Understanding the Limitations of Replaying Relay-Created COMTRADE Event Files Through Microprocessor-Based Relays

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Presented at the
20th Annual Georgia Tech Fault and Disturbance Analysis Conference
Atlanta, Georgia
May 1–2, 2017

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Abstract—**The Common Format for Transient Data Exchange (COMTRADE) file format is an IEEE standard by which power system disturbance data are stored for analyzing system events. COMTRADE files can be viewed using software from various manufacturers, and with a compatible test set COMTRADE files can be replayed into relays. COMTRADE files allow users to analyze system events and improve the protection algorithms used in relays. This paper highlights critical parts of the COMTRADE standard and discusses the limitations to replaying event files into a relay. It also provides a deeper understanding of COMTRADE files and how replaying system disturbances can yield responses in the protection elements different from those of the original event. The paper focuses specifically on system disturbances that involve frequency excursions and provides recommendations for replaying event files that contain frequency deviations.**

I. Introduction

Relay engineers use COMTRADE files to analyze system events and evaluate the performance of protective relays. COMTRADE files contain time-stamped, digital data that can be used to review and replicate a power system disturbance [1]. A relay test set reproduces these data and injects the corresponding analog and digital signals into a protective relay. The protective relay is then evaluated on its response. The results of this process are commonly assumed to be definitive. This paper demonstrates why this assumption is not always correct.

Time stamps, along with frequency, are both critical to the success of replaying a COMTRADE file into a protective relay. If there is an error in the recorded sampling rate used to acquire the data, the quality of the data in the COMTRADE file can be affected.

Even replaying COMTRADE files containing valid data into a relay can result in inconsistent responses. The amount of predisturbance data contained in a COMTRADE file matters. Adjusting the amount of predisturbance data can yield different relay responses for the same system disturbance. The time at which an event is replayed into a microprocessor-based relay is not synchronized with the processing interval from the original event. This is difficult to control, but it is necessary for a consistent relay response. This paper demonstrates how time stamps, predisturbance data, and relay processing times influence the data produced by a microprocessor-based relay for power system events with frequency excursions.

II. Review of COMTRADE Files

The digital data contained in a COMTRADE file conform to the IEEE C37.111-2013 standard [1]. This common format for organizing power system disturbance data is powerful. It allows a relay test set to accept event files from multiple intelligent electronic device (IED) and software providers, which provides a fair method to judge the performance of relays from different manufacturers. The IEEE C37.111-2013 standard divides each COMTRADE file into separate files, each with its own extension [1]. This paper describes three of these files that are useful for replaying events into a relay.

A. Header File

The header file has the file extension .HDR. The header is a text file meant to be read by the user. It provides context about the recorded power system disturbance and contains information about the substation and equipment that experienced the disturbance. The file can include nominal voltage ratings, relay settings, a substation name, and/or system parameters.

B. Configuration File

The configuration file has the file extension .CFG and is an ASCII text file. The .CFG file can be read by a relay engineer, but it is intended to be read by a machine (e.g., a relay test set). It is used to interpret the .DAT file. This subsection only describes information crucial to sampling data. Reference [1] provides a detailed description of the entire .CFG file.

The .CFG file stores sampling rate information using a pair of values called "samp" and "endsamp." The samp value represents the sampling frequency used to acquire the data in Hertz. The endsamp value describes the last sample in the .DAT file that the associated sampling rate applies to.

A COMTRADE file can accommodate fixed or variable sampling. If the value of endsamp is equal to the last sample number in the .DAT file, the COMTRADE file will use a fixed sampling rate throughout. In this case, only one set of samp and endsamp values will be defined in the .CFG file. If instead the COMTRADE file uses a variable sampling rate, the .CFG file will list multiple sets of samp and endsamp values sequentially. The total number of sampling rates for any COMTRADE file is equal to the "nrates" value stored in the .CFG file.

