# COMPUTER BASED HARMONIC SIMULATION AND TESTING FOR MICROPROCESSOR-BASED PHASE DISTANCE RELAY WITH PHASE LOCATOR.

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**Abstract-This paper addresses the effect of harmonics on the operation of Microprocessor-Based Phase Distance and Ground Directional Overcurrent Relay with Fault Locator. The testing facility consists of a computer-based three phase harmonic source, programmable three phase voltage and current amplifiers, and a digital to analog interface board. The software generates the harmonics and detects any trip action by the relay. Extensive experiments were performed in which the relays were subjected to a matrix of distortion frequencies, magnitudes, and phases. The results of these experiments are discussed, and suggestions on the applications of the relay are given.**

## I. INTRODUCTION

In recent years there have been considerable developments in industrial processes that rely on power electronic for their operation, and therefore generate current and voltage harmonics. A recent survey of Kansas utilities revealed that customers intend to install vast numbers of power electronic devices in the near future[10]. These devices produce distortion in voltage and current waveforms during normal operation and during fault conditions. And since these relays are one of the most important normal and emergency controls, they must retain their normal basic operation such as fault detection, fault location and fault interruption under distorted environments to provide complete protection and reliability needed by the distribution system. And since most of the U.S relay manufacturers calibrate their relays and publish performance data based on pure sine-wave currents and voltages.

Therefore the response of the protective relays to distorted waveforms is poorly documented[1-4]. So for these reasons a relay testing system and a software package were developed at The Wichita State University (WSU) to test relays for their response to distortion.

Since harmonics in current and voltage waveforms, can distort or degrade the operating characteristic of protective relays, depending on the design features and principles of operation[4]. And since microprocessor distance relays are built to variety of designs. It is not practical to generalize on their response to distorted currents and voltages. However, by applying basic principles to a specific relay, one should be able to predict the general effect of waveform distortion on that relay[3].

A canadian study documents the effects of harmonics on mechanical relays as overcurrent, overvoltage, balanced beam impedance relays and some others[5]. Our paper addresses the operation of a microprocessor relay, when distortion is introduced to the system. The proliferation of loads using power electronic devices is greatly increasing efficiency and productivity of electric utility customers. These loads, in which current is not linearly related to voltage, degrade the quality of power on the utility system by drawing non-sinusoidal currents. In general, harmonic distortion levels are increasing. Already, there have been numerous problems directly attributed to harmonic distortion. Utility customers are getting lower quality power which can upset digital equipments and other devices. Also harmonic distortion will affect the operation of the Microprocessor-Based relays, which is discussed here in details. Harmonic distortion can get into the power system in many ways, and there are many sources for this distortion, here are the most common sources of harmonic distortion, saturated transformers, industrial machines and motors, static var compensator, adjustable speed drives and electric transit systems (railway)[5-9]. This distortion can cause some problems as overvoltage and overcurrent on capacitor banks, resulting in breakdown or degradation, or interference affecting distribution-line carrier (DLC) system, these systems provide power utility load control.

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## II. STUDY METHODOLOGY

A testing system for measuring the effects of power quality disturbances on protective relay operation has been developed at WSU for the Kansas Electric Utilities Research Program. The system can test almost any protective relay or recloser device for operation with any voltage or current wave shape. Any test, including trip current, reach, and angle of maximum torque, can be conducted. The equipment for the testing program and the software package can supply three current phases of up to 8 A rms each, or one current phase of up to 45 A rms, and three voltage phases of 120 V rms or less. These will drive almost any protective relay, most of which require either three voltage and one current input, one voltage and three current, or only one voltage and one current input to test.

All output channels are independent; any waveform with any magnitude and phase angle can be supplied on each channel, regardless of the waveform on the other channels. This is necessary to properly simulate the transformer (CT) and potential transformer (PT) secondaries that normally drive the relays. Voltage and current circuits inside the relay are independent, and distortion on each phase and in voltage and current will, in practice, often all be different. The testing method is shown in Figure 1. All channels are controlled by the software, so a large number of tests can be performed, giving meaningful information about a device's response to power quality disturbances.

