Applied Research Tools and Instruments (ARTI) Grant

An Analysis of Harmonics' Impact on Distribution Protection System Relays

Report #4 - Final Report

Smart Grid Integration, Protection and Control

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INTRODUCTION

As part of the ongoing LDC Tomorrow Fund project undertaken to create a model of the impacts which distributed generation sources will have on protection and distribution systems, Mohawk College undertook a study to identify the impacts of harmonics on distribution utility protection and control systems.

With field waveform capturing, construction of a power amplified waveform injector, and construction of a microgrid test bed now complete, the research is moving focus onto the protection and control systems in use by utilities, with specific focus on their performance characteristics when exposed to non-sinusoidal waveforms (fundamental waveforms contaminated with harmonics).

BACKGROUND

Due to the significant increase in non linear loads (such as modern appliances, renewable generation sources and plug-in hybrid/electric vehicles), harmonic are increasingly present in distribution systems. In addition to their impact on power quality, harmonic currents can have a devastating effect on power system protection performance, especially on the operating characteristics of protection and control systems which are designed to operate at the fundamental frequency [1].

It is well documented that protection systems are affected by the presence of harmonic components on voltage and current waveforms. Harmonic content can result in relay misoperation, which in turn results in discontinuity of service (interrupting the supply of electricity to a customer when there is no fault), or result in permanent fault being present and undetected due to a failure of the protection system [2].

Harmonics have varying impacts on both electromechanical, digital and intelligent electronic device (IED) based protection systems. Depending on which power quality parameter is distorted, the influence on the performance of digital protection relays will be different [3].

Since harmonic content can significantly influence the performance characteristics of protective systems, it is critical to fully evaluate the individual characteristics which are altered by harmonics, as well as the harmonic orders which are most likely to cause misoperation or missed trips.

METHODOLOGY

Protective relay performance testing was undertaken on both conventional and modern protection and control relay packages using a test setup designed to minimize the number of unknowns and provide results with high confidence. A function generator was used both to supply the waveform to the relay, and evaluate the timing difference between the moment when the waveform was applied, and the moment the relay tripped. AC waveforms (of sufficient magnitudes and currents to trigger a trip) consisting first of the fundamental frequency (60Hz) were applied directly to all the relays under test in order to determine a baseline performance time response (1 per unit). Harmonic distortion was then added to the generated waveform, and the timing response testing was repeated n times, until all of the tests had been evaluated for the connected relay. Data from these tests (currents and harmonic distortion levels) were downloaded from the from the function generator and plotted for mathematical and visual analysis. Figure 1 shows the hierarchy of testing completed on both types of protection equipment. Note that differential testing of electromechanical relays is planned for future work, but at this time has not yet been completed.

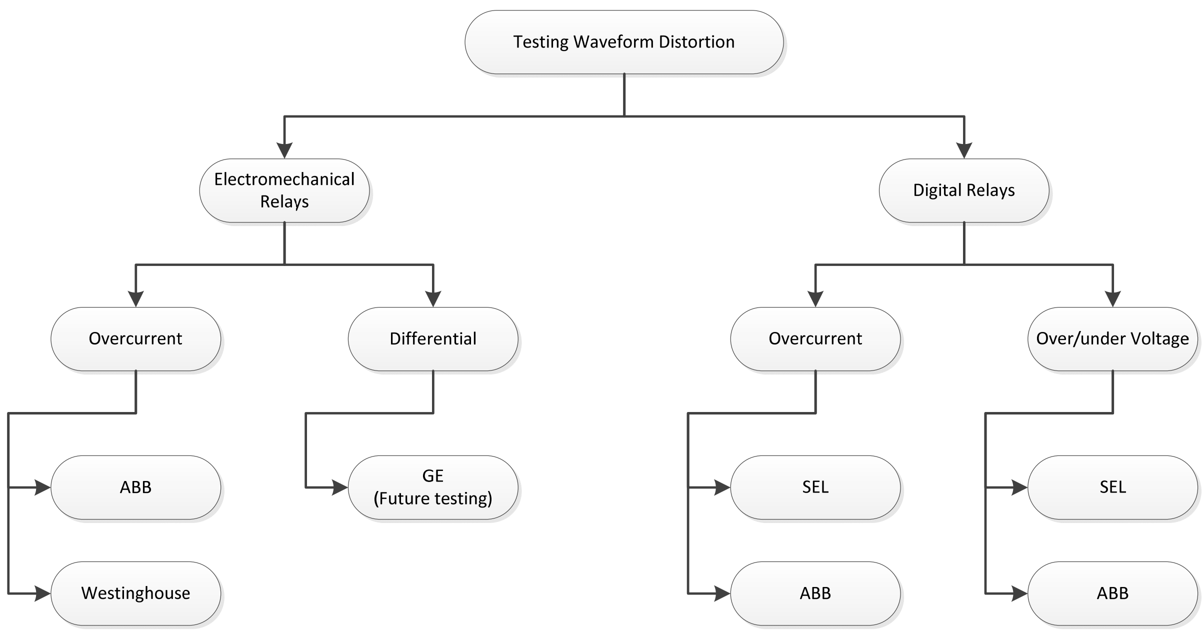

Figure 1 - Test Scope Overview

TEST SETUP & EQUIPMENT

An Omicron CMC 256 Plus high-precision relay test set was connected directly to the various relays being evaluated. Current outputs from the CMC 256 were connected to the relay without the use of current transformers or other intermediary components (figure 2). 24VDC was supplied from the CMC 256 to the relay's common control terminal, with the relay output connected directly to a CMC 256 digital input. This input was used (along with Omicron software) to determine the amount of time between the injection of the current (to cause the trip) to the relay and the time the relay activated.

