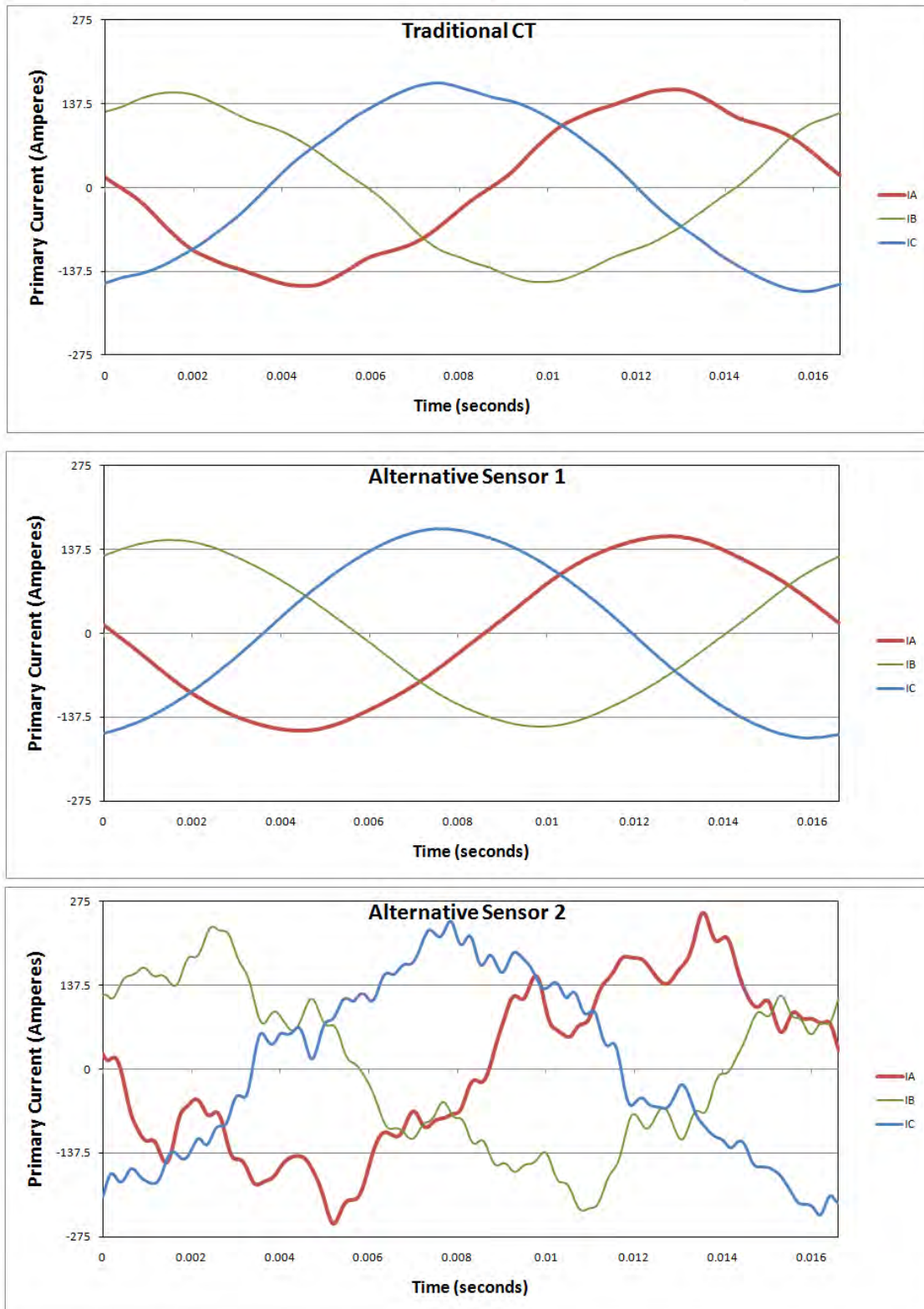


Figure 2: Steady-state phase currents

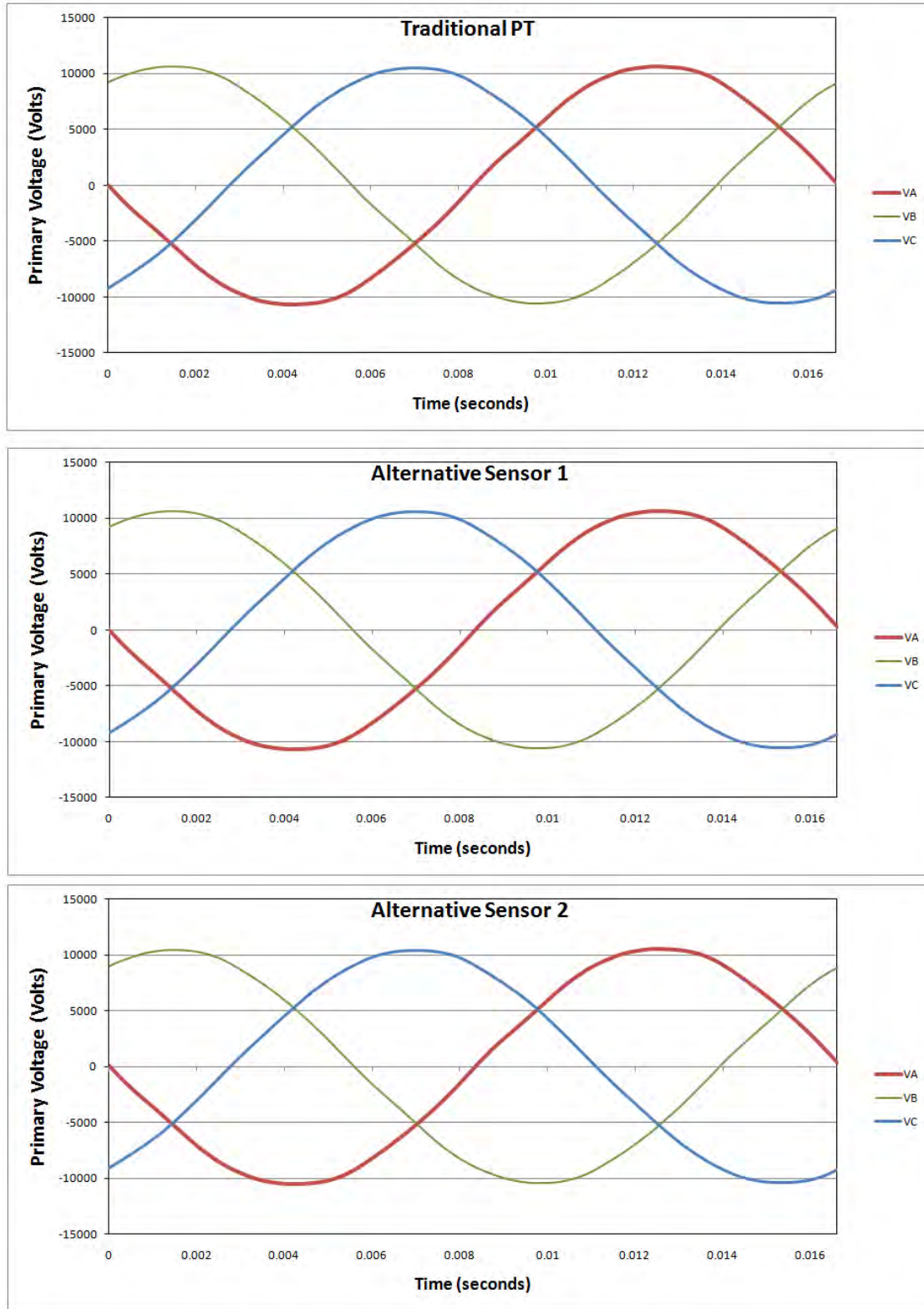


Figure 3: Steady-state phase voltages

3.1.2 Overcurrent faults

3.1.2.1 Fault 1

3.1.2.1.1. Currents

Overcurrent faults are transient events of particular interest to utilities. In particular, many applications attempt to estimate fault location or distance based on current and voltage waveforms. Overcurrent faults present problems for sensors and measurement devices, because they produce currents and voltages well outside “normal” operating range.

Figure 4 shows simultaneous current waveforms from all three sets of sensors, during an overcurrent fault. Visual inspection of these waveforms shows patterns in keeping with observations from steady-state data. In particular, Alternative Sensor 1 tends to minimize harmonic content, as compared to the Traditional CT, while Alternative Sensor 2 tends to amplify harmonic content. Both alternative sensors indicate higher-than-normal current waveforms, which might enable basic fault-detection algorithms to detect a fault, but differences in the characteristics of the waveforms may affect the ability of fault-location algorithms to perform their function. The effect on any particular algorithm is unpredictable, without knowing specifics of that algorithm’s implementation.

Differences between the waveforms are most apparent when they are presented in an overlaid fashion, as in Figure 5. Alternative Sensor 1’s waveform matches the general shape of the waveform from the Traditional CT to a certain extent, but its low-pass filtering effect results in the first half-cycle of current having substantially lower magnitude than the waveform from the Traditional CT (i.e., negative peak of approximately 750 amperes from Alternative Sensor 1 versus negative peak of approximately 1,300 amperes from Traditional CT). Alternative Sensor 1 also appears to add a final positive half-cycle peak of approximately 750 amperes that is not present in the waveform from the Traditional CT.

The fault-current waveform from Alternative Sensor 2 differs substantially from the corresponding waveform from the Traditional CT. Alternative Sensor 2’s waveform contains substantially more high-frequency content than that of the Traditional CT. This is consistent with that sensor’s tendency to amplify higher-frequency components, as previously noted in the visual analysis of steady-state output. During the first 1-1/2 cycles of the fault, the Traditional CT waveform exhibits the non-linearity typical of faults with an arcing component, and the waveform of Alternative Sensor 2 amplifies that non-linearity. The final cycle of the fault is more sinusoidal, and the waveform from Alternative Sensor 2 contains less distortion. These observations are consistent with those from the earlier, steady-state waveforms.

Each alternative sensor obviously responds differently to the fault current than does the Traditional CT. Each alternative sensor also responds quite differently than the other alternative sensor. This brings into question how devices and algorithms (i.e., calculation of fault current or fault impedance for location purposes) might respond differently to the different waveforms. There is no generic answer to this question, because the response is

device-specific and dependent on how those devices condition, digitize, and process those waveforms. However, in the way of an illustrative example, the three waveforms from this fault were processed by algorithms that Texas A&M routinely uses to estimate fault-current characteristics. When supplied waveforms from the Traditional CTs and PTs, the algorithm estimated an 893-amp, 2.5-cycle fault. By contrast, the same algorithms estimated an 885-amp, 2-cycle fault when applied to the waveforms from Alternative Sensor 1 and a 1029-amp, 3-cycle fault when applied to the waveforms from Alternative Sensor 2. This represents a difference of just one percent (negative) for Alternative Sensor 1, but a difference of 15 percent (positive) for Alternative Sensor 2. As noted, these numbers are not meant to be generic in any way, but rather to provide one specific example of the effect of waveform fidelity on an application's output.