The time stamps of a COMTRADE file are determined by the values of nrates and samp. If both values are equal to zero, the sampling information is not defined. In this case, the timing is determined using the time stamps for each sample contained in the .DAT file. Alternatively, if the sampling information is defined in the .CFG file, the time stamps in the .DAT file are considered noncritical. The timing of the stored event is instead determined by multiplying the corresponding sample rate in the .CFG file by each sample number in the .DAT file. The latter method is the preferred COMTRADE timing method [1].

Time-stamp discrepancies can occur between channels. COMTRADE files resolve this issue using the “skew” value in the .CFG file. The skew setting is a timing offset (in microseconds) that can be applied to each analog channel individually to account for discrepancies.

This standard allows digital data to be collected from multiple sources. IEDs such as digital fault recorders, relays, and meters can capture data during a system disturbance. Data can also be created mathematically through software and formatted to adhere to the standard.

C. Data File

The data file has the file extension .DAT and can contain either ASCII or binary data. Both file types have a similar structure. For this reason and for the sake of brevity, this paper only discusses .DAT files in ASCII format. The .DAT file lists the samples taken during the power system disturbance in chronological order. The length of the event corresponds to the number of samples contained in the .DAT file.

Each sample in the .DAT file is represented as a row of information. The first entry in each row is the sample number. The next entry is the time stamp of when that sample was obtained. After the time stamp there is a series of entries that store the data values for each analog channel. A second series of entries contains the data values for each digital status channel. The total number of data entries associated with each sample is equal to two, plus the number of analog channels, plus the number of digital samples.

III. Sources of COMTRADE Files

A. Protective Relay-Created COMTRADE Files

Microprocessor-based relays can create COMTRADE files using either timing method described in the Section II (i.e., using a varying sampling rate or a fixed sampling rate). The timing method is dictated by how the relay samples the measured signal. Frequency tracking is a method commonly applied in microprocessor-based relays [2] [3] [4]. Frequency tracking can be achieved in hardware or firmware. Both methods must achieve an integer number of samples per power system cycle; doing so is necessary for accurate phasor calculations, as described in [2]. Microprocessor-based relays that use firmware-based frequency tracking sample the measured signal at a fixed rate and mathematically resample the signal at a variable rate to attain an integer number of samples per cycle.

Relays that use hardware-based frequency tracking vary the time at which samples are obtained. This is done through the use of an analog-to-digital converter to adjust the sampling rate based on the measured power system frequency [2] [3] [4]. Therefore, COMTRADE files created using the firmware-based frequency tracking method include the raw measured samples at a fixed sampling rate regardless of whether the system frequency is varying. COMTRADE files created using hardware-based frequency tracking can have different time intervals between when consecutive raw measured samples are recorded.

B. Software-Created COMTRADE Files

Relays can also generate event files that do not conform to the COMTRADE format. The event file format can vary depending on the relay manufacturer and can contain filtered and/or raw event data. Nonstandard event files can apply time stamps to data that do not match the time at which the data were originally sampled.

Software tools can be used to convert these event files to COMTRADE format for replaying and analyzing events. It is important to realize that relay-created COMTRADE files apply the measured raw samples and corresponding time stamp. However, when applying software to convert an event file that does not conform to the COMTRADE standard, the data samples can be inadvertently skewed when replaying the event. The degree to which the true event data are altered is contingent on two things. The first is how the data are stored within the nonstandard relay event file. The second is how the software interprets the data stored in the event file to generate a corresponding COMTRADE file.

For example, the software may only export the data as a fixed sampling rate. This can cause inconsistencies in the stored data when comparing them with a COMTRADE file where the sampling frequency varies throughout. When replaying an event file in which the original data are adjusted, the measured response can also differ from the original.

Nonstandard filtered event files are useful for event analysis because most operating quantities are derived from the filtered data. Filtered event files can remove the dc and harmonic content from the raw waveform. When filtered event files are used to create COMTRADE files, however, the removal of the dc and harmonic content must be considered carefully. Replaying filtered events into the relay can introduce errors because the data are altered from their original values. For instance, if a filtered event file is used for testing protection elements that block or restrain based on harmonic content, the outcome will differ from that of the raw event file. Additionally, some relay elements operate on root-mean-square (rms) quantities, and replaying event files using the filtered values can influence the replay accuracy.