Relays of the traditional, electromechanical, digital and IED relay types were tested. Table 1 lists the make and model of the relays which were used for testing.

Electromechanical	Digital
ABB CO-8	ABB REU 523
Westinghouse CO-11	SEL 451

Table 1 - Relays Tested

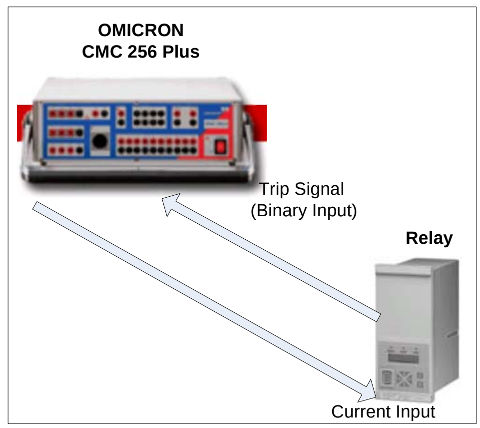

Figure 2 - Test Setup

MAJOR FINDINGS

1. INVERSE TIME CHARACTERISTICS

1.1 ELECTROMECHANICAL RELAYS

Waveform distortion greater than 10% has a significant and non-linear impact on electromechanical relay performance. However, with total harmonic distortion 20% or higher, two trends become apparent: the low order harmonics have less impact on the tripping time, as opposed to the higher order harmonics (greater than 19^{th}) which do not.

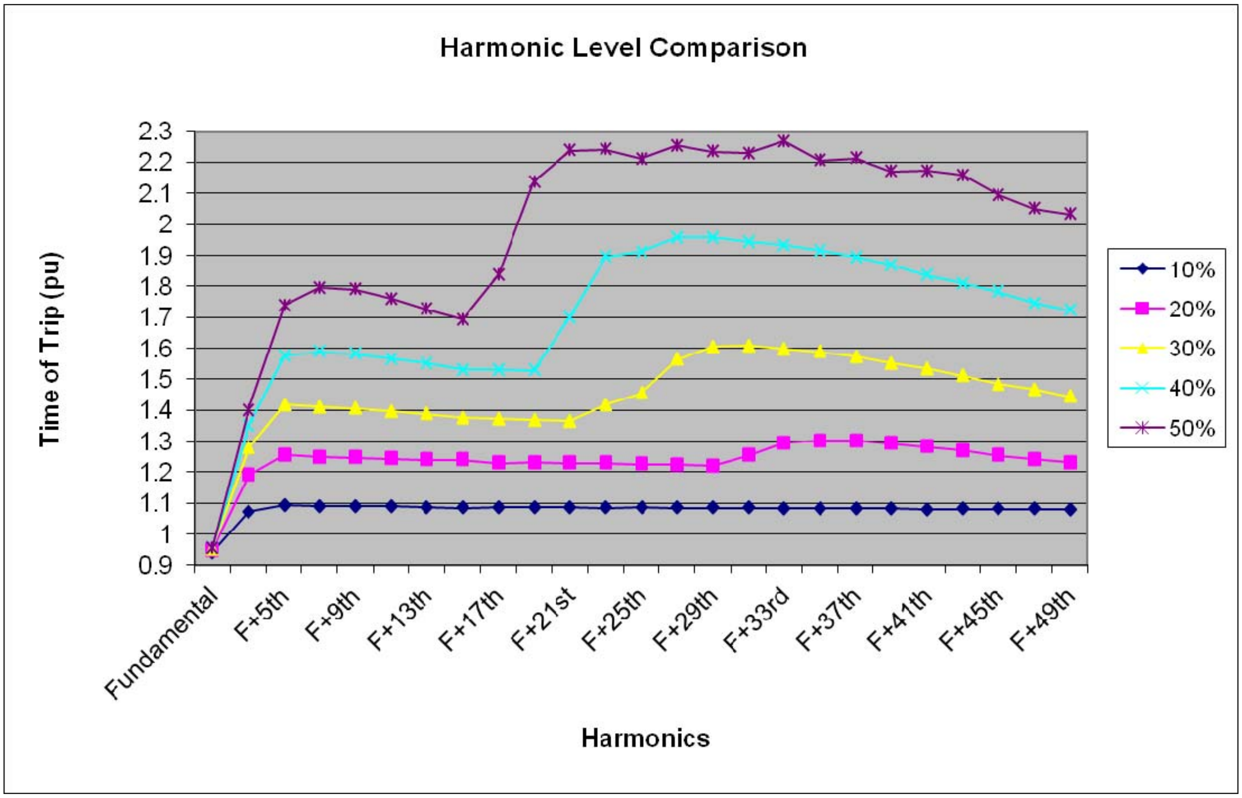

Figure 3 - Inverse Time Characteristics - Electromechanical Relays

1.2 DIGITAL RELAYS

For digital relays, harmonic orders or magnitudes have little to no effect on relay operation (the harmonics appear invisible to the relay). It has been observed by other researchers that a filtering circuit is eliminating harmonics at the relay input terminals before they can be scanned by the device [2]. Figure 4 illustrates the operation of an electromechanical relay vs. a digital relay. Note that the tripping time for the digital relay is constant regardless of harmonic content.