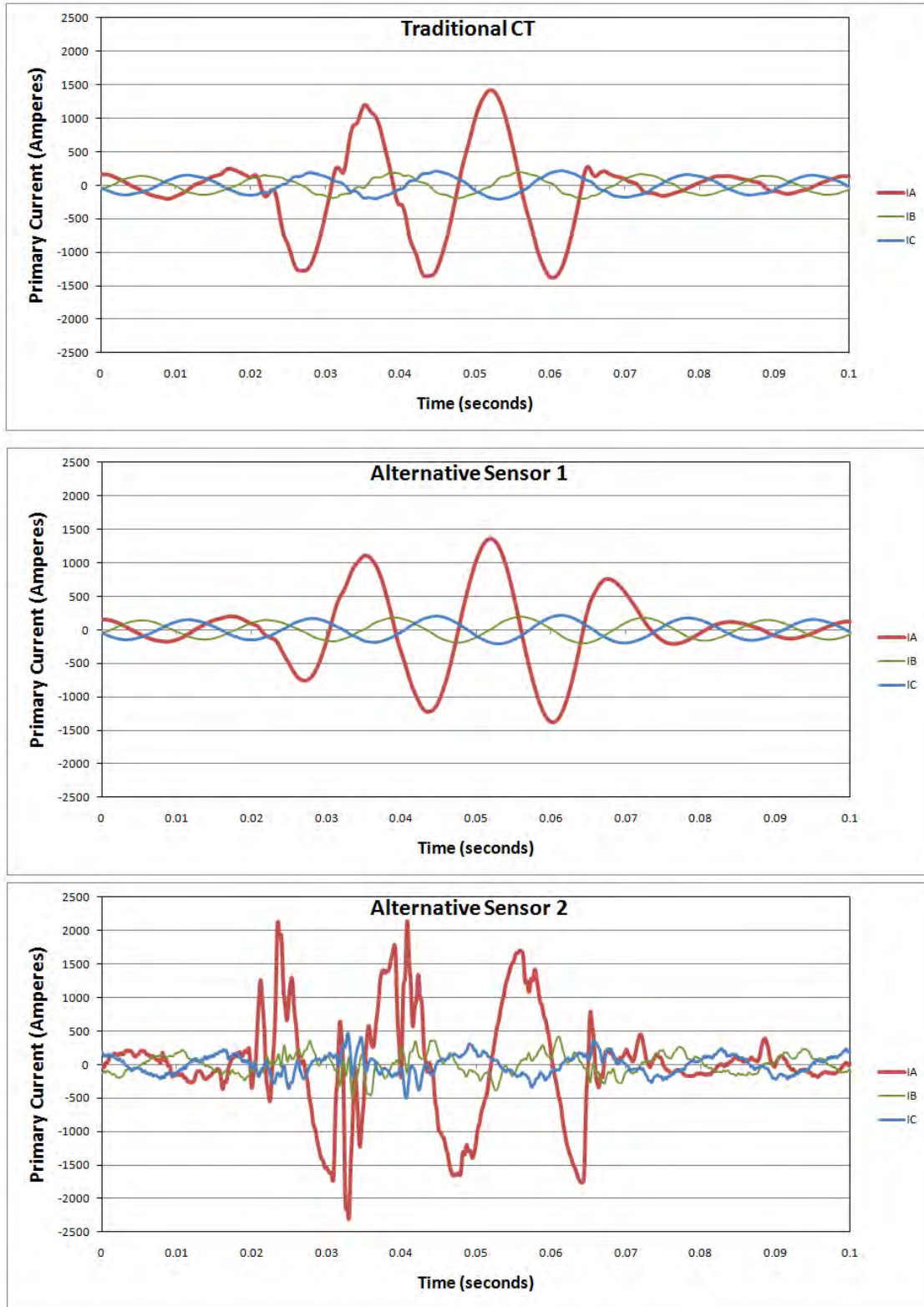


Figure 4: Current waveforms, overcurrent fault 1

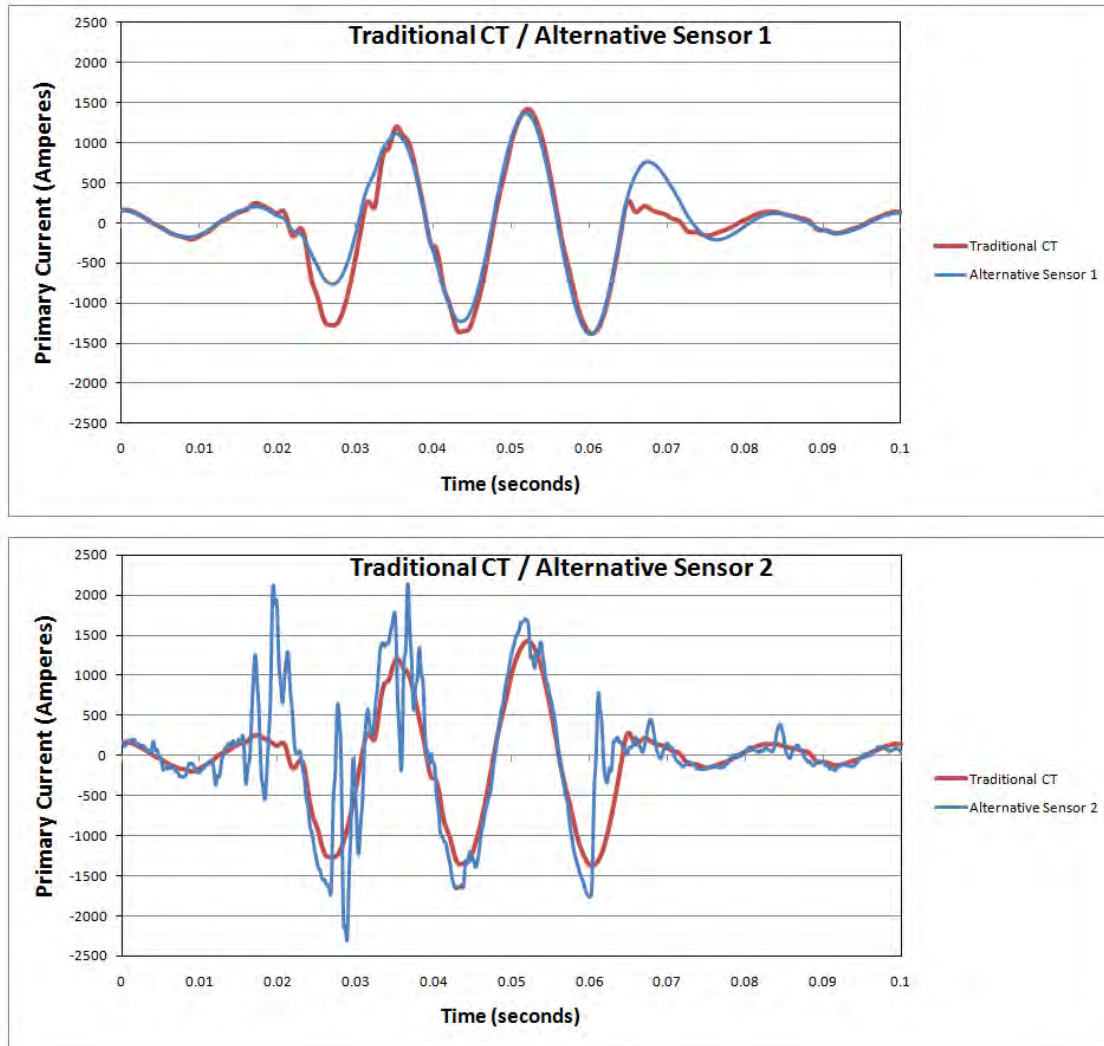


Figure 5: Overlaid current waveforms, overcurrent fault 1

3.1.2.1.2. Voltages

Figure 6 shows voltage waveforms recorded during overcurrent fault 1. From visual inspection, both alternative voltage sensors appear to perform significantly better than their current-sensing counterparts, although close inspection shows that Alternative Sensor 1 appears to attenuate higher frequencies somewhat more than the Traditional PT.

Figure 7 overlays the alternative sensors' voltages with those from the Traditional PTs. In these figures, slight harmonic suppression of the alternative sensors can be observed in the somewhat suppressed peaks of the higher-frequency transient ringing portions of the waveforms. In general, however, both alternative voltage sensors appear to track transient voltages rather well.

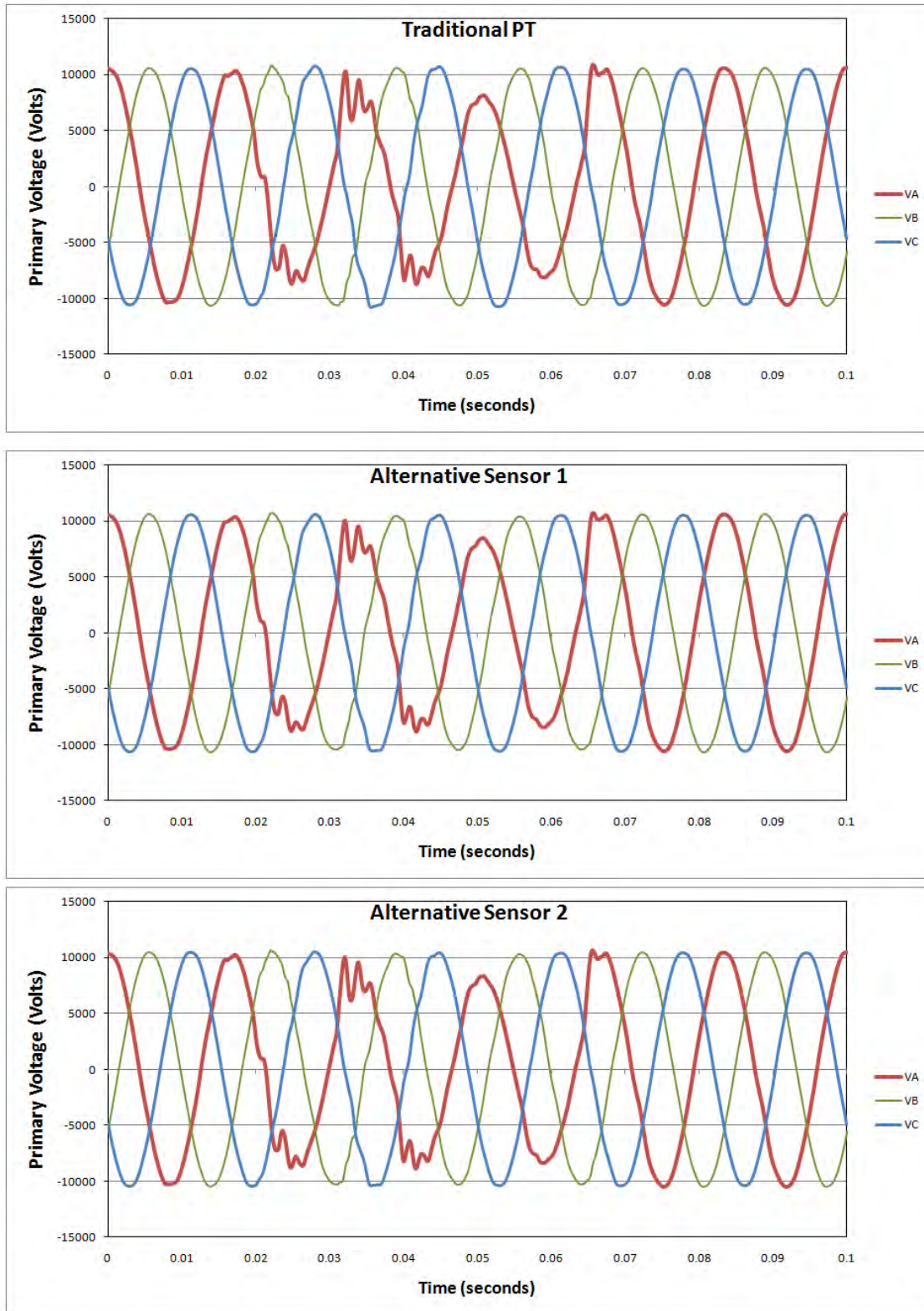


Figure 6: Voltage waveforms, overcurrent fault 1

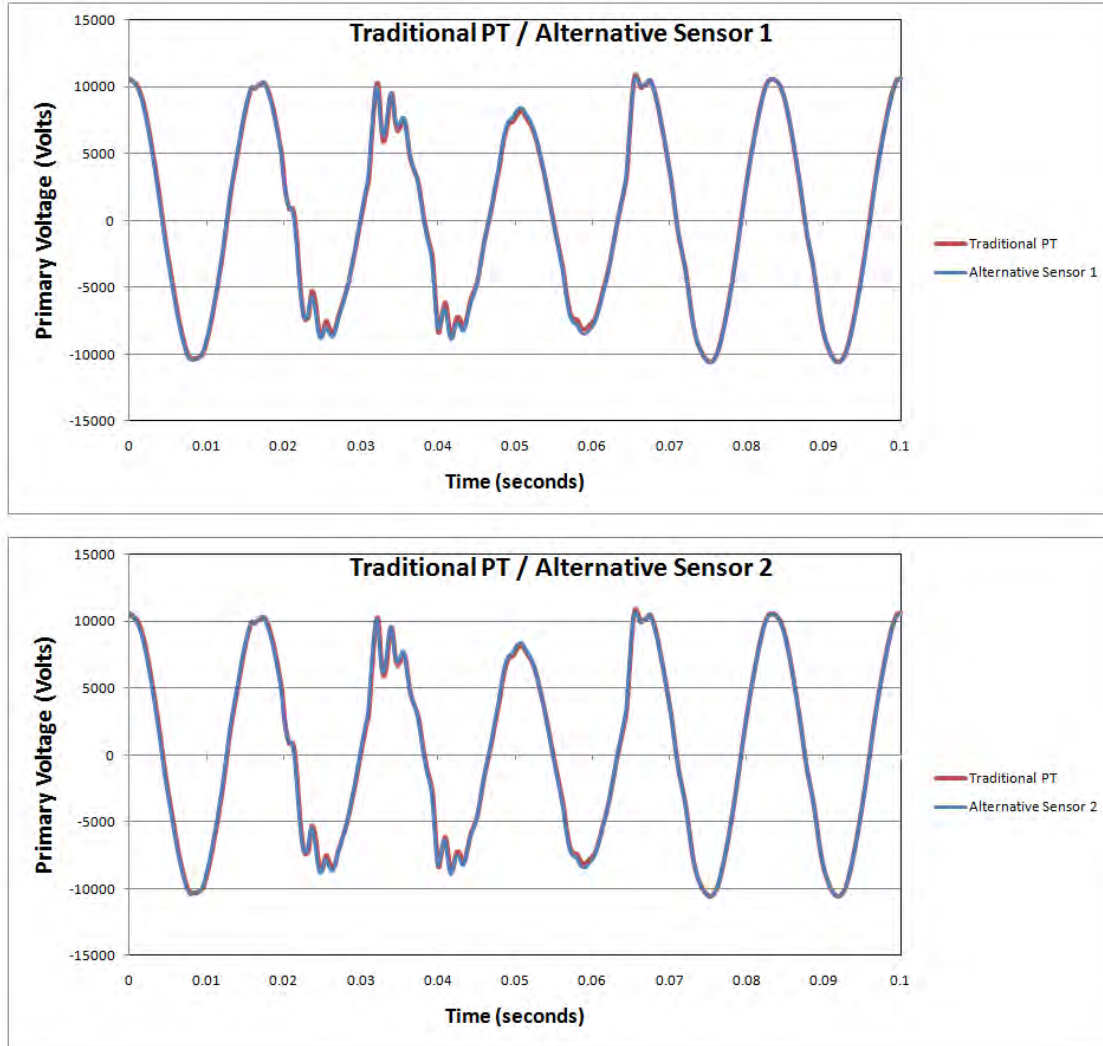


Figure 7: Overlaid voltage waveforms, overcurrent fault 1

3.1.2.2 Fault 2

3.1.2.2.1. Currents

This fault has shorter duration than the previous fault. Sensor characteristics exhibited during the previous fault are evident again in this fault, and are made more pronounced by the fault's sub-cycle duration. Figure 8 shows phase currents recorded by the three sensors during this event. Figure 9 overlays the faulted-phase current waveform from each alternative sensor with the waveform from the Traditional CT.

As in the previous fault case, Alternative Sensor 1 tends to suppress harmonic content, under-represent the initial half-cycle of the fault, and over-represent the final half-cycle of the fault. Also as before, Alternative Sensor 2 substantially over-represents the high-frequency content and the peak currents, as compared to the Traditional CT. This

sensor's tendency to amplify or introduce higher frequencies is particularly evident in this event, causing it to over-represent peak fault current substantially, as compared to the Traditional CT (approximately 3000-amp negative peak for Alternative Sensor 2 versus approximately 1700-amp negative peak for Traditional CT). In addition, because of the "ringing" high-frequency content, Alternative Sensor 2 actually has three peaks with absolute values greater than the single 1700-amp peak for the traditional CT.

Conversely, the short nature of this fault, combined with Alternative Sensor 1's low-pass filtering characteristic, results in this sensor's output under-representing the maximum fault current, and potentially over-representing the fault duration. Alternative Sensor 1's peak current value is only 70% of the peak produced by the Traditional CT. This would be significant for algorithms attempting to calculate fault magnitude or distance for fault-location purposes.

As with the previous fault example, both alternative sensors' waveforms might enable a device or algorithm to detect that a high-current event had occurred, depending on the device or algorithm, but predicting how a device or algorithm would calculate specific fault parameters cannot be predicted generically. Researchers again ran detection and characterization algorithms on waveforms from each sensor. Whereas Alternative Sensor 1 and the Traditional CTs/PTs produced similar fault-current estimates for the first example, they differed substantially for this fault. The algorithm estimated fault current of 1,128 amps from the Traditional CT/PT waveforms, but 779 amps (31 percent lower) from Alternative Sensor 1's waveforms. The particular algorithm used for this test did not classify the waveform from Alternative Sensor 2 as a fault, and therefore did not produce an estimate of fault current.