IV. Relay Performance and Frequency

It is a common practice for relay engineers and technicians to evaluate relay performance by testing the operation of the individual protective elements set in the relay. With few exceptions, these elements have operating quantities that require current and/or voltage phasors. Errors in frequency cause errors in these operating quantities and can lead to the unintended operation of these elements [2] [3]. The performance of a microprocessor-based protective relay is at the mercy of its frequency tracking (or estimation) method.

V. Case Studies

To demonstrate inconsistencies when replaying COMTRADE files, a mathematically generated event varying the magnitude, phase angle, and frequency was created to simulate a power system disturbance. All of these variables can fluctuate during true system disturbances [3] [4]. The mathematically generated event was created using a sampling frequency of 8 kHz and a predisturbance length of 1 second. The data were created and formatted to conform with the COMTRADE standard using a MATLAB® script. The event included three analog signals representing the system voltage. The event was imported into a three-phase test set where it was then replayed into a hardware-based frequency tracking (varying sampling rate) relay.

A. Predisturbance Data Analysis

In addition to the relay processing time, the amount of predisturbance data can affect the reported response. The purpose of predisturbance data is to allow the imposed transients from the relay test set to settle. This occurs when the test set initializes the replay of the event file. The injected currents and voltage are at zero just prior to the test initialization and then immediately change to the first values in the event report.

The event file from a relay in the field can incorporate an unintentional delay between the steady state and the disturbance in the signal. This delay is included in the predisturbance data and is contingent on the criteria for the triggered condition. This means that if the relay triggers an event after a system disturbance, and the delay between the true disturbance and the triggered condition is significant, the predisturbance data in the event file could contain little to no information about the steady-state system conditions.

It is common for relays to have a setting specifying the amount of predisturbance data collected. These data can help identify the cause of the event by showing the system and relay states prior to the disturbance, and they are essential during the replay of an event. Depending on the observed analog or digital channel, the relay can respond differently based on the amount of predisturbance data.

To illustrate this point, the mathematically generated event was replayed into the relay three times using different predisturbance lengths each time. Fig. 1 displays the frequency measurement response for each of the cases.

The *Measured 1* trace contains 1 second of predisturbance data, the *Measured 2* trace contains 10 cycles (10/60 seconds) of predisturbance data, and the *Measured 3* trace contains 5 cycles (5/60 seconds) of predisturbance data. The *Measured 1* trace represents the system frequency measurement a relay connected to the power system would be subjected to. Specifically, the relay would have a full second of predisturbance data. A COMTRADE file generated from this event would reduce the amount of predisturbance data to match the predisturbance setting in the relay. Traces *Measured 2* and *Measured 3* represent the same disturbance replayed through the same relay but as COMTRADE files containing 10 and 5 cycles of predisturbance data, respectively. Each trace shows a relay response that yields a different calculated frequency. This is because the reported frequency value of a relay is heavily reliant on predisturbance data. Depending on the amount of user-defined predisturbance data, the relay response can differ.

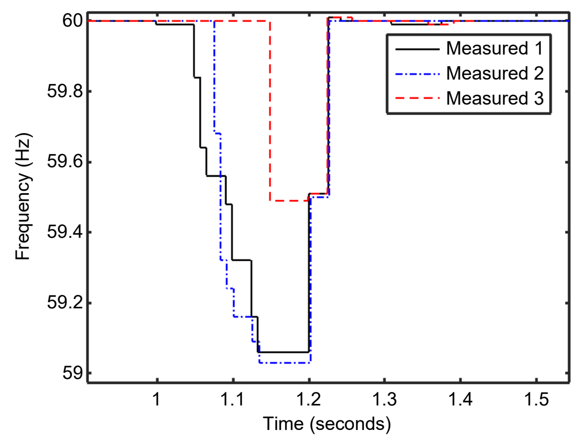

Fig. 1. Effects of varying the length of predisturbance data recorded within the event.