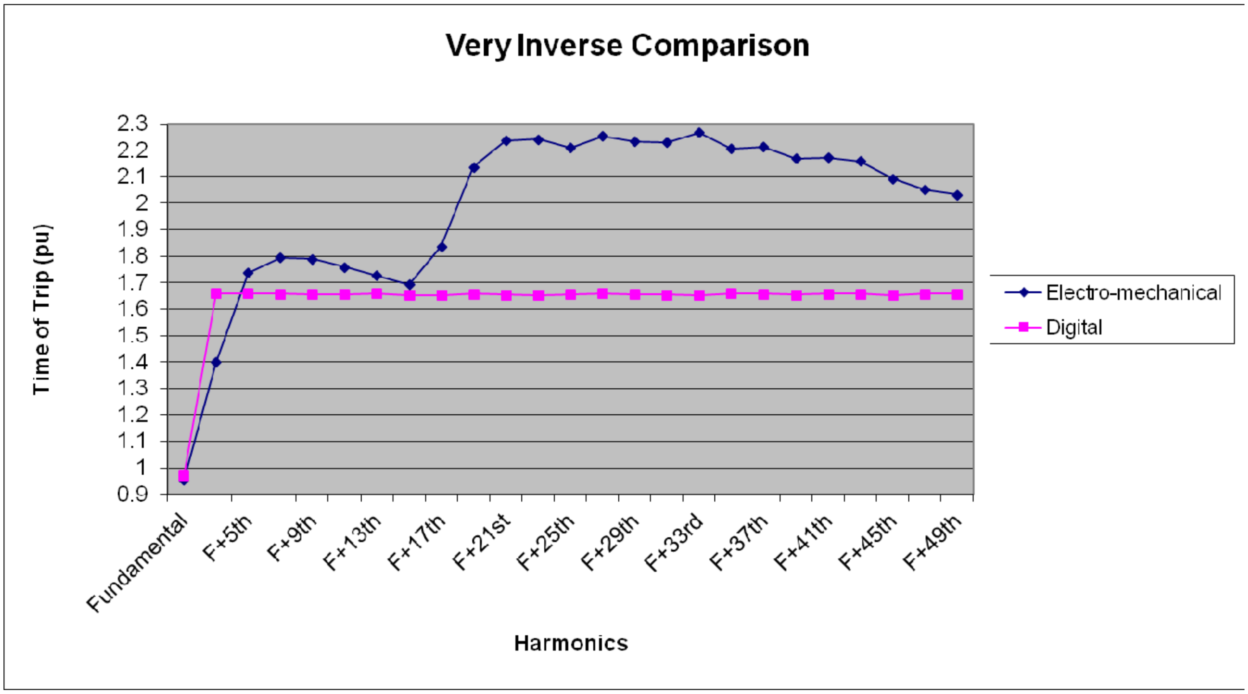

Figure 4 - Inverse Time Characteristics - Electromechanical vs. Digital Relays

2. TRIPPING TIME

2.1 ELECTROMECHANICAL RELAYS

2.1.1 HARMONIC ORDER & PHASE ANGLE

Tripping time was impacted by harmonics; specifically it was found that the tripping time is dependent on the harmonic order and phase angle. From figure 5, it is interesting that the 3rd and 5th harmonics affect the device in different ways with respect to tripping time. This variation is dependent on the harmonic phase shift relative to the fundamental. The phase angle is more dominant only for low order harmonics (3rd and 5th) whereas higher harmonics have minimal impact.