## III. COMPONENTS OF THE TESTING SYSTEM

Waveforms are generated by the computer and are output by a digital-to-analog (d/a) converter. These waves are then filtered, if necessary, to remove noise added by the d/a conversion process. The filtered signals are then amplified to produce up to three voltage and three current waveforms, which are the fed to the relay.

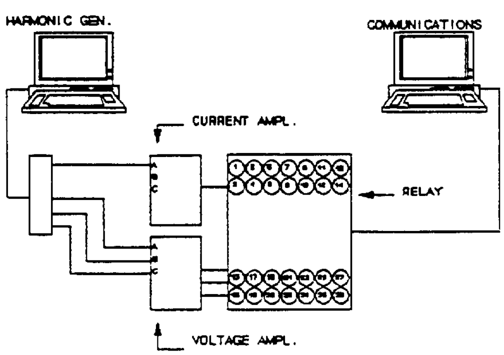


Figure 1. WSU relay test circuit.

A. Computer

The entire test system is based on an 80386 25 MHz computer. The 80386 processor is needed for its speed. Waveforms are generated digitally by using a C-language software package developed at WSU. Waveform data is generated using a complex Fourier series. Data are stored in an array, which is then sent to the d/a converter circuit for output.

B. Digital-to-Analog Converter

A commercial d/a converter circuit generates the analog voltage from digital waveforms. The circuit has 12-bit, ±10 V output (7.07 V rms ac). After amplification, the 12-bit output gives 1.7 mA per step accuracy in the current phases, and accuracy in the voltage phases of 29 mV per step. Analog output waveforms generated by the system are shown in Figures 2, 3, 4, and 5. Figure 2 shows current and voltage waveform without any distortion, Figure 3 shows 100% Total Harmonic Distortion (THD) in the third harmonic in the current waveform. Figure 4 shows 50% THD in the third harmonic in the voltage waveform, and Figure 5 shows third harmonic in both waveforms with 100% (THD). A digital input to the d/a circuit can be monitored by the computer to detect when the relay trips.

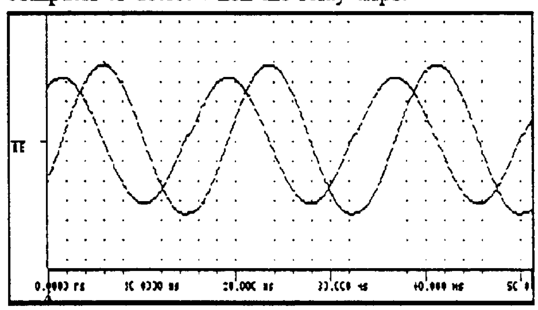

Figure 2. Voltage and current waveforms at 60 Hz.

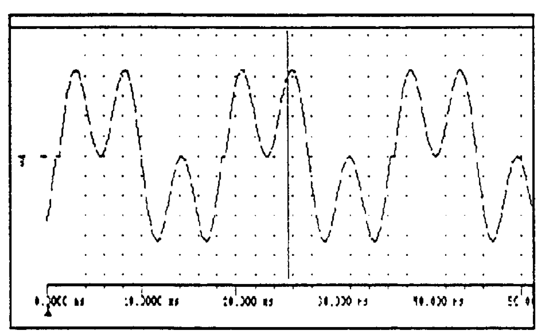

Figure 3. Third harmonic with 100% THD.

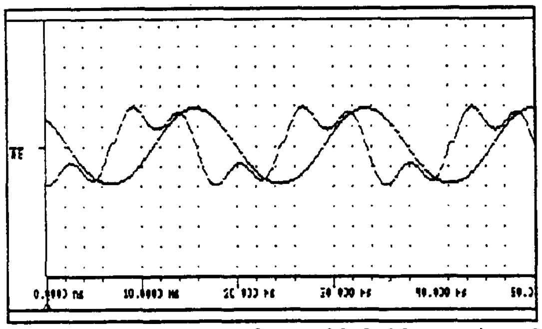

Figure 4. Voltage waveform with 3rd harmonic and 50% THD, and pure current waveform.