As stated multiple times, these algorithmic results are presented not as absolute performance metrics for the sensors, but rather to illustrate the inherent unpredictability involved with providing different inputs to automated algorithms which have been designed, developed, and tested for traditional CTs and PTs or for any other particular sensor.

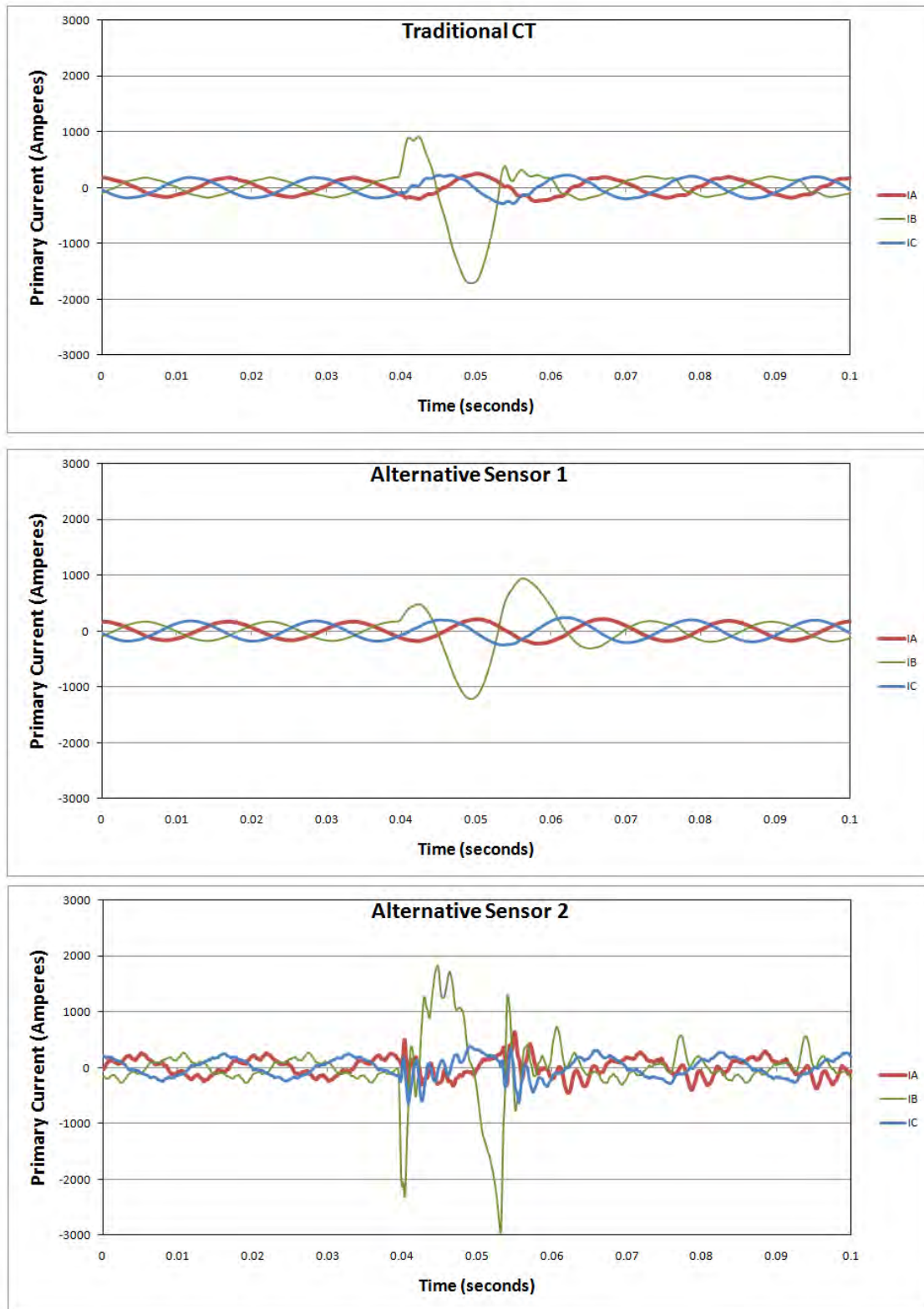


Figure 8: Current waveforms, overcurrent fault 2

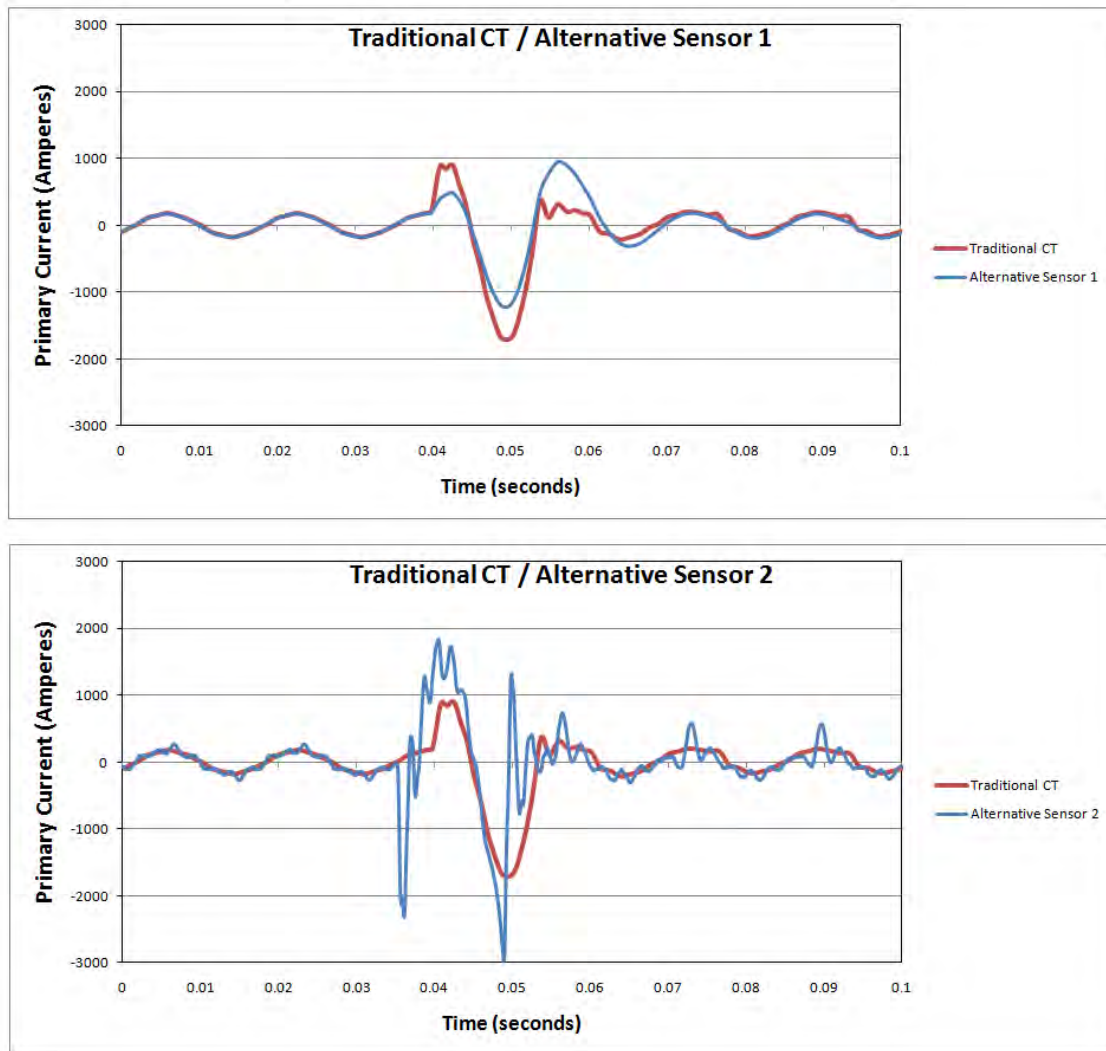


Figure 9: Overlaid current waveforms, overcurrent fault 2

3.1.2.2.2. Voltages

Figure 10 shows voltage waveforms from short-duration fault 2. Again, the voltage sensors appear to track the transient response measured by the Traditional PTs reasonably well. Figure 11 shows measurements from the alternative sensors overlaid on simultaneous measurements from the Traditional PT. Differences can be observed in the transient behavior of both alternative sensors compared to the PT output, but overall response is substantially similar.