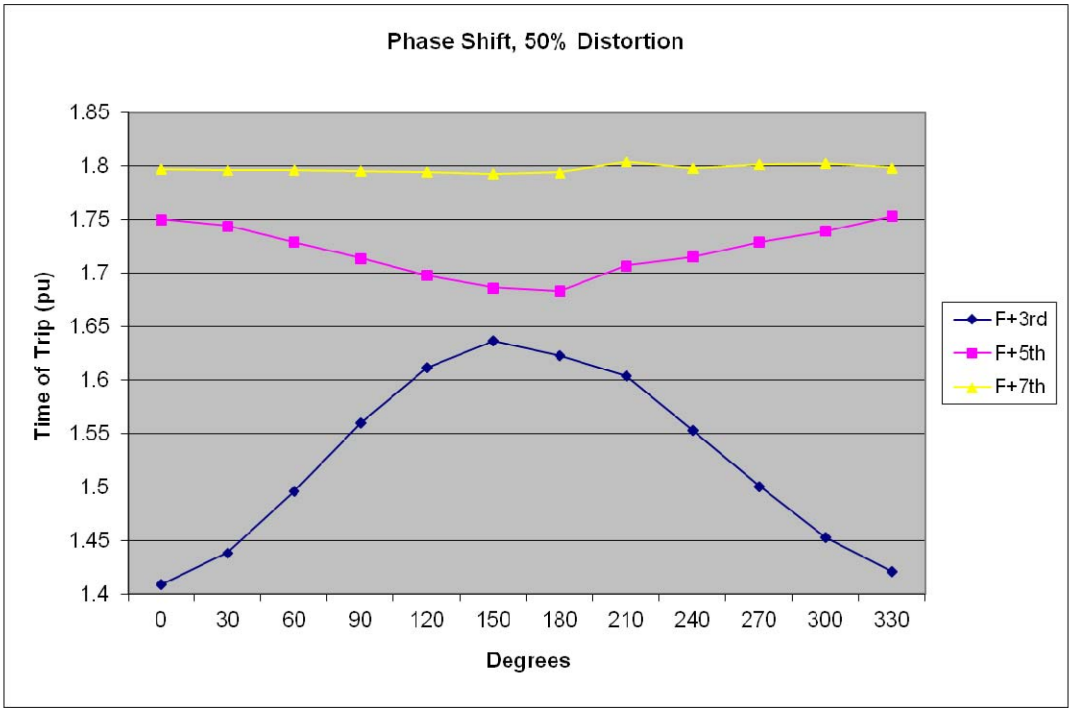

Figure 5 - Trip Time - Harmonic Order and Phase Angle

Figure 6 illustrates that for the 3rd harmonic, increasing distortion levels (as a percentage of the fundamental) results in a trend of increasing trip time.

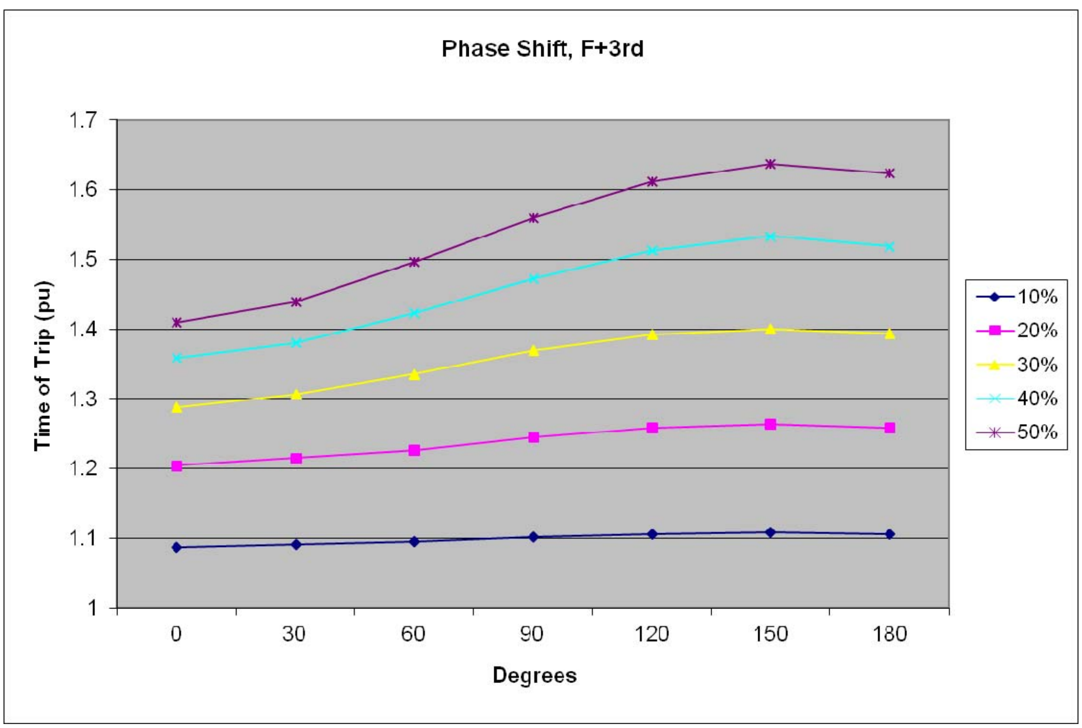

Figure 6 - Trip Time - 3rd Harmonic Distortion Percentage

2.2 DIGITAL RELAYS

2.2.1 HARMONIC ORDER AND PHASE ANGLE

Harmonic order had limited (and minimal) impact on the performance of the digital relays; however, changing the phase angle of the 3rd harmonic caused a noticeable impact on tripping time. Figure 7 shows that the 5th and 7th order harmonics were not detected by the relay, however the 3rd order harmonic at 120-270 degree phase shift resulted in an increase of tripping time. This can be attributed to the software algorithm for the DSP stage of the relay.