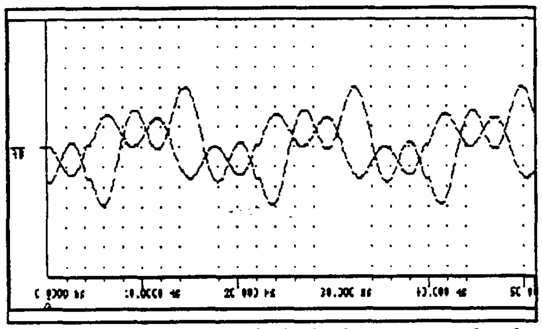

Figure 5. Third harmonic in both current and volta ge with 100% THD.

C. Current Amplifier

A current amplifier to change the 7 V rms ac waveform to 8 A ac rms was not readily available, so a circuit to do this is designed to do this at WSU. The amplifiers are solid-state. They take the ±10 V d/a outputs and convert them to a maximum of 8 A rms ac. Each current amplifier will drive a circuit with up to approximately 2.5 ohms impedance; this is significantly higher impedance than most relay current circuits. Any change in the input voltage to the amplifier gives a proportional linear change in the output current. Frequency response is flat up to 20 KHz; around the 333rd harmonic of 60 Hz. This is sufficient for testing a 60 Hz relay. A commercial current amplifier was also purchased that will provide one phase of up to 45 A rms. This amplifier is used to test relays with higher impedance, or relays that require higher currents.

D. Voltage Amplifier

The voltage amplifier needed to drive the relay voltage circuits was also designed and constructed at WSU. The voltage amplifier consists of three solid-state linear amplifiers that convert ±10 V to a maximum of 120 V rms ac. Frequency response is flat up to 20 KHz, and each amplifier will drive a 120 V circuit with 480 Ω impedance or more. This again satisfies the needs of almost any relay voltage circuit. A commercial three-phase amplifier that will provide up to 277 V, 6 kVA is also available.

## IV. TEST PROCEDURE

The test for each relay is begun by running the manufacturer's "Acceptance Tests" described in most relay instruction manuals. These tests are run with undistorted waveforms, and the results are compared with manufacturer's data to confirm that the relay is operating properly. This gives a starting point for distorted tests. As the tests are run with distorted waveforms, the undistorted test is repeated periodically to provide a benchmark. Distorted tests begin by distorting only the current waveform. This is usually what is seen in practice; a strong, clean voltage signal, with distortion in the current. Next the voltage alone is distorted. While this rarely occurs on an actual utility system, these tests are run to help understand and verify how the relay operates under varying conditions. finally, both voltage and current are distorted. The following summarize the tests:

1) 180 Hz to 900 Hz distortion, tests run every 120 Hz, with 100% THD.
2) 1 KHz to 20 KHz distortion, tests run every 1 KHz, with 100% THD.
3) For both 1 and 2, the phase between the fundamental voltage and the distortion voltages is varied from 0° to 270°, with 90° step size.
4) For selected harmonic frequencies the THD was varied from 10% to 100%, in 10% step size.

One should not be mislead by 100% THD, because large voltage and current THD does not occur in present-day power systems, and will never occur in future power systems, but it will give some idea on how the relay will respond as distortion increases. The assumed voltage THD present in the power systems should not exceed 20 to 30%, and the assumed current THD should not exceed 50 to 60%. The third harmonic is common for many loads, and is the lowest frequency above 60 Hz commonly encountered in significant magnitudes on a power system. The 7th harmonic is common in Kansas, and it represents a middle frequency of common harmonic distortion. Other harmonics gives an idea of how the relay responds to relatively high frequency distortion. Additional tests are run to clearly define the relays performance at all frequencies.