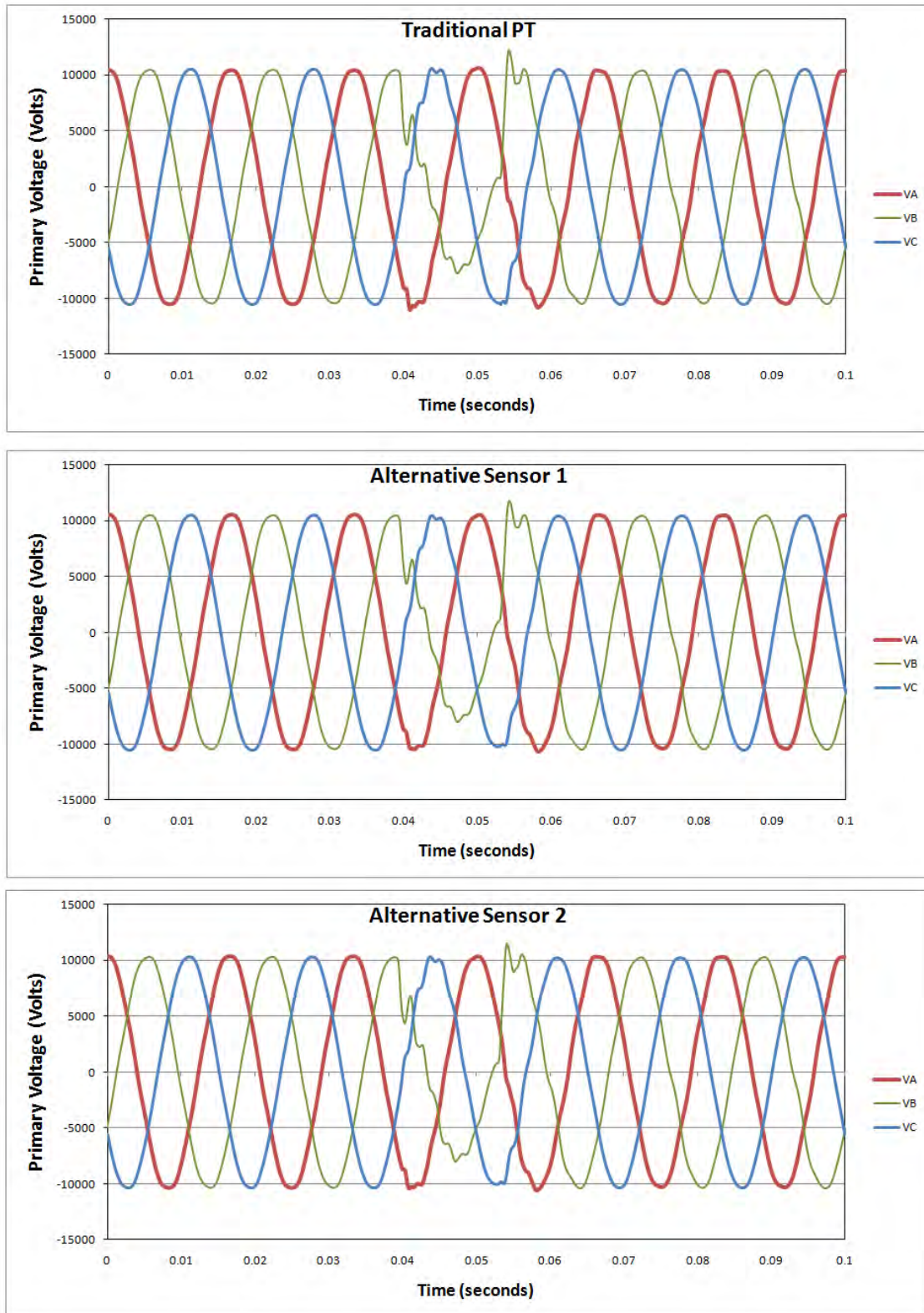


Figure 10: Voltage waveforms, overcurrent fault 2

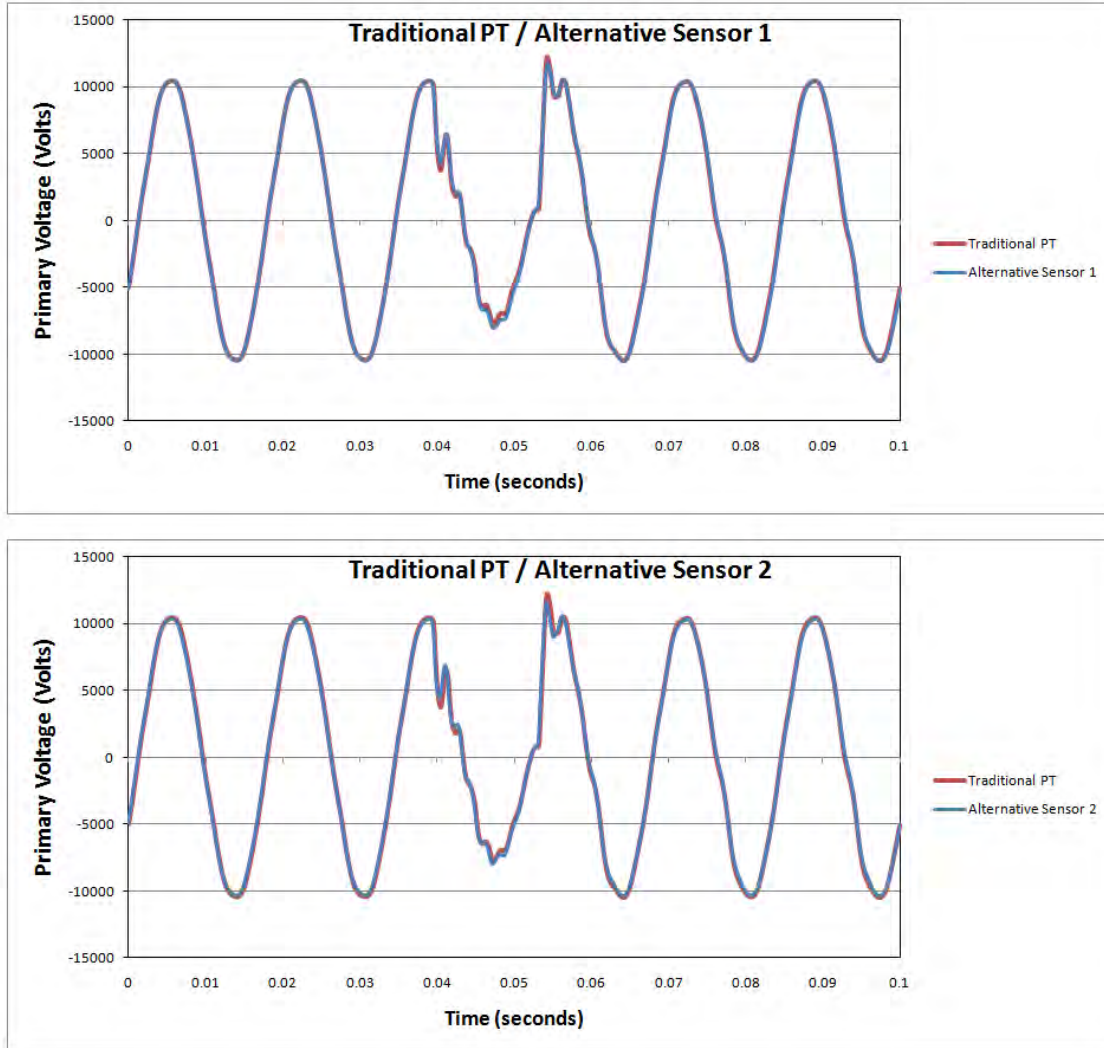


Figure 11: Overlaid voltage waveforms, overcurrent fault 2

3.1.2.3 Conclusions

Voltage waveforms from both alternative sensors were similar to those from Traditional PTs. However, each alternative sensor produced current waveforms substantially different than those from Traditional CTs. Alternative Sensor 2's tendency to amplify higher-order harmonics results in current waveforms substantially different in magnitude and shape than those from Traditional CTs. Alternative Sensor 1's tendency to attenuate higher-order harmonics results in current waveforms which track the general shape of the fault, but can differ significantly from the Traditional CT near the fault inception and extinction.

3.1.3 Capacitor Switching

Capacitor switching operations are common on distribution feeders. A capacitor bank switching on typically produces significant high-frequency transient voltages and currents. These transients are generally damped in less than one power-system cycle, but

they have the highest magnitudes of any “normal” power system event. It is common for there to be multiple transients over a time interval of a few cycles to a few seconds, because the three switches used for controlling three-phase capacitor banks often do not close at the same time. Therefore, for grounded-wye capacitor banks it is common to observe three distinct transients, and two for ungrounded banks.

Figure 12 shows voltage transients recorded from Alternative Sensor 2 and Traditional PTs during a capacitor-switching event. The Phase-B capacitor switch closes and causes a transient at 0.053 seconds, and the Phase-C switch at 0.078 seconds. The Phase-A switch closing is not represented in the figure.

Transient response reflects observations previously made regarding steady-state and overcurrent events, namely, that Alternative Sensor 2’s voltage waveforms tend to track the Traditional PT’s waveform, although with high-frequency components slightly attenuated. This is most evident during the Phase-C switching transient (0.078 seconds), where Alternative Sensor 2’s waveform under-represents the transient dip in voltage.

No capacitor-switching transients were recorded for Alternative Sensor 1 during this project. This was because the data-acquisition device originally used for Alternative Sensor 1 had been re-tasked for monitoring a third type of alternative sensor part-way through the project, as described elsewhere in this report. During the time when Alternative Sensor 1 was installed, no capacitor-switching transients were recorded.

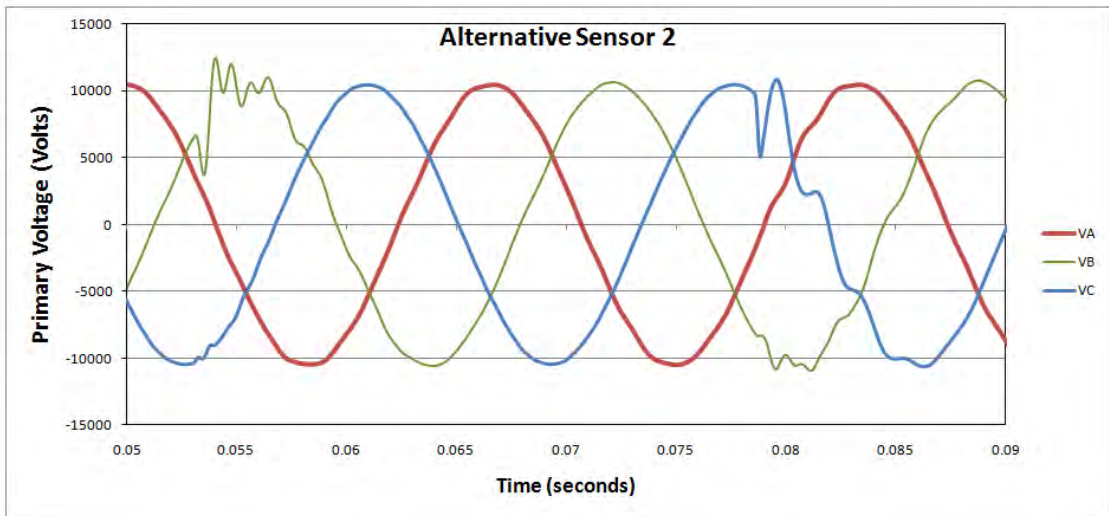
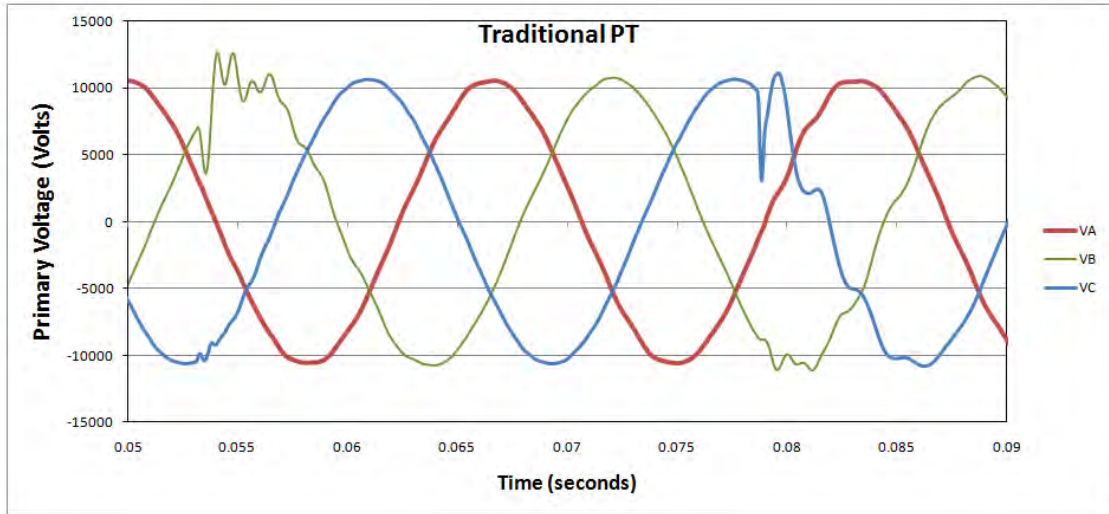


Figure 12: Voltage transients, capacitor switching on

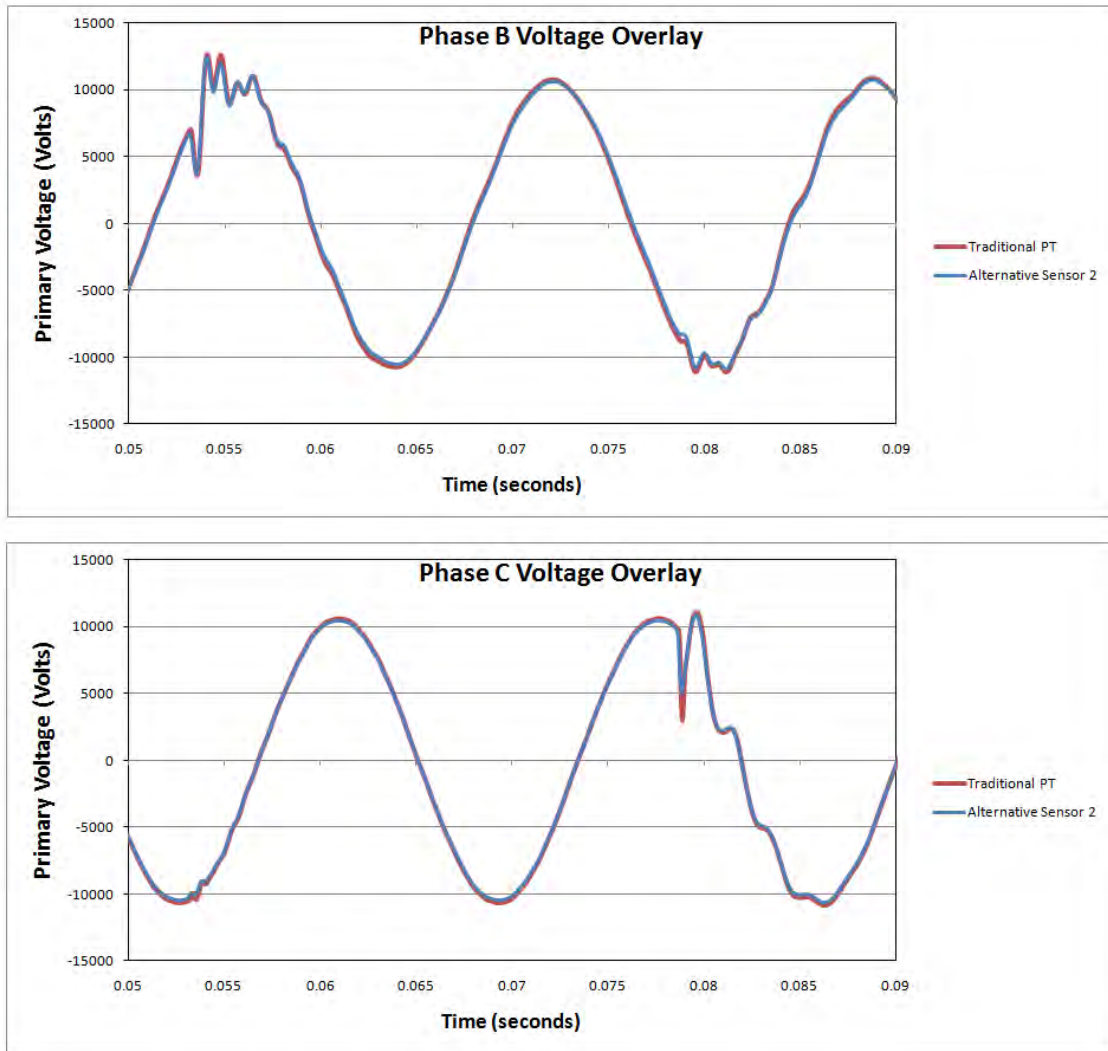


Figure 13: Overlaid voltage waveforms, Traditional PT/Alternative Sensor 2, capacitor switching on

As previously noted, Alternative Sensor 2 amplifies higher-order harmonic currents. This is of special concern during capacitor switching, when the current transients have significant high-frequency content, generally on the order of a few hundred Hertz, but on the order of several thousand Hertz in specific circumstances.

Figure 14 and Figure 15 show current waveforms from all three phases during the capacitor-switching transient. As before, Alternative Sensor 2 substantially amplifies high-frequency current content, resulting in exaggerated peaks in its current waveform. The Traditional CT peak currents on Phase B and Phase C were 325A and 350A respectively. For the same phases, Alternative Sensor 2 produced peak waveforms of 2,800A and 4,400A. These peaks are eight to twelve times those in the waveforms from the conventional CTs. Figure 14 shows the current with sufficient range to accommodate the range of the waveform from Alternative Sensor 2. Figure 15 shows the same

waveforms, but on a scale that permits better identification of the waveforms produced by the Traditional CTs.

The waveform envelope of Figure 15 also indicates that the steady-state current values from Alternative Sensor 2 are larger than those from the Traditional CT. This is because of the feeder's normal, steady-state current harmonics, which also are amplified the Alternative Sensor 2.

Figure 16 and Figure 17 show the same capacitor-switching event, but only for a period of about 40 milliseconds surrounding the first two phase closings (B and C). The same scaling factors have been used in these two figures to show appropriate detail from each set of sensors. This view provides more detail about Alternative Sensor 2's representation of the current transients and its amplification of the higher-frequency components of these transients. It is impossible to know what might result if such a waveform were given as an input to a protective relay, or a fault location algorithm, but one obviously cannot assume proper or desired response.