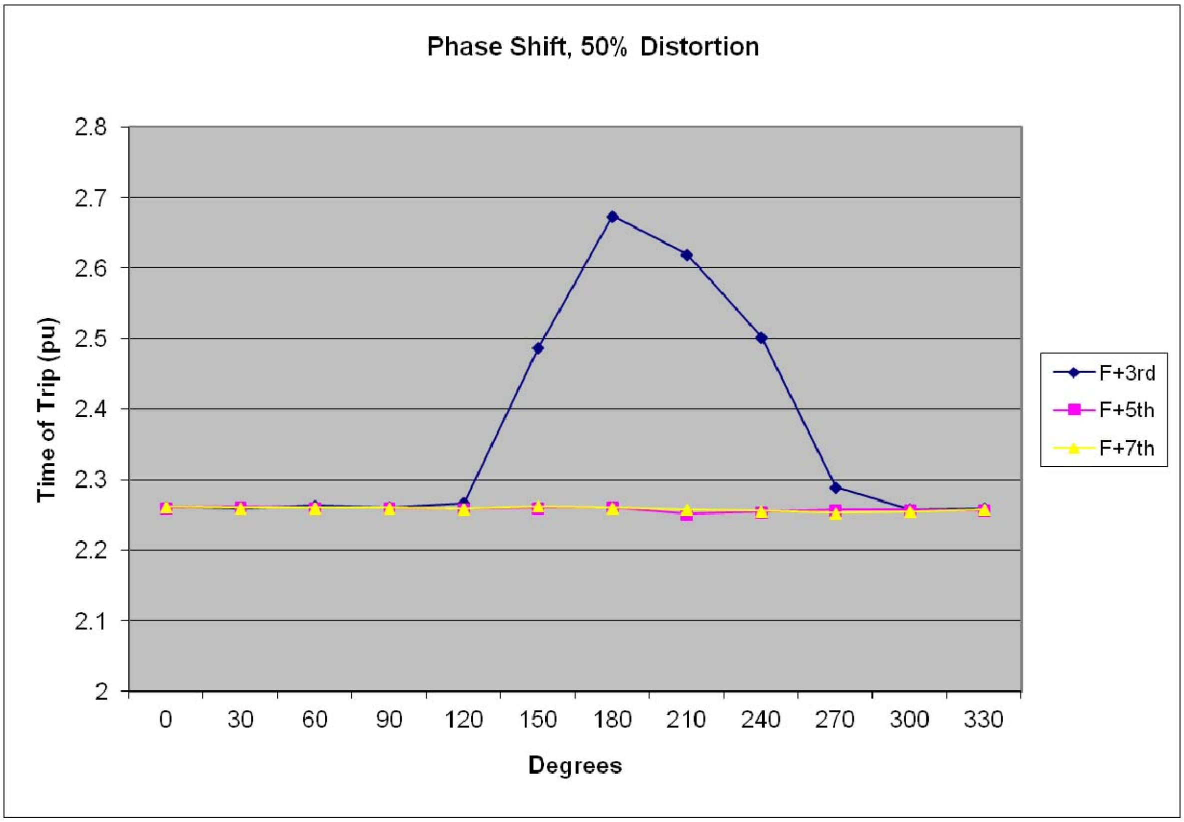

Figure 7 - Trip Time - Harmonic Phase Shifting

3. TAP ORDER

3.1 ELECTROMECHANICAL RELAYS

Tap order had a minimal impact on the performance of the relays tested.