Most protection elements within digital relays are phasor-based. To maintain the accuracy of phasor quantities, the frequency of the measured signal must be known. To ensure that the replaying of a system event is unaffected by the predisturbance data length, perform tests to verify the proper setting length. The length of the predisturbance data should be selected so that sufficient data are provided to test the protection elements when a frequency excursion occurs.

B. Relay Processing Interval Versus Test Set Start Time

Protective relays can process measured data at a submultiple rate of a measured power system cycle (e.g., one-eighth of a power system cycle). The measured signal can yield different calculated responses based on when the computation is performed. To illustrate the measured differences caused by relay processing, including relay measurement error and test set error, the mathematically generated event was injected into a relay ten times.

Fig. 2 shows the frequency measurement for each time the mathematically generated event was replayed in the relay. Each frequency measurement for each of the ten tests is superimposed on each response.

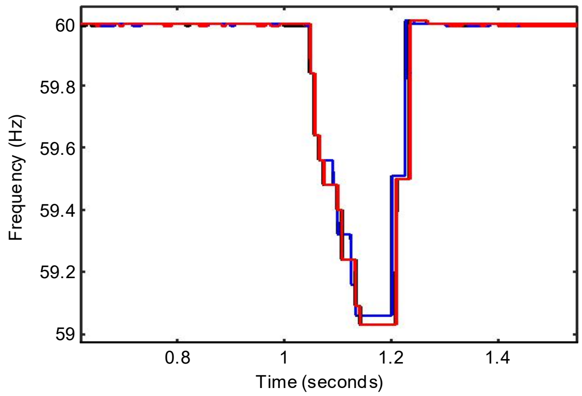

Fig. 2. Consistency test results for the mathematically generated event.

The difference of the maximum and minimum frequency measurements for the ten tests is shown in Fig. 3.

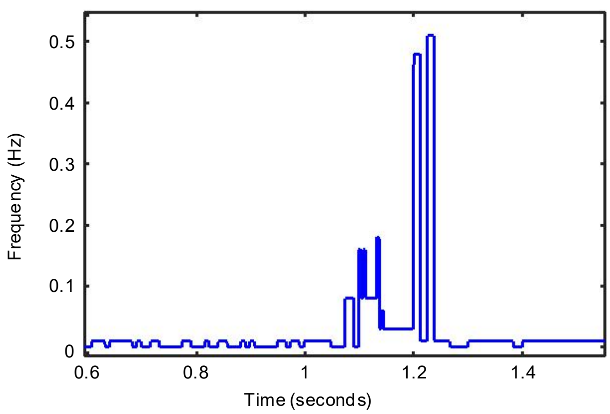

Fig. 3. Mathematically generated event measurement differences for the consistency test.

Fig. 2 and Fig. 3 show that a relay can produce different responses each time the COMTRADE file is replayed. The reported difference for this test was as great as 0.5 Hz. The duration of the variance is short, but it can vary the relay response. This is because the user (or test set) cannot inject the signals at the same point in the relay process interval consistently. The relay measurement error and test set error are embedded in the measurement differences. Subsequently, the relay can produce different responses when a COMTRADE file is replayed multiple times because the relay is not processing the data at the exact same point on the wave each time.

VI. Relay-Recorded System Event

For additional understanding, a relay-recorded system disturbance was analyzed. A hardware-based frequency tracking relay recorded the disturbance at 128 samples per cycle. The event retrieved by the relay was not exported as a COMTRADE file. Instead, it was retrieved in a format proprietary to the relay manufacturer. As discussed in Section III, software can convert such a file to satisfy the COMTRADE format. This event file was converted and then replayed into a relay with similar hardware and a similar frequency measurement method.

A. Predisturbance Length Analysis for a System Event

The measured event was triggered using the timed underfrequency element with 15 cycles of predisturbance data. Because the device was triggered using a timed element, the duration of the steady-state condition was less than the selected 15 cycles. There were approximately 8 cycles of steady-state data recorded on the actual event. Fig. 4 shows three relay responses to this event.