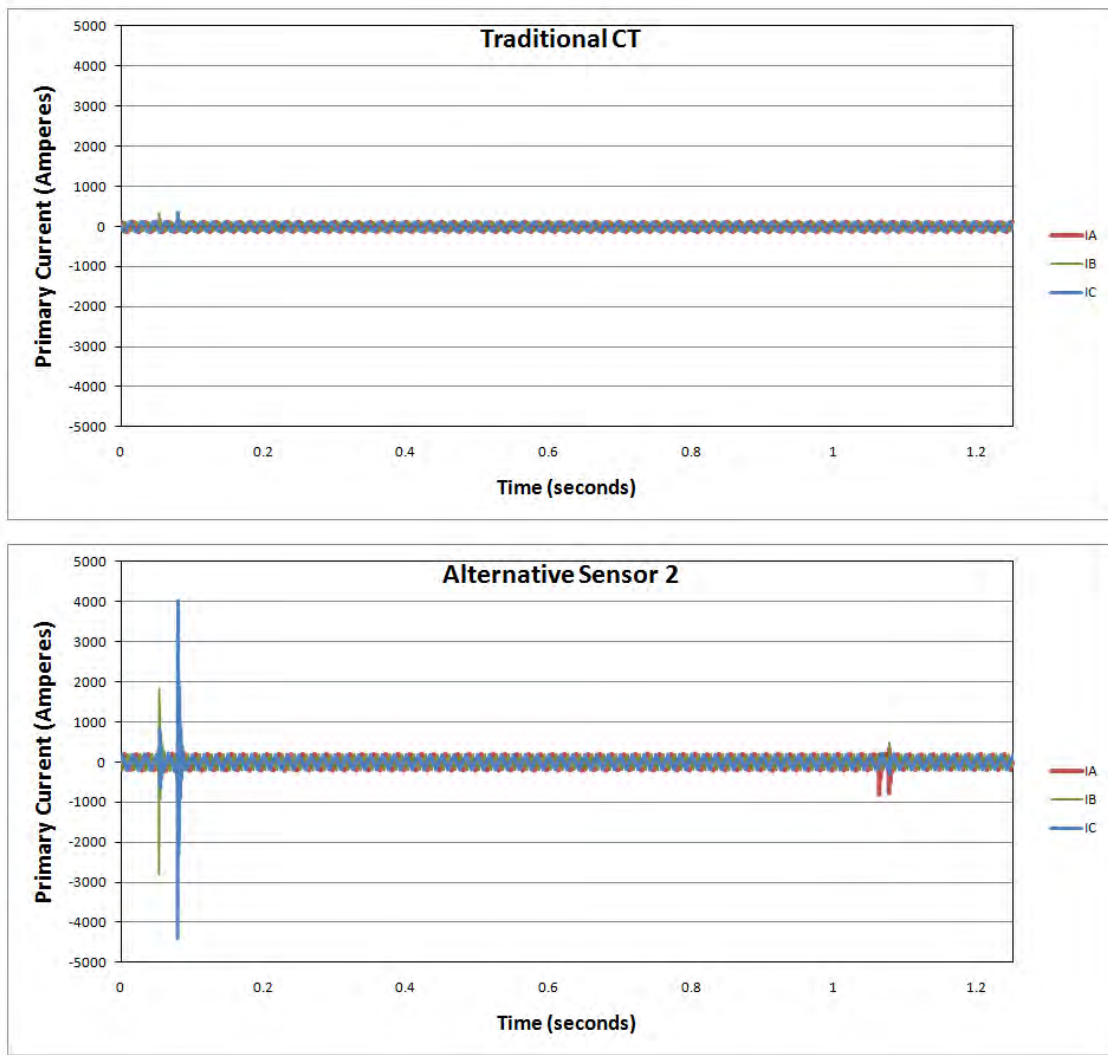


Figure 14: Current transients, capacitor switching on (full range)

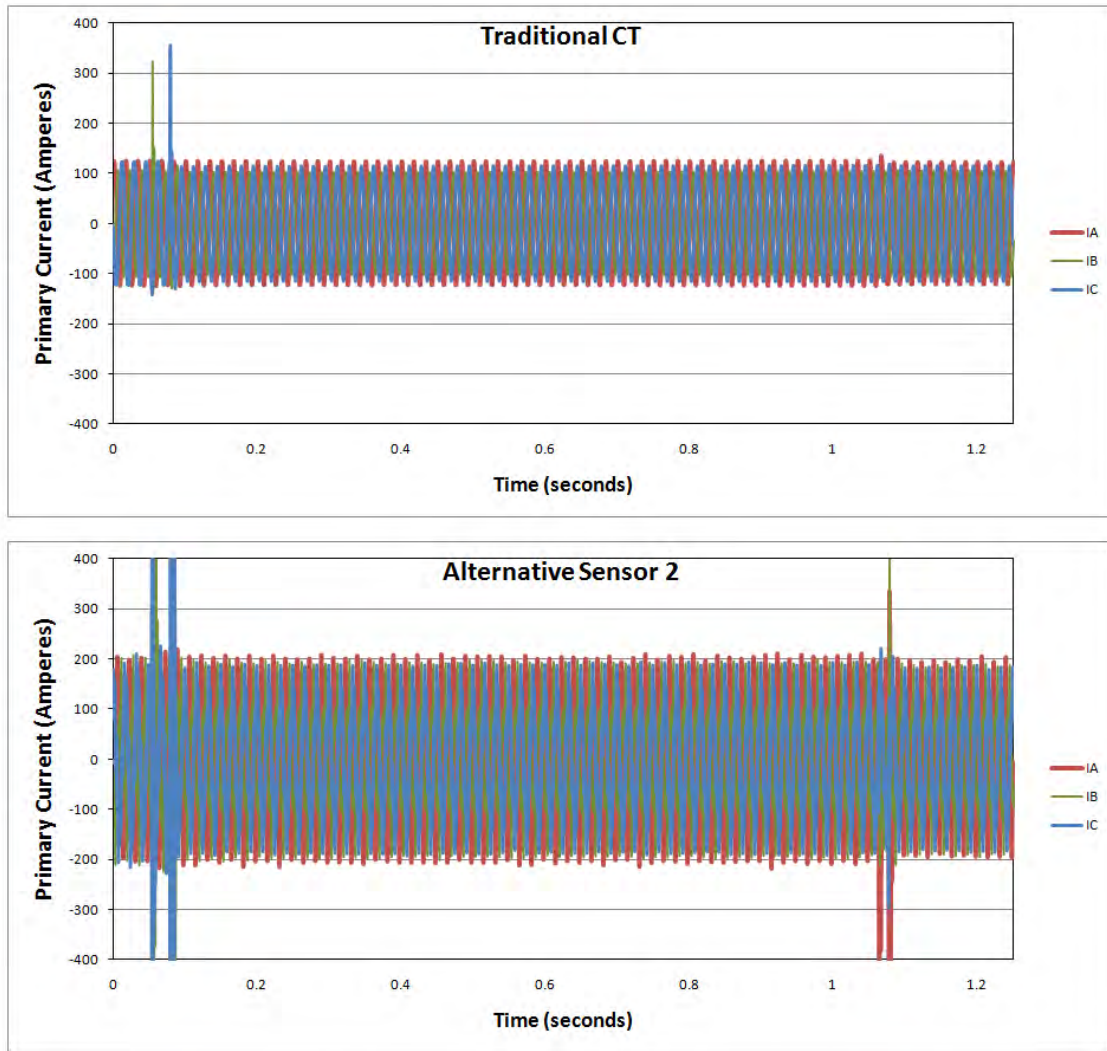


Figure 15: Current transients, capacitor switching on (narrow range)

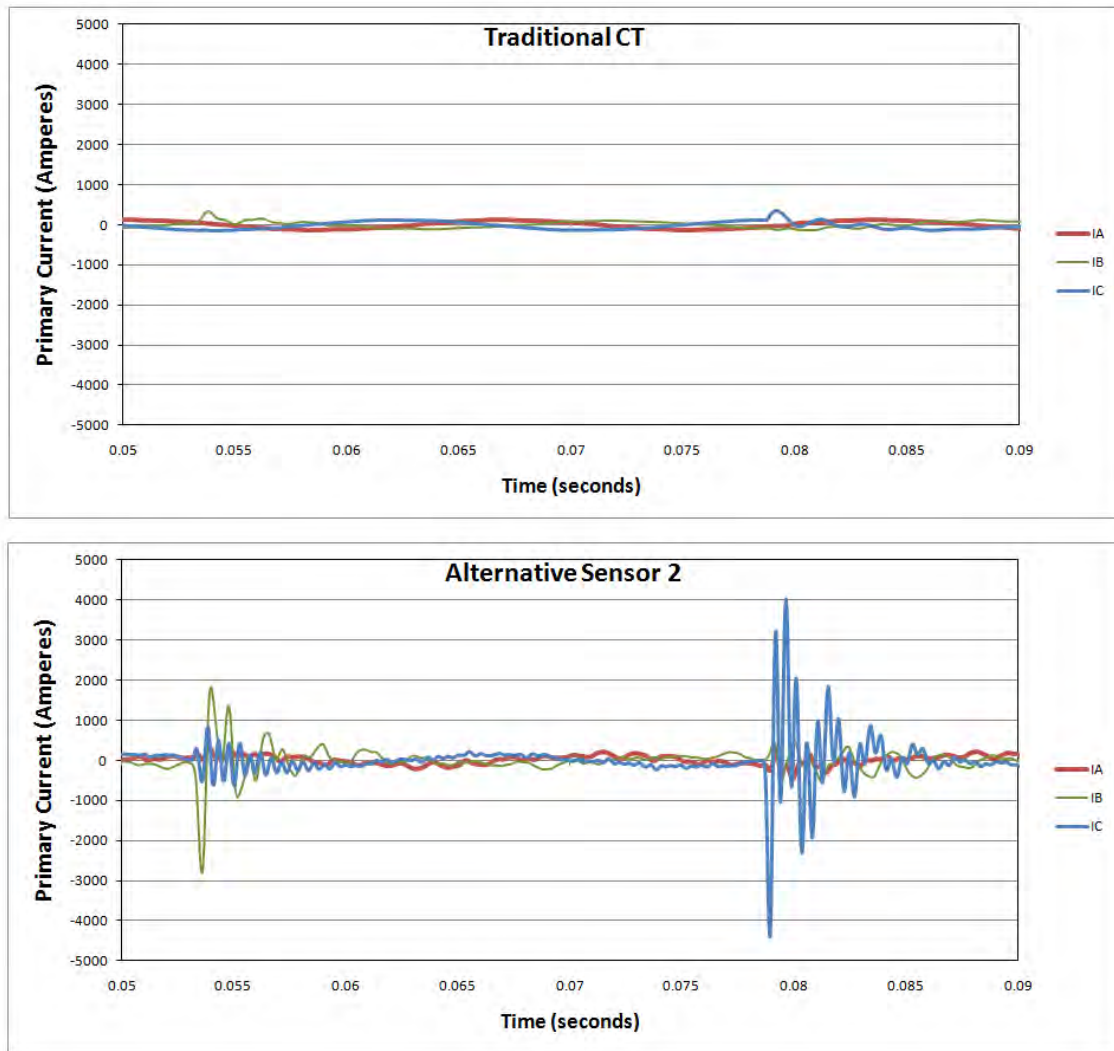


Figure 16: Current transients, capacitor switching on, zoomed (full range)

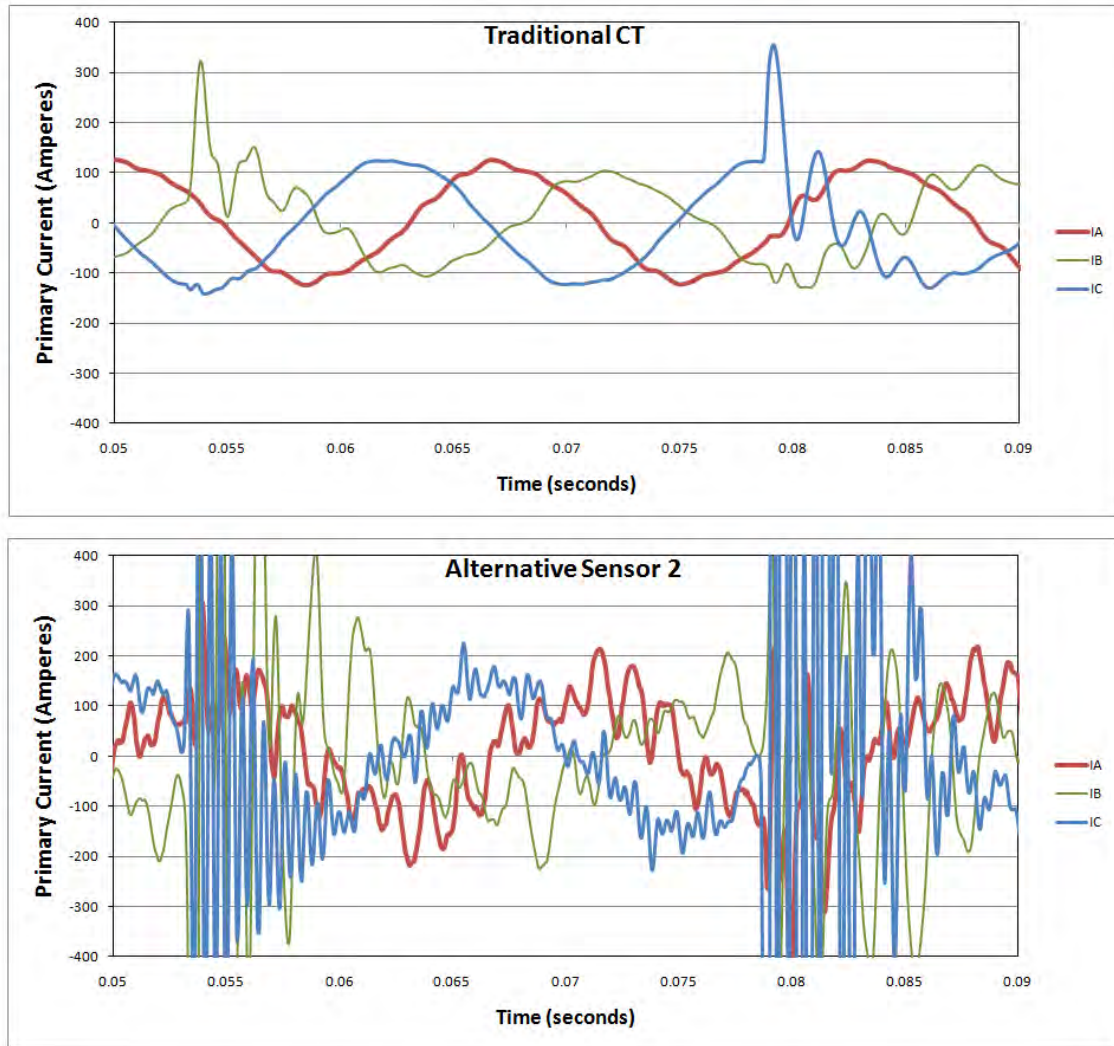


Figure 17: Current transients, capacitor switching on, zoomed (narrow range)

3.1.4 Motor Start

Motor starts are common events on distribution feeders. They typically produce measurable changes to phase currents, with lesser effect on voltages. As a result, analysis presented in this section will focus on current measurements.

Figure 18 shows a 0.8-second interval of waveforms recorded by all three sensors during a motor-start event. The shape of the envelope of each sensor's waveform resembles a classical motor-start transient. As a motor starts, the starting current is relatively high. In the figure, the motor-start transient begins at approximately 0.05 seconds. The elevated level of current lasts approximately 0.6 seconds and then gradually decreases, leveling off at its final value just after 0.7 seconds. The general shape of the envelope is similar for all three sensors' waveforms.