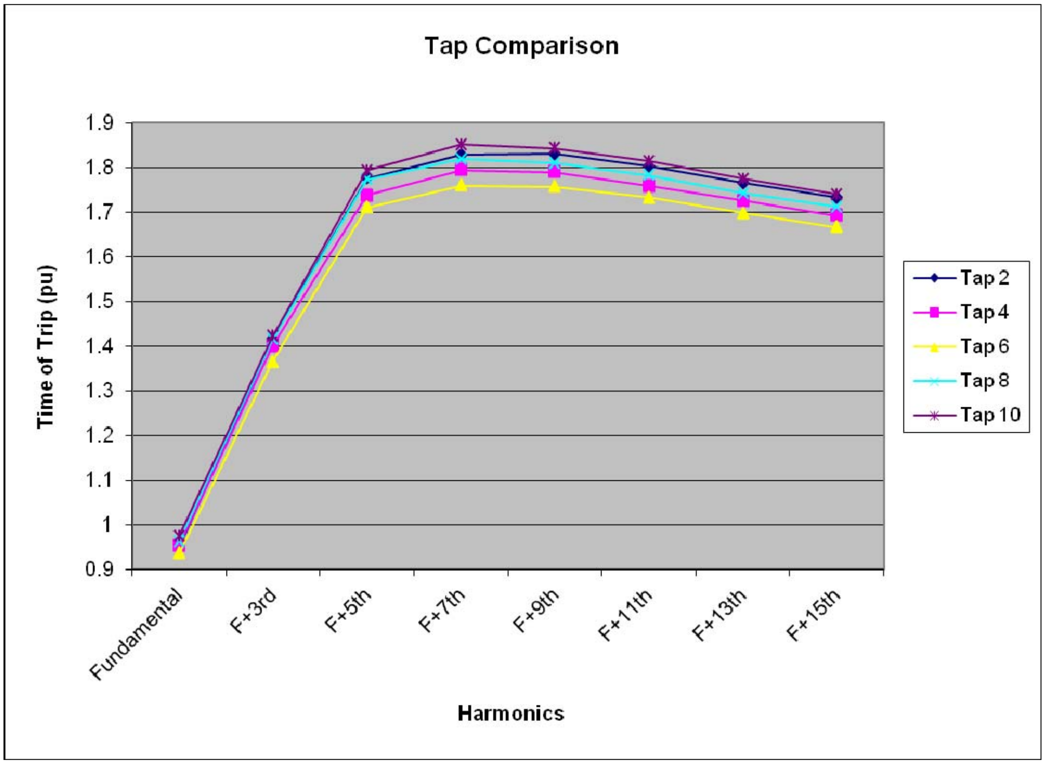

Figure 8 - Tap Order - Electromechanical Relays

3.2 DIGITAL RELAYS

As there are no tap connections on digital relays, there can be no impact to relay performance based on the tap setting.

4. MIXED HARMONIC IMPACTS

Mixed harmonics were observed to have a non-liner impact on relay performance; further investigation is needed to determine the mechanism of action.

4.1 ELECTROMECHANICAL RELAYS

Mixed distortion had a minimal impact on the tripping time of the electromechanical relays tested.

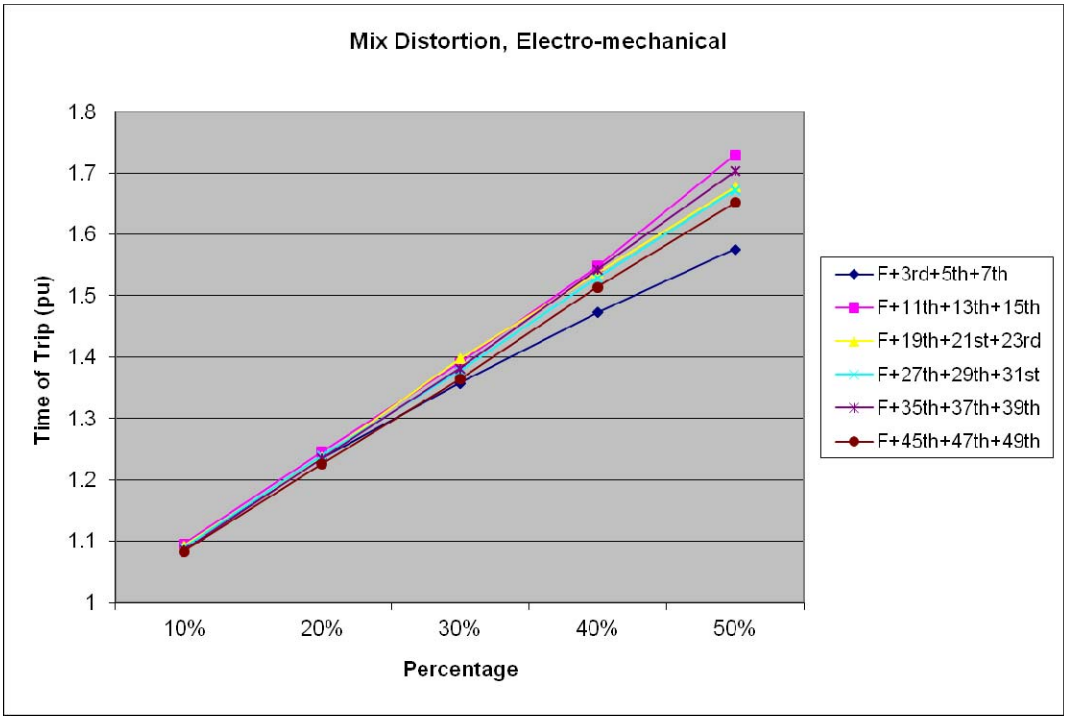

Figure 9 - Mix Distortion - Electromechanical Relays

4.2 DIGITAL RELAYS

There was no impact on digital relay tripping time due to mixed distortion.