The *Measured 1* trace is the replay of the original software-generated COMTRADE event file with approximately 20 cycles of predisturbance data added. The predisturbance data were not substantial for replaying the event. In this case, it was considered prudent to add predisturbance data assuming a 60 Hz steady-state signal and an amplitude similar to that of the measured predisturbance signal.

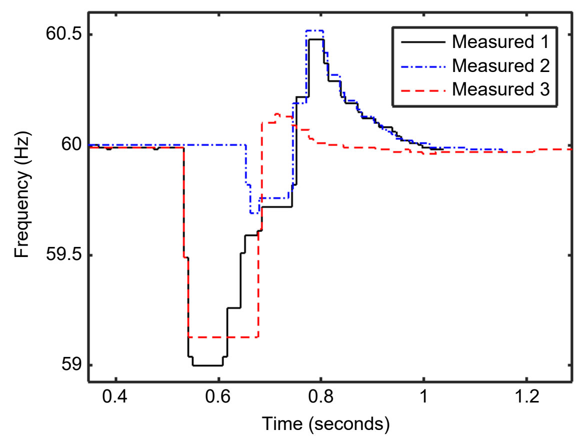

Fig. 4. Effects of varying the length of predisturbance data recorded within the relay-recorded system event.

The *Measured 2* trace is a direct playback response using the software-generated COMTRADE event file. The original response of the frequency measurement for the in-service relay is shown by the *Measured 3* trace. Notice that there are drastic differences between the *Measured 2* and *Measured 3* traces. One reason for the differences is the lack of predisturbance data.

The *Measured 1* and *Measured 2* traces are similar in the initial frequency change, but thereafter they vary significantly. There are two main reasons for this.

First, it is clear from the presented data that predisturbance information is essential. While including 20 extra cycles of data led to a response that closely resembled the original measured response (as compared with the *Measured 2* trace), the added predisturbance data were an assumption and not the actual measured data.

The second reason is that the original event file was not downloaded in the COMTRADE file format, and the time stamps were not stored within the relay event file for each measured sample. Instead, the software that created the event file calculated the time stamps based on the available data (measured frequency and sampling rate of the relay). This provided close estimates, but because the timing of the frequency tracking adjustments is made differently than that of direct frequency measurements, error was introduced [2]. Therefore, the event could not be successfully reproduced without substantial predisturbance data and actual time stamps for each sample.

Relay-created COMTRADE files do not exhibit the same time-stamp issue as software-created COMTRADE event files. Relay-created COMTRADE files assign the appropriate time stamps to the measured samples using the methods discussed in Section II. The accuracy of the time stamps for software-created COMTRADE files, on the other hand, is contingent on the information provided within the converted event file.

This system event demonstrates the importance of understanding the context in which the COMTRADE file was captured and created. The original relay response was influenced by a power system that was likely to be operating at a nominal frequency several seconds before the disturbance occurred. Reducing the predisturbance data to 15 cycles and then replaying the event into the relay would more closely resemble a cold start than the system conditions the in-service relay is subjected to.

It is also important to consider how the COMTRADE file was created. Software tools that convert event files to a COMTRADE format are limited by the data they are provided. Software-created COMTRADE files can be useful, but they may not produce the same relay response as the original event when they are replayed.

B. *Relay Processing Interval Versus Test Set Start Time*

The original event with added predisturbance data was replayed within a relay ten times, similar to the mathematically generated event. The measured frequency responses for each of the ten tests were similar to what was experienced with the mathematically generated event. The fluctuation in the measured response, seen in Fig. 5, is an artifact of the relay processing time, relay measurement error, and error introduced by the test set.