At 0.05 seconds, Alternative Sensor 1's waveform envelope exhibits a more gradual increase in current than the step increase of the Traditional CT's waveform. Alternative Sensor 2's waveform is similar in shape, but the magnitude is markedly higher. This is a result of that sensor's harmonic-amplification effect, applied to the normal, steady-state harmonics in the feeder's load current.

Figure 19 shows a shorter period of time, thereby enabling closer examination of the shape of the waveforms. As before, harmonic components are suppressed substantially in Alternative Sensor 1's waveform, but amplified in Alternative Sensor 2's waveform.

In summary, the envelope of all sensors' current waveforms are similar and resemble a classic motor-start waveform, but each Alternative Sensor's harmonic content varies substantially from that of the Traditional CT.

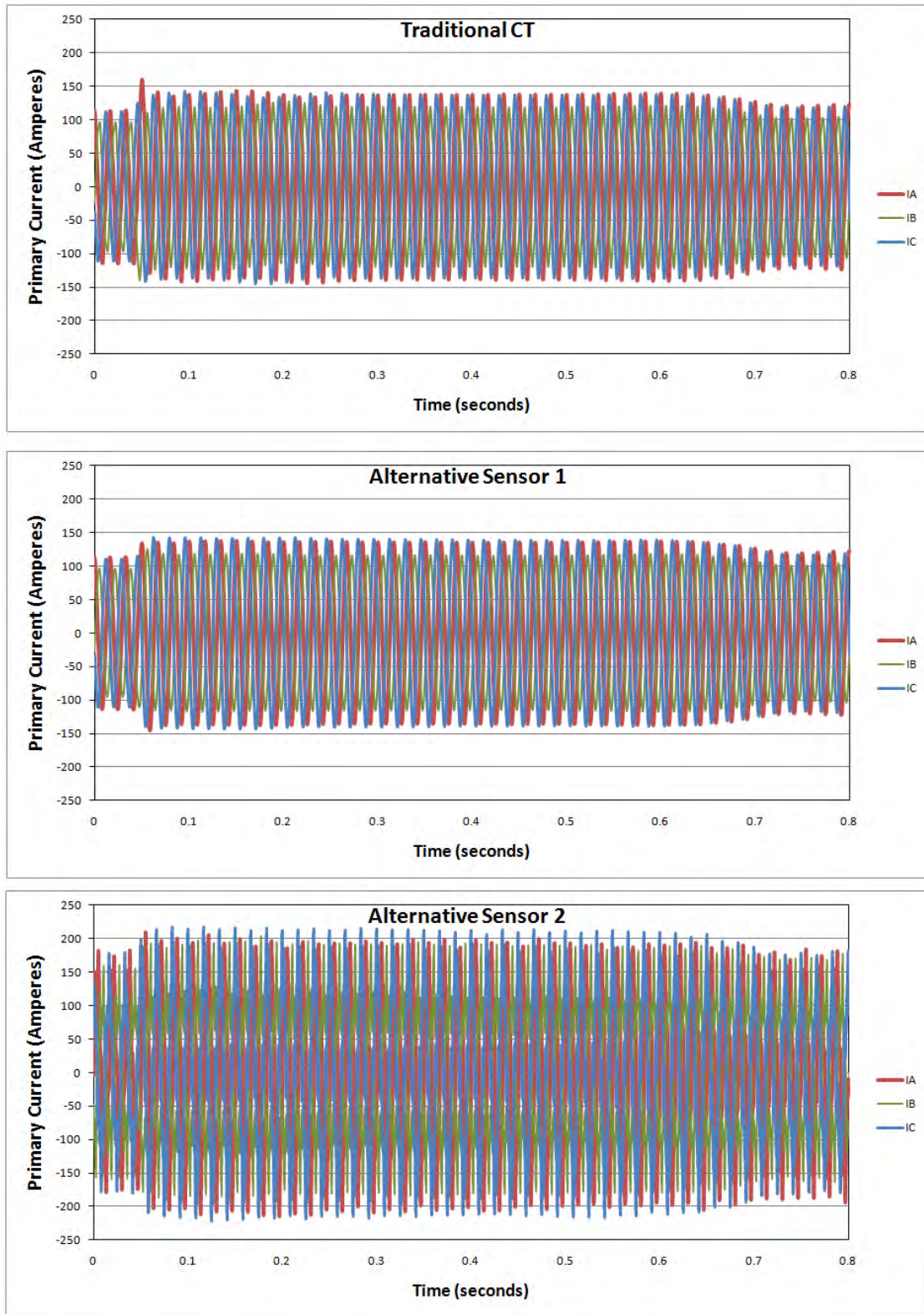


Figure 18: Current waveforms, motor starting

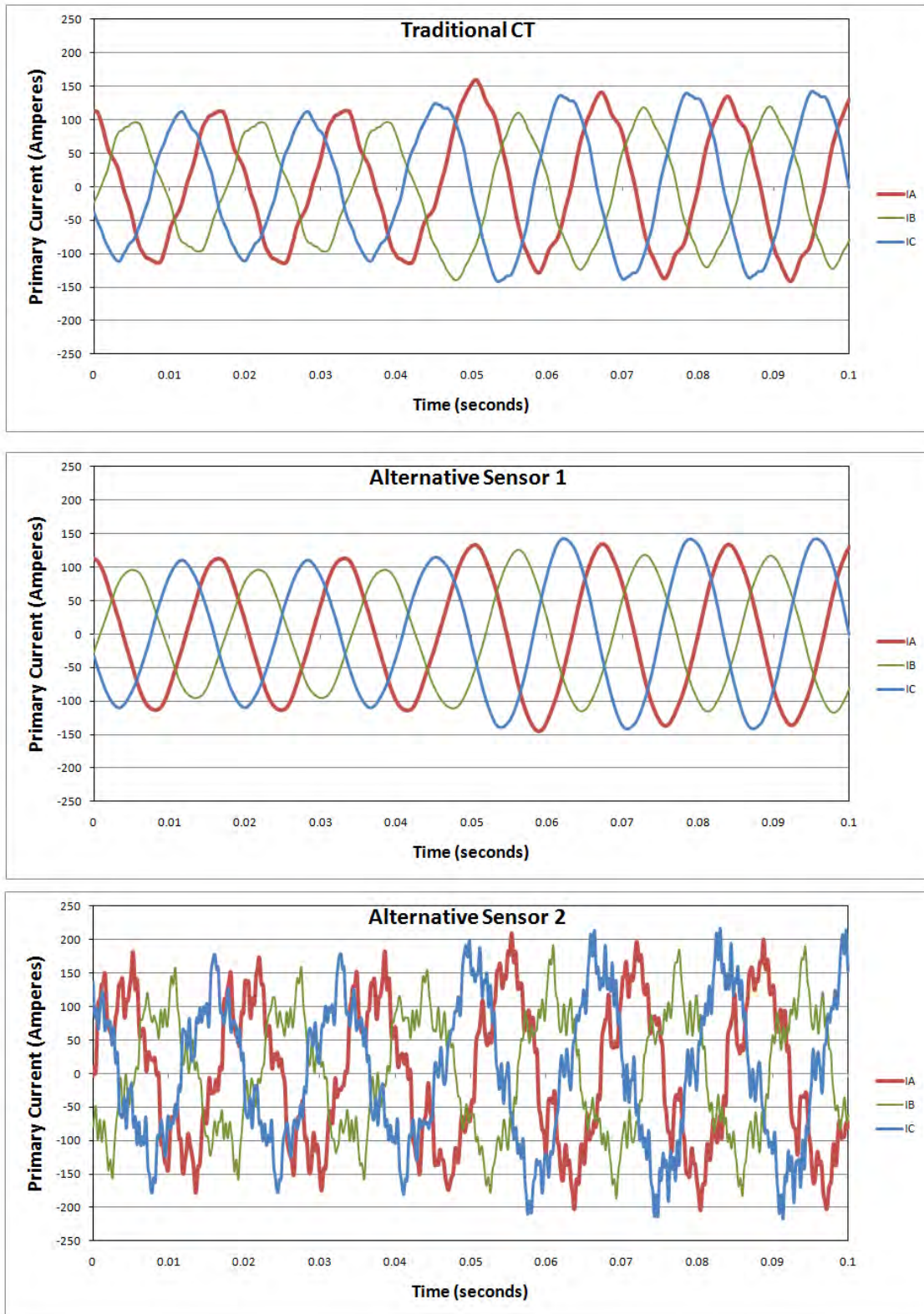


Figure 19: Current waveforms, motor starting, zoomed

3.1.5 Arcing

Arcing events are particularly important for detecting incipient faults and downed conductors. Arcs are transient events that may occur on a sub-cycle basis and have low magnitude. Accurate reproduction of waveshapes is of particular importance in the analysis of arcing faults, because harmonic content and the timing of waveform zero crossings are important in the process of distinguishing arcing-fault waveforms from those of other low-current events.

Like motor starts, arcing events are most clearly observed on current waveforms, and often are not readily observed on voltages. The following series of waveforms were recorded by Alternative Sensor 1 and the Traditional CTs/PTs during an arcing event. No arcing events occurred during the time Alternative Sensor 2 was installed alongside Alternative Sensor 1.

Figure 20 shows simultaneous waveforms from Traditional CTs and Alternative Sensor 1 during a short-lived arcing fault. Three peaks of interest are circled for each sensor. In the Traditional CT waveform, the arcing fault current is observed as an increase of approximately 30 amperes at the peak of the first circled, positive half-cycle. The arc restrikes on the subsequent negative half-cycle, resulting in a current burst of approximately 60 amperes, as compared to its pre-fault value. In the third half-cycle, the current has returned to approximately its pre-fault level, an increase of only 6 amperes over its pre-fault value.

The same three corresponding peaks are circled in the waveforms from Alternative Sensor 1. The first peak contains an increase of 11 amperes as compared to the previous cycle. The second peak is 50 amperes larger than the pre-fault peak, and the third peak is approximately 40 amperes larger than the pre-fault peak. The discrepancies in the waveforms can be seen in the overlaid currents of Figure 21. In effect, Alternative Sensor 1 makes sharp transitions smoother, lessening the first peak and prolonging the trailing peak.

This effect is more obvious in Figure 22, which shows waveform recordings from Alternative Sensor 1 and Traditional CTs during another arcing event. In the Traditional CT waveform, the arcing-fault current is a single half-cycle with a 20-ampere increase. In the lower portion of the figure, Alternative Sensor 1's output for the same half-cycle is marginally higher than the pre-fault current, by approximately 5 amperes. The negative half-cycle current, also circled in black, is approximately 15 amperes higher than the pre-fault current. By contrast, the same peak on the Traditional CT waveform has returned to its pre-fault value in the negative half-cycle. Thus the current waveform of Alternative Sensor 1 again demonstrates a filtering effect that deemphasizes and smoothes sharp transitions, with the effect of making the transient appear smaller in size but longer in duration. Figure 23 overlays the current waveforms to better illustrate these differences.

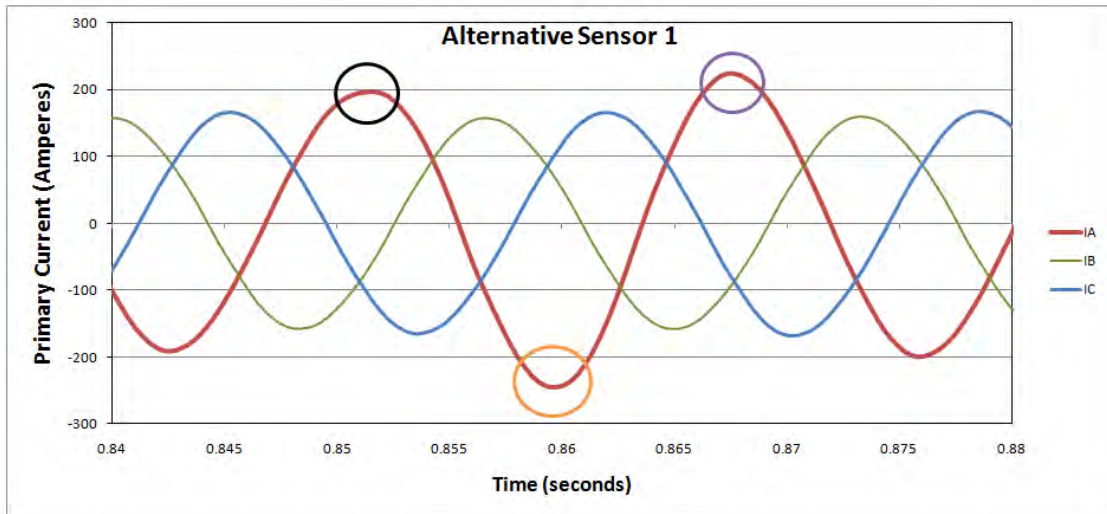
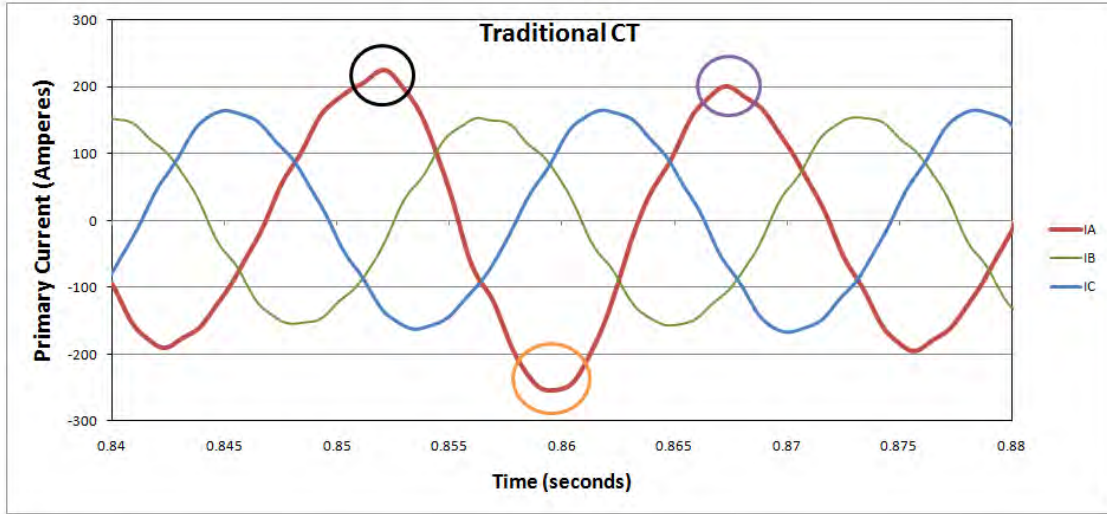