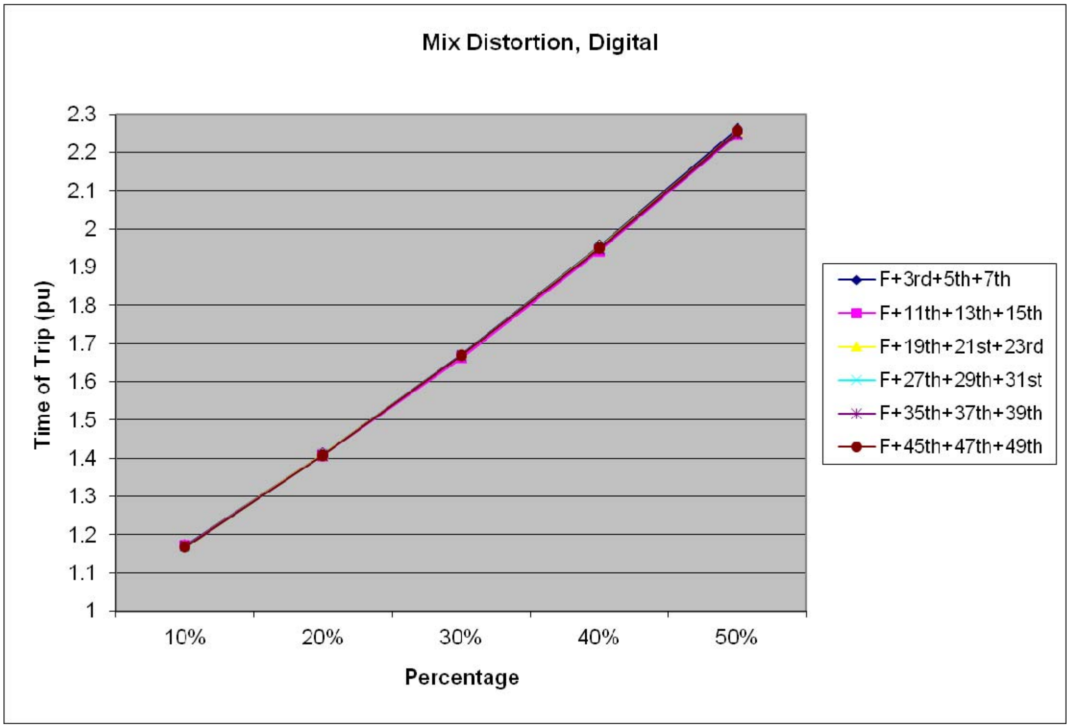

Figure 10 - Mix Distortion - Digital Relays

5. VOLTAGE DISTORTION

5.1 ELECTROMECHANICAL RELAYS

UNDERVOLTAGE

Harmonics of all orders (20% total distortion) resulted in essentially the same impact to the relay trip time. Figure 11 shows that a per-unit trip time of 1 (for fundamental voltage only) was observed as expected. Any harmonic order beyond the fundamental (up to the 49th) resulted in a per unit trip time of less than 0.3.

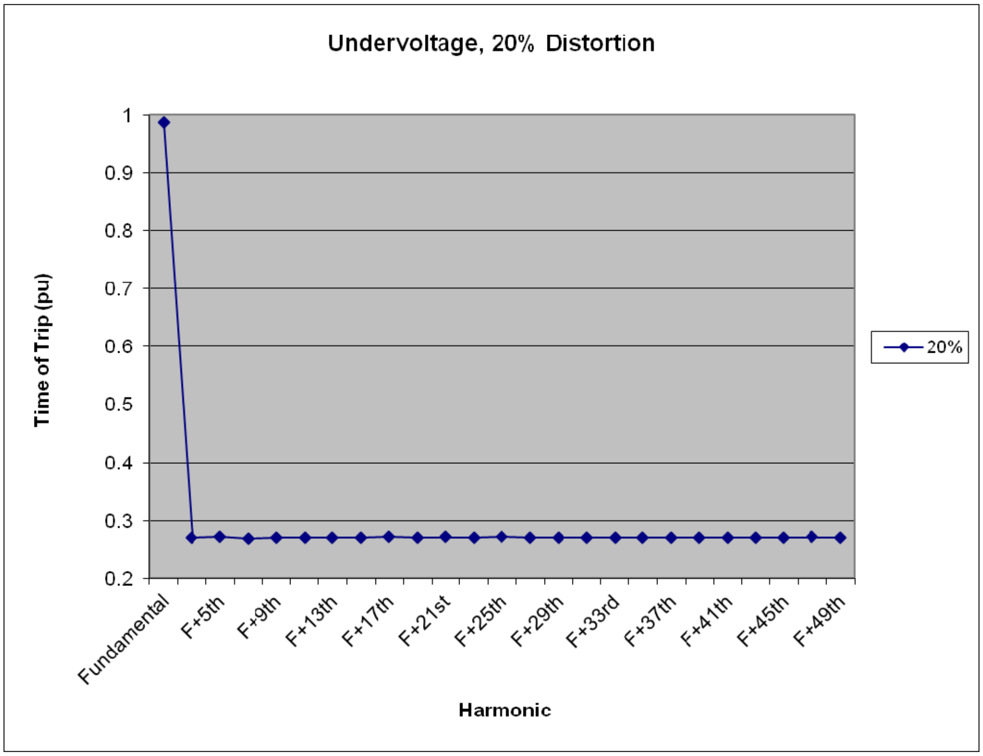

Figure 11 - Voltage Distortion - Electromechanical Undervoltage

OVERVOLTAGE

Harmonics of all orders (20% total distortion) resulted in essentially the same impact to the relay trip time. Figure 12 shows that a per-unit trip time of 1 (for fundamental voltage only) was observed as expected. Any harmonic order beyond the fundamental resulted in a per unit trip time of greater than 8.