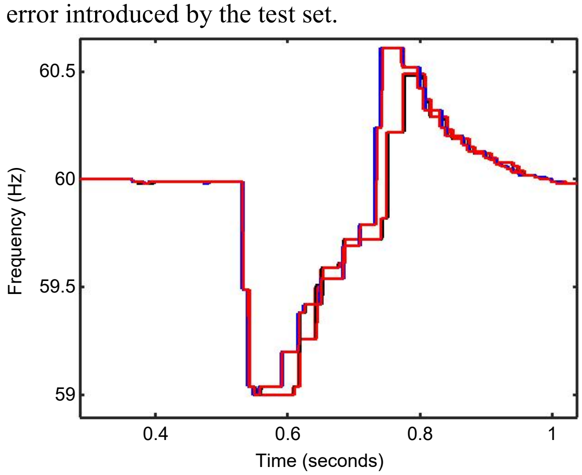

Fig. 5. Consistency test results for the relay-recorded system event.

Fig. 6 shows the difference of the maximum and minimum frequency measurements for the data presented in Fig. 5.

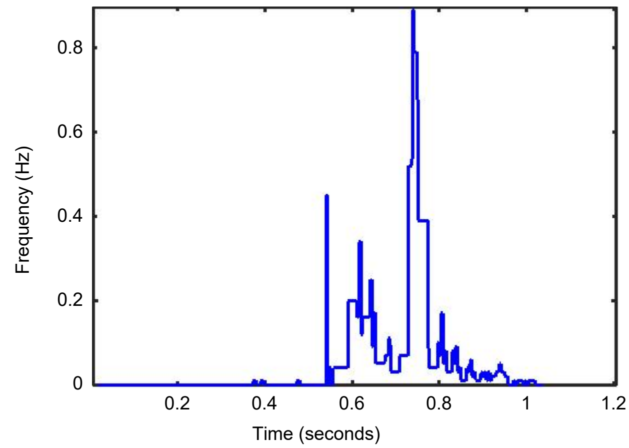

Fig. 6. Relay-recorded system event measurement differences for the consistency test.

The data presented display a maximum difference in excess of 0.8 Hz in one instance. This is even larger than that seen for the mathematically generated event difference shown in Fig. 3. Although the measured difference appears excessive, the duration of the difference is minimal. However, this could cause a protection element to respond differently for the tests performed. Therefore, it is essential to understand how the differences could impact the user during event playbacks.

VII. Conclusion

Replaying a COMTRADE file into a protective relay has limitations. Errors can be introduced if the data contained in the COMTRADE file have too little predisturbance information or if samples are time-stamped incorrectly by software. Set the predisturbance length long enough that the COMTRADE files can be replayed directly into the relay being tested while achieving minimal differences in the reported frequency. If the predisturbance data are limited, the replayed event can be inaccurate. To overcome this, the steady-state data can be added to the COMTRADE signal data. The basis of the added data assumes that the system frequency did not vary prior to the recorded disturbance. This can improve the relay response in some cases.

Responses from replaying a COMTRADE file through the same relay can be inconsistent because of other limitations, such as timing issues between the test set and the internal processing of the relay. The inconsistencies can be severe, especially for events with frequency excursions. However, COMTRADE files are still a useful tool for evaluating the performance of a protective relay if these limitations are understood by the relay engineer or technician.

VIII. References

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IX. Biographies

Brett M. Cockerham earned his B.S., summa cum laude, in 2014 and his M.Sc. in applied energy and electromechanical systems in 2016. Both degrees were awarded by the University of North Carolina at Charlotte. His graduate school research focused on power system frequency and frequency estimation methods. Brett joined Schweitzer Engineering Laboratories, Inc. in 2016 as a protection application engineer in Charlotte, North Carolina.

John C. Town received a B.S. in electrical engineering in 2009 and an M.S. specializing in power systems in 2014, both from Michigan Technological University. From 2008 to 2012 he worked for Patrick Energy Services (renamed Leidos in 2013) in Novi, Michigan designing transmission and distribution substations. The scope of his work included protection and control schemes, SCADA systems, and physical substation designs. From 2012 to 2014 he was employed at PowerSouth Energy Cooperative in Andalusia, Alabama working in the system protection department. There he designed system protection schemes and developed relay settings for transmission and distribution systems. Additional responsibilities included testing microprocessor-based relays and commissioning protection system designs. He joined Schweitzer Engineering Laboratories, Inc. in 2014 and currently works as a field application engineer focusing on system protection.

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