Figure 20: Current waveforms, full-cycle arcing fault

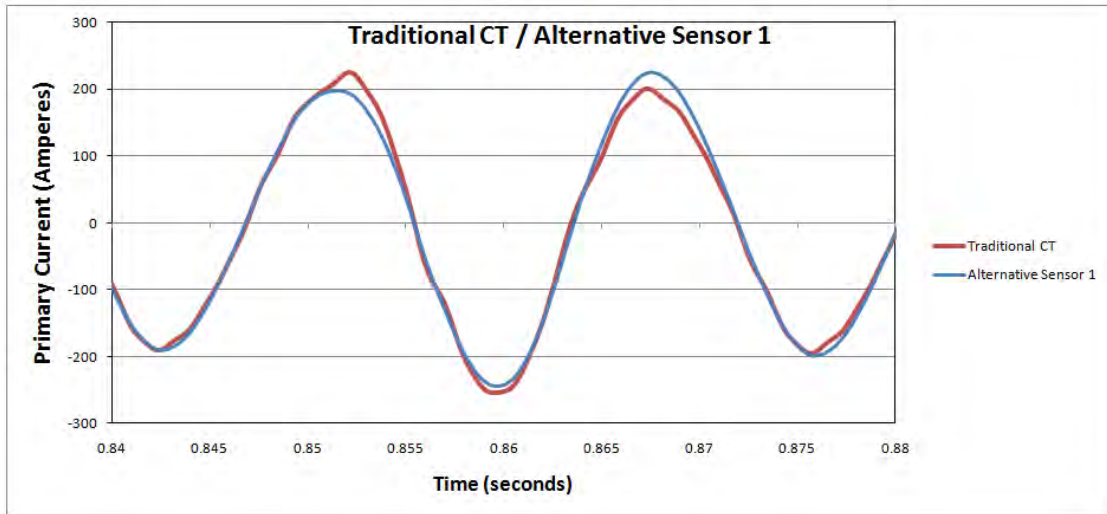


Figure 21: Overlaid current waveforms, full-cycle arcing fault

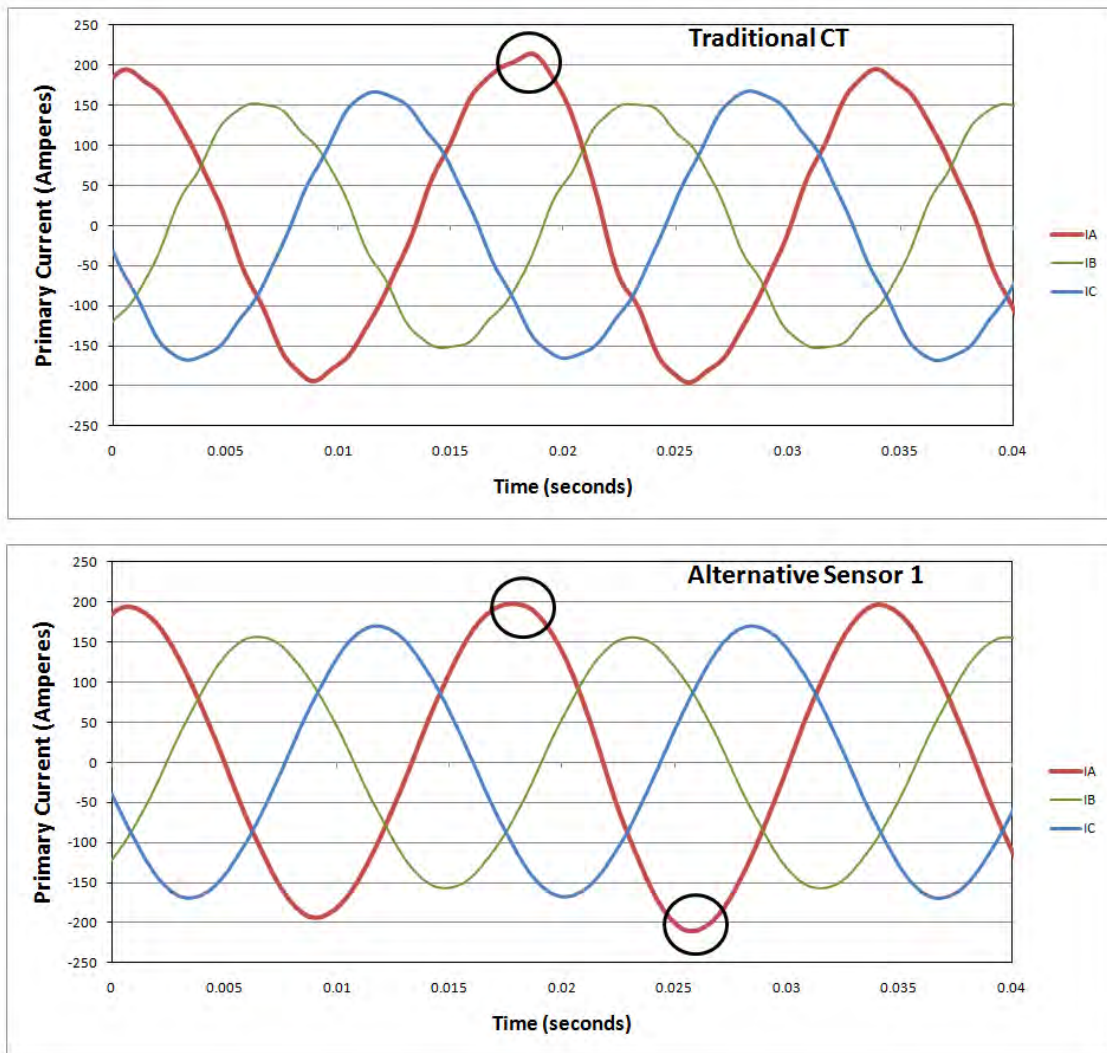


Figure 22: Current waveforms, half-cycle arcing fault

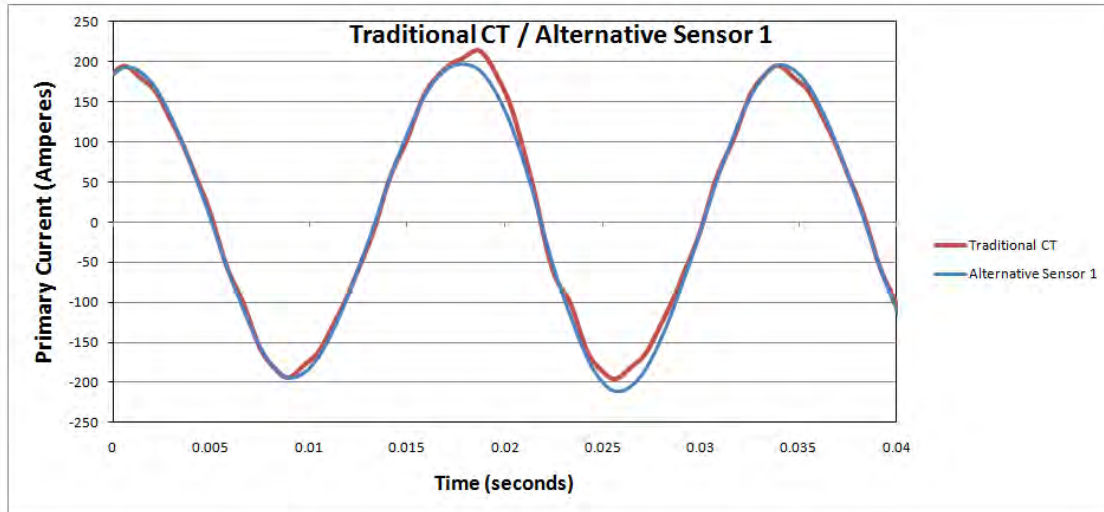


Figure 23: Overlaid current waveforms, half-cycle arcing fault

3.2 Steady-state Frequency Analysis

To analyze differences in frequency spectra between the three sensors, researchers analyzed twenty simultaneous waveforms from each sensor. Waveforms were captured by manually triggering the data-acquisition system. While no strict effort was made to ensure a truly random sample of data, researchers included samples collected at various times of day on both weekdays and weekends, to encompass a variety of system loading conditions. Each set of waveform recordings was triggered on all three data recording devices at the same time, resulting in each sensor capturing the same period of data. Each waveform recording was for a period of 30 seconds.

Researchers performed multiple, consecutive, two-cycle FFTs on current and voltage waveforms for each phase for the duration of each 30-second capture. The resulting 900 FFT magnitudes for each channel were then averaged on a per-channel, per-harmonic basis, resulting in an overall average harmonic content for each channel in every recorded waveform. Each channel's average harmonic content was then normalized in two ways. First, each harmonic component was normalized to the fundamental-frequency (60 Hertz) value for that sensor. This was done to eliminate absolute load-level variations, and to eliminate absolute-accuracy errors between sensors. This normalized harmonic spectrum was then normalized a second time by dividing it by the normalized value from the Traditional CT/PT at the corresponding harmonic. The result of the first normalization is that each sensor's value at fundamental frequency is unity, by definition. The result of the second normalization is that the values for the Traditional CT/PT also are unity at every frequency, because that component has been used as the basis for comparison for the other sensors' frequency components at the corresponding frequency.

These normalized averages are presented in Table 1 and Table 2 for voltages and Table 3 and Table 4 for currents. They also presented graphically in Figure 24 and Figure 25.

Table 1: Voltage sensor harmonic response normalized to fundamental frequency

Frequency (Hz)	Traditional PT	Alternative Sensor 1	Alternative Sensor 2
60	1.0000	1.0000	1.0000
120	0.0002	0.0002	0.0002
180	0.0052	0.0035	0.0034
240	0.0002	0.0002	0.0002
300	0.0069	0.0063	0.0063
360	0.0002	0.0002	0.0002
420	0.0052	0.0046	0.0048
480	0.0002	0.0002	0.0002
540	0.0023	0.0019	0.0021
600	0.0001	0.0001	0.0001
660	0.0021	0.0017	0.0020
720	0.0000	0.0000	0.0000
780	0.0000	0.0000	0.0000
840	0.0000	0.0000	0.0000
900	0.0001	0.0001	0.0001
960	0.0000	0.0000	0.0000

Table 2: Voltage sensor harmonic response normalized to Traditional PT

Frequency (Hz)	Traditional PT	Alternative Sensor 1	Alternative Sensor 2
60	1.0000	1.0000	1.0000
120	1.0000	1.0471	1.1242
180	1.0000	0.6751	0.6620
240	1.0000	0.9571	0.9295
300	1.0000	0.8959	0.9022
360	1.0000	0.9291	0.9407
420	1.0000	0.8897	0.9383
480	1.0000	0.8577	0.9319
540	1.0000	0.8083	0.9200
600	1.0000	0.8633	0.9673
660	1.0000	0.8096	0.9877
720	1.0000	1.0879	1.2073
780	1.0000	1.3202	1.4796
840	1.0000	1.3202	1.4796
900	1.0000	0.6444	0.8564
960	1.0000	1.2602	1.5015

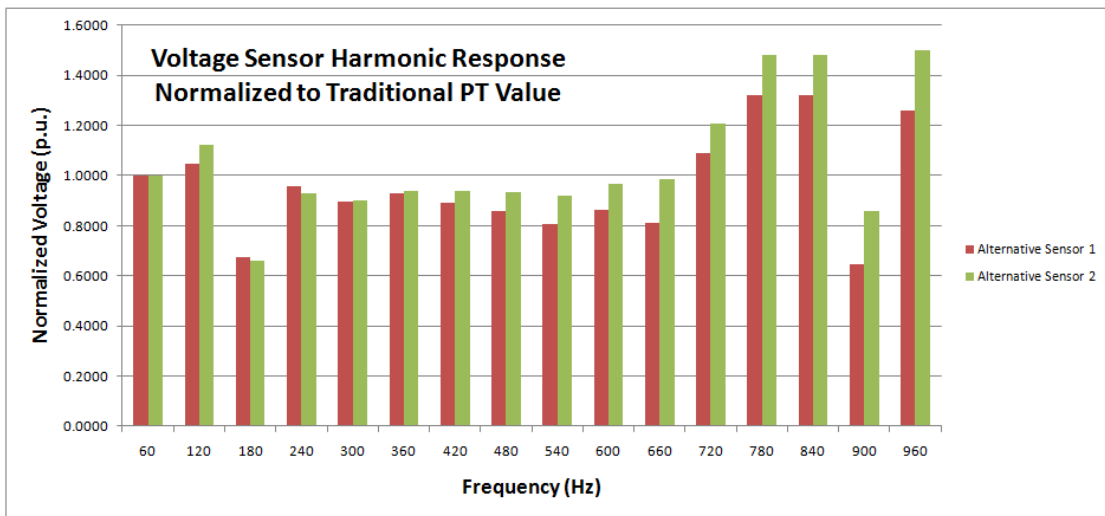
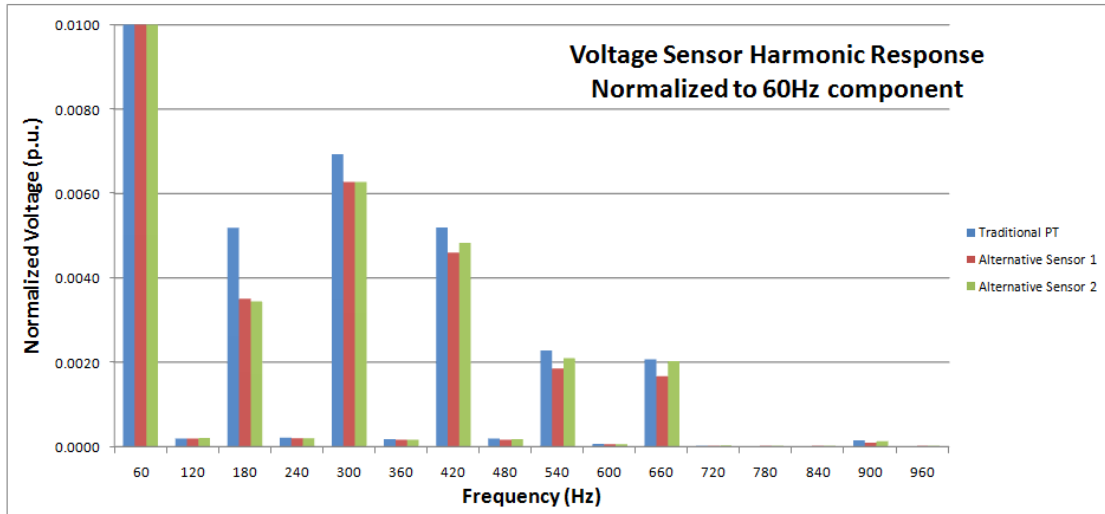