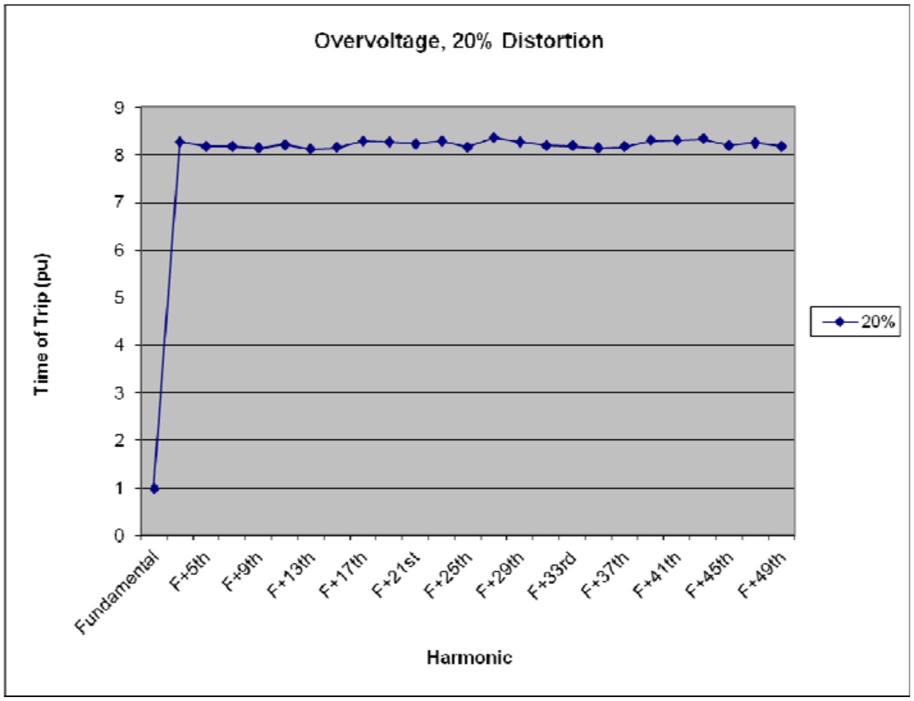

Figure 12 - Voltage Distortion - Electromechanical Overvoltage

5.2 DIGITAL RELAYS

UNDER VOLTAGE

No impacts were observed during undervoltage conditions, i.e. the relay performed as expected even in the presence of harmonics (20% distortion up to the 49^{th} order).

OVER VOLTAGE

Instantaneous overvoltage tripping time of the digital relays without harmonic distortion is defined as a PU time of 1 (approximately 0.037 seconds as expected). Any harmonic content at any order (20% distortion relative to the fundamental), resulted in the relay missing the trip condition; i.e. After 3 full minutes of testing under these conditions, the relay failed to trip.

CONCLUSIONS

For electromechanical relays, activation times were observed to be dependent on harmonic amplitude, order and phase angle. In contrast, digital relays are limited in that they can only respond to changes in magnitude of the fundamental.

Both types of protection relays tested provided a change in speed of operation that is inconsistent with the simple equivalent RMS value of the current. This makes it impossible to arrive at one simple solution as to how grading should be carried out when harmonics are present in an electrical system.

Data acquisition and filtering stages are essential parts of a digital relay since the presence of harmonic pollution on input signals may result in the malfunction of digital algorithms and therefore in the miss-operation of digital relays [2].

Modern digital relays, integrate a pre-filtering stage and an analog bandpass filter, which function to eliminate higher order frequencies. Such frequencies can produce aliasing and thus the presence of nonexistent components on sampled and digitalized signals can be detected. Since these kinds of relays have implemented a low pass filter before digital filtering, they do not respond to higher order harmonics. As a result, they are incapable of including energy within the higher frequency harmonics into their trip algorithms.

FUTURE WORK

Given that the harmonics' impact was significant and non-linear on electromechanical relays, additional testing on other types of electromechanical relays (differential protection from multiple vendors) will be undertaken.

Testing revealed that mixed harmonics resulted in a variety of performance changes to relay tripping time; however the mechanism of action was not determined during the experiments. Further experiments and analyses will be devised to determine the mechanism of action for mixed harmonic impacts on relay performance.

The test setup used to determine the harmonic impact on relay performance was deliberately made to be as simple as possible with only the required components (the waveform generator and the relay under test). While ideal for determining the impacts of harmonics on the relays directly, this configuration does not match that found in a typical utility environment. Current and potential transformers (CTs and PTs) will by the nature of their design act as filters for harmonic content, or will introduce errors and uncertainty of measurement when acting as sensing elements between the protective relay and the power system. As such, additional testing will be undertaken to determine the impacts of harmonics on CTs/PTs, as well as the impacts which CT/PT usage will have on relay timing performance in the presence of harmonic distortion.

The results indicate that the characteristics of feeders and distribution lines could be elements which would be affected by harmonic distortion. Specifically, if protection and control devices are unable to react to an overcurrent condition as the harmonic content is invisible to the device, the feeder line may experience overheating or premature failure. A study on the impacts of harmonics on feeder and distribution lines (with consideration given to the limitations of protection and control systems) will be carried out.

WORKS CITED

[1] A. Abu-Siada, H. Tin, M. Masoum and Y. Quian, "Improving the Performance of Smart Grid Over Current Protection Relays," IEEE.

[2] A. Medina and F. Martinez-Cardenas, "Analysis of the Harmonic Distortion Impact on the Operation of Digital Protection Systems," IEEE.

[3] I. Zamora, A. Mazon, V. Valverde, J. San Martin, G. Buigues and A. Dysko, "Influence of Power Quality on the Performance of Digital Protection Relays," IEEE.