## V. RELAY

The phase distance and ground directional overcurrent relay with fault locator considered in this paper; may be used to protect transmission, subtransmission, and distribution lines. A fault locator is included which uses fault type, as well as prefault and fault conditions to provide an accurate estimate of fault location. Analog inputs from current and voltage transformers are delivered to the protective relaying elements and saved for additional features, such as metering and fault. locating. The relay elements process the analog data. Some intermediate logic is performed, such as over current supervision of the mho elements, directional supervision of the residual-overcurrent elements, and grouping of certain elements into zones. The states of the intermediate results and some other information are recorded in the relay word. The current and voltage inputs are isolated by magnetic input transformers. The signals are low-pass filtered, sampled by sample/hold amplifiers, and then multiplexed to a programmable-gain amplifier. Its output drives an analog-to-digital converter. This analog-input network gives the microcomputer measurements of the measurands four times per power-system cycle. The microcomputer consists of an eight-bit microprocessor, ROM for program storage, RAM for data storage, and EEPROM for storing the relay settings. The EEPROM saves settings even during power loss. Input/output devices connected to the microcomputer bus provide control of the output relays and targets, and for monitoring inputs, such as the state of the breaker contact. Other I/O devices provide communications for setting, reporting fault location, and other purposes. The relay is set and operated via serial communications interfaces, which connect to a computer terminal and/or modem or the protective relay terminal unit. The testing is done by applying the acceptance test suggested by the manufacturer, where the fault is 50 miles from the relay(for pure waveforms). Then the harmonics are introduced for the same fault, and the variations in the distance reported by the relay, under this distortion, are recorded and graphed.

## VI. RESULTS

The results of testing are shown in Figures 6 through 12. Figures 6 through 9 show the effects of current distortion only; voltage is pure 60 Hz. These figures show the change in fault location recorded by the relay as THD is varied. Each curve represent distortion at different frequency.

The effect of distorted voltage, with pure 60 Hz current, is shown in Figures 10, and 6. These figures show the results of varying the THD level at selected frequencies. When both voltage and current are distorted, the relay operates as shown in Figures 7 through 12. Figures 7 shows fault location with varying distortion frequency and phase. Figure 8 shows the effect of varying the phase between the fundamental and harmonic at frequency 180 Hz and 300 Hz. Figures 10, 11, and 12 present the result of varying THD levels in voltage and current at different distortion frequencies. For frequencies 420 Hz - 20 kHz; the phase between the fundamental and harmonic waveform in current and voltage, has no affect on the readings of the relay.

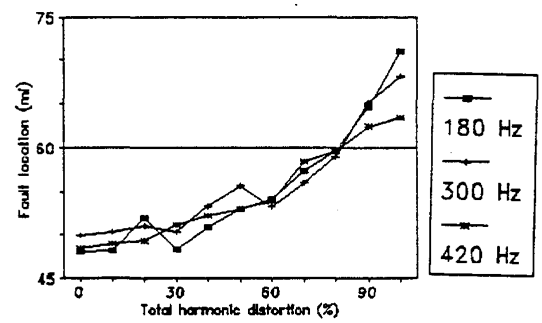


**Figure 6.** Fault location with varying current THD.

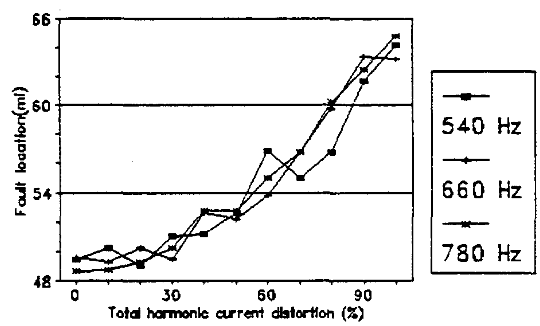


**Figure 7.** Fault location with varying current THD.

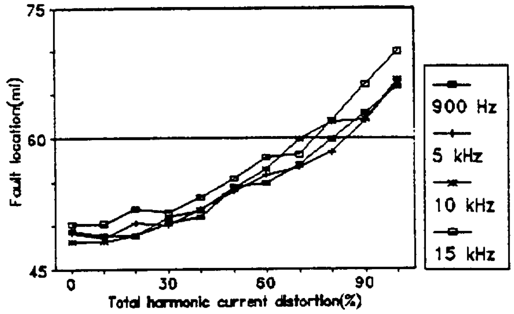


Figure 8. Fault location with varying current TH D.

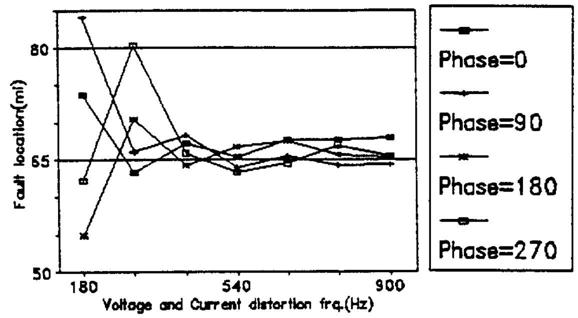


Figure 11. Fault location with 100% current and voltage THD.

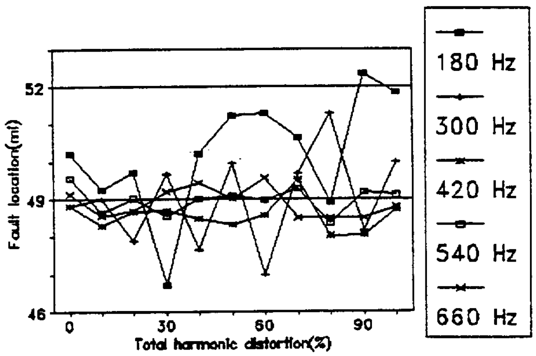


Figure 9. Fault location with varying voltage THD.

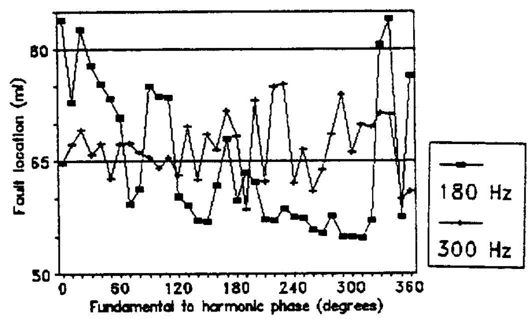


Figure 12. Voltage location with 100% V & I.

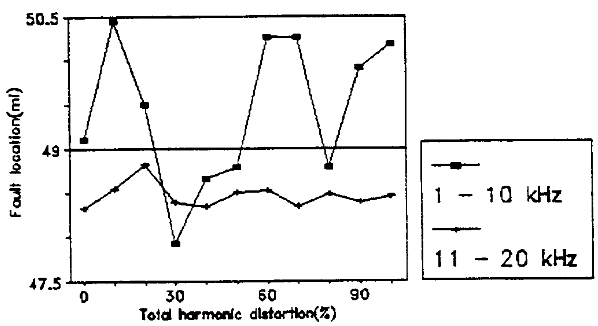


Figure 10. Fault location with varying voltage THD.

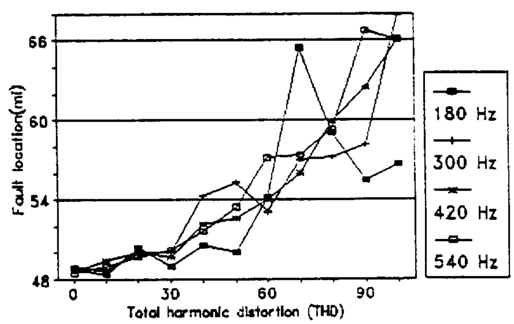


Figure 13. Fault location with varying V & I THD.

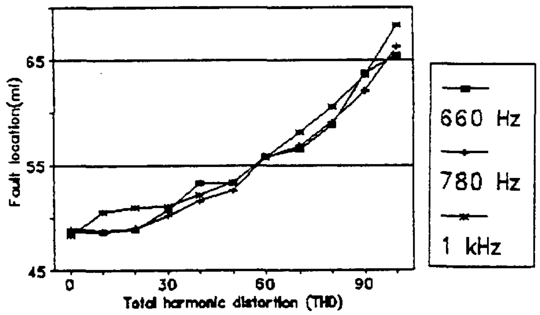


Figure 14. Fault location with varying V & I THD.