Figure 24: Voltage sensor harmonic response

Table 3: Current sensor harmonic response, normalized to fundamental frequency

Frequency (Hz)	Traditional CT	Alternative Sensor 1	Alternative Sensor 2
60	1.0000	1.0000	1.0000
120	0.0012	0.0007	0.0024
180	0.0373	0.0149	0.1267
240	0.0007	0.0003	0.0031
300	0.0250	0.0066	0.1304
360	0.0009	0.0002	0.0058
420	0.0223	0.0047	0.1571
480	0.0009	0.0002	0.0079
540	0.0091	0.0018	0.0902
600	0.0003	0.0001	0.0030
660	0.0045	0.0009	0.0542
720	0.0001	0.0001	0.0011
780	0.0001	0.0001	0.0011
840	0.0001	0.0001	0.0011
900	0.0003	0.0001	0.0058
960	0.0001	0.0001	0.0015

Table 4: Current sensor harmonic response, normalized to Traditional CT value

Frequency (Hz)	Traditional CT	Alternative Sensor 1	Alternative Sensor 2
60	1.0000	1.0000	1.0000
120	1.0000	0.6063	1.9512
180	1.0000	0.3860	3.2779
240	1.0000	0.3652	3.9693
300	1.0000	0.2508	5.0042
360	1.0000	0.2759	6.1410
420	1.0000	0.2111	6.9107
480	1.0000	0.2425	8.0886
540	1.0000	0.1886	9.4694
600	1.0000	0.4264	9.9786
660	1.0000	0.1811	11.3805
720	1.0000	0.9743	11.4226
780	1.0000	1.2641	13.4996
840	1.0000	1.2641	13.4996
900	1.0000	0.3898	16.5355
960	1.0000	1.2018	16.9757

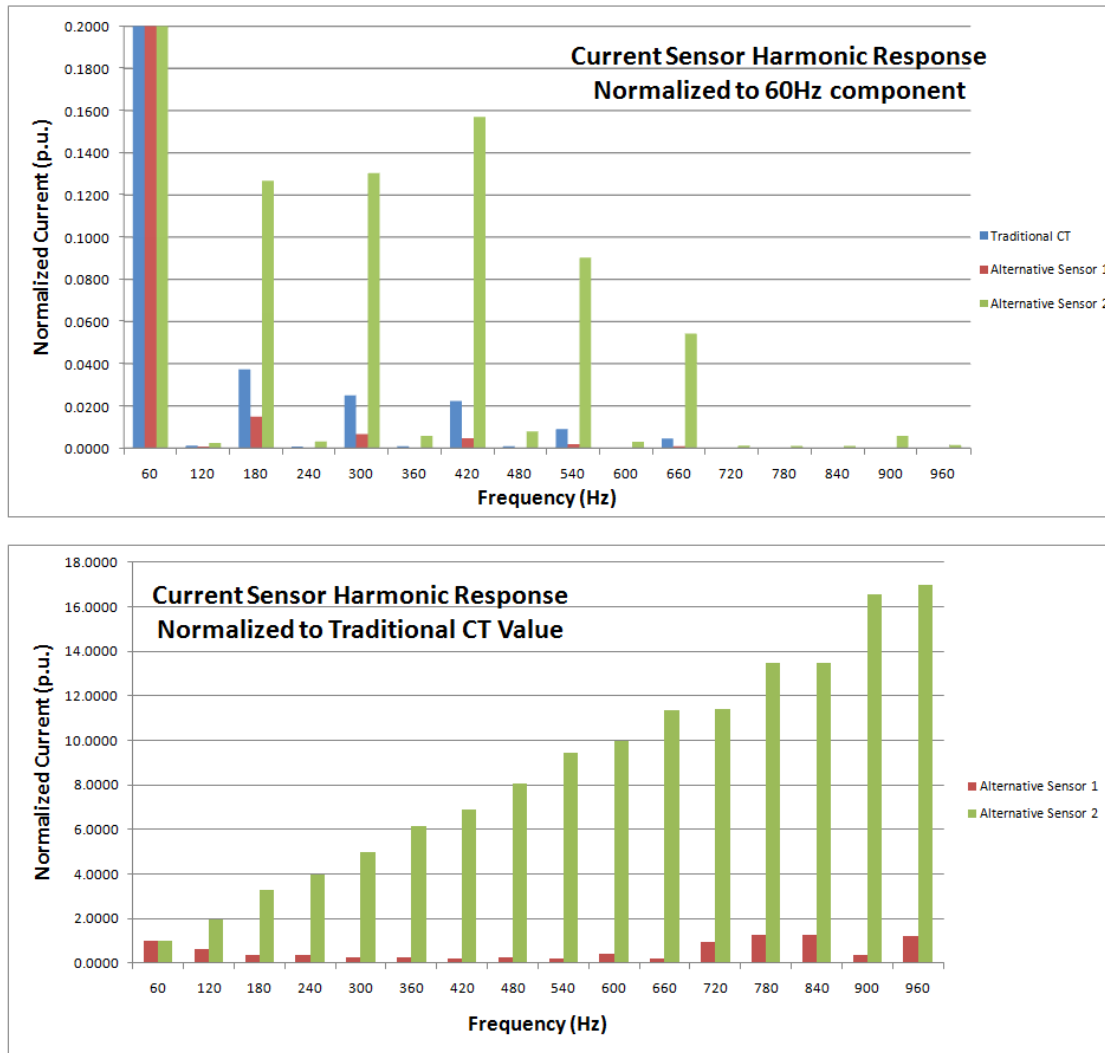


Figure 25: Current sensor harmonic response

Values from the first normalization were then analyzed in a two-tailed t-test as a means to determine the statistical significance of the measured differences at each harmonic. Results of this analysis are presented in Table 5 and Table 6. The critical t-statistic for a two-tailed test for $df=59$ at $\alpha=0.05$ is 2.00. Some values in Table 5 and Table 6 are calculated, but those components in the original waveforms are too small for accurate measurement by the data-collection devices. Therefore, they are included in the tables but identified therein as not meaningful.

The results presented from the t-test are not in themselves a metric of how well a particular sensor's characteristics match the Traditional CT/PT characteristics, but rather represent the likelihood that the observed samples could be drawn from the same population. In other words, the results of the t-tests demonstrate that at every harmonic level except for the second harmonic voltage, there were statistically significant differences between all three sensors' normalized harmonic spectra. Although in some cases the absolute differences between observed harmonic levels between two sensors

may be small, particularly in the case of higher-order harmonics, the variance between observed normalized samples on each individual sensor was small enough to allow statistical separation between the two populations. The p-values presented in the table represent the probability that one would expect to see the results that were observed if the two sensors had an identical harmonic response.

Table 5: t-statistic and p-values for normalized voltage t-test

Frequency (Hz)	Alternative Sensor 1		Alternative Sensor 2	
	t-Statistic	p-Value	t-Statistic	p-Value
120	0.314	7.55E-01	-1.857	6.82E-02
180	52.516	3.10E-51	52.774	2.33E-51
240	4.026	1.64E-04	5.364	1.43E-06
300	19.039	7.18E-27	12.238	7.82E-18
360	7.734	1.54E-10	6.226	5.44E-08
420	12.866	9.02E-19	8.455	9.36E-12
480	14.965	9.50E-22	11.443	1.30E-16
540	33.216	6.91E-40	17.017	1.97E-24
600	7.699	1.77E-10	5.120	3.51E-06
660	29.847	2.68E-37	2.129	3.74E-02
720	-0.991	3.26E-01	-6.664	1.00E-08
780	19.299	3.59E-27	2.211	3.09E-02
840	-2.977	4.22E-03	-8.959	1.34E-12
900	18.798	1.37E-26	12.738	1.39E-18
960	-2.548	1.35E-02	-9.282	3.89E-13

*Note: Values in shaded cells are calculated, but their absolute magnitudes fall below the recording device's threshold to accurately represent.

Table 6: t-statistic and p-values for normalized current t-test

Frequency (Hz)	Alternative Sensor 1		Alternative Sensor 2	
	t-Statistic	p-Value	t-Statistic	p-Value
120	12.536	2.80E-18	-14.091	1.54E-20
180	22.589	9.90E-31	-32.566	2.09E-39
240	11.705	5.09E-17	-13.852	3.36E-20
300	17.104	1.54E-24	-21.244	2.51E-29
360	10.425	5.28E-15	-12.619	1.05E-18
420	9.561	1.35E-13	-10.344	7.14E-15
480	11.465	1.20E-16	-13.428	1.36E-19
540	18.519	2.92E-26	-22.364	1.68E-30
600	10.350	6.98E-15	-15.879	5.71E-23
660	16.143	2.58E-23	-19.989	5.92E-28
720	1.451	1.52E-01	-25.856	4.65E-23
780	15.947	4.65E-23	-19.782	1.01E-27
840	-2.291	2.56E-02	-24.268	2.16E-32
900	9.193	5.45E-13	-11.862	2.93E-17
960	-0.775	4.42E-01	-20.856	6.57E-29

*Note: Values in shaded cells are calculated, but their absolute magnitudes fall below the recording device's threshold to accurately represent.

The numerical harmonic analysis quantifies and confirms what was observed visually, with a few important additions. First, whereas it was observed visually that both sensors showed signs of harmonic filtering on voltage waveforms, numerical analysis shows this effect to be most pronounced at the third harmonic. Because both sensors showed roughly the same attenuation coefficients, researchers questioned whether the recording equipment or the Traditional PT might be the cause of the measured difference, instead of the alternative sensors. To evaluate this, a National Instruments data-acquisition device was used to record Traditional CT and PT waveforms simultaneously with the DFA device connected to the same CTs and PTs. Voltage waveforms from the DFA and NI devices had third-harmonic values within 2% of one another. Given that both alternative sensors showed a difference of 30% from the PT value at the third harmonic, researchers believe the power-system PT may be amplifying this harmonic. In other words, the alternative sensors may be more correct than the Traditional PT at this harmonic. The reason for this is unknown but worthy of further exploration.

Numerical analysis also confirms the conclusion from visual inspection that Alternative Sensor 1 tends to attenuate higher-frequency current components, whereas Alternative Sensor 2 tends to amplify them. For Alternative Sensor 2, this effect increases approximately linearly for all current harmonics analyzed.

4. Summary and Conclusions

Electric utilities have an increasing number of technology options to enhance the performance and reliability of distribution systems. Electrical current and voltage measurements are foundational to many of these technologies, and certain minimum levels of sensor competency are required to provide these measurements and enable proper function. The required level of accuracy, frequency response, transient response, etc. depends on the application, but any application will have some basic minimum requirements.

Costs associated with deploying such technologies can be a significant impediment to their use. The installed cost of sensors constitutes a significant portion of the total cost. For historical reasons, conventional current and potential transformers (CTs and PTs) are the de facto standard for sensing, both in the substation and at distributed locations on a feeder. However, the installed cost of CTs and PTs can be significantly higher than the installed cost of some commercially available alternative sensors that are being used or considered by utility companies.

Results of this PSERC project fill certain gaps related to the knowledge of the technical performance of alternative sensors. Specific models of alternative sensors were selected by consensus with a group of industry advisors. Using conventional CTs and PTs as the baseline for comparison, the project evaluated the response of alternative sensors to a variety of naturally occurring phenomena on a distribution feeder. Sensor response was characterized under a variety of power-system conditions, including normal, harmonic-rich steady-state operation, capacitor switching, motor-start operations, overcurrent faults, and subtle arcing faults.

It was found that voltage waveforms produced by the selected alternative sensors were similar to those from conventional PTs, and even may be more accurate than conventional PTs in certain aspects. However, in general, current waveforms produced by the alternative sensors introduced marked changes in the characteristics of those waveforms.

Because of the poor results obtained from the current sensors, researchers involved in this project have not identified specific makes and models, particularly because the number of sensors tested in this project was too small to form statically valid conclusions. General conclusions reached by researchers are as follows:

- The accuracy and usefulness of any measurement or control system is limited to the quality and accuracy of the sensors used to provide inputs to that system.
- Even if a device had infinite resolution and sample rate, it would produce unpredictable results if the signals at its input terminals were not faithful representations of the underlying power-system quantities.

- It is the experience of the researchers in this project that application engineers may incorrectly assume sensor characteristics are “good enough” for a particular application.
- Performance of current sensors, in particular, may have substantial impact on fault-location algorithms and systems that many utility companies are deploying or considering.
- Although the linearity, frequency response, and transient characteristics of traditional CTs and PTs cannot be considered perfect representations of line signals, they are the de facto standard on which many technologies have been developed, and therefore the logical standard for judging alternative sensors.
- Data sheets for various types of alternative sensors typically specify absolute accuracy of the sensors, under specific test conditions. However, information from data sheets may be limited to steady-state performance of the sensors and/or be limited to response to pure, sinusoidal waveforms at the power system’s fundamental frequency. These specifications do not address the characteristics of the sensors under other common conditions, such as harmonics or transient conditions, including overcurrent faults.
- Based on side-by-side comparison of this project’s selected sensors and conventional CTs and PTs, practitioners considering the use of alternative sensors should not presume the adequacy of any alternative sensor. It is imperative that they fully investigate and understand a sensor’s performance and its implications for the application under consideration.
- There were substantial differences in the waveforms produced by the two alternative sensors used in this project. Therefore, an additional caution is that different types of alternative sensors should not be mixed for any given application, at least not without full understanding of the characteristics, their differences, and their ramifications for the application.

Utilities seeking additional information on the sensing characteristics of particular alternative sensors should be aware of a concurrent EPRI report which analyzed frequency and phase response characteristics for multiple alternative sensors in laboratory conditions, and reached similar conclusions about the shortcomings of sensors currently on the market [1].

Researchers remain hopeful that alternative sensing technologies will continue to advance and improve, so that they can be considered competent for more general use in advanced power-system applications.

References

- [1] Sensor Technologies for Real-Time Distribution System Monitoring. Electric Power Research Institute, Palo Alto, CA: 2009. EPRI Report No. 1017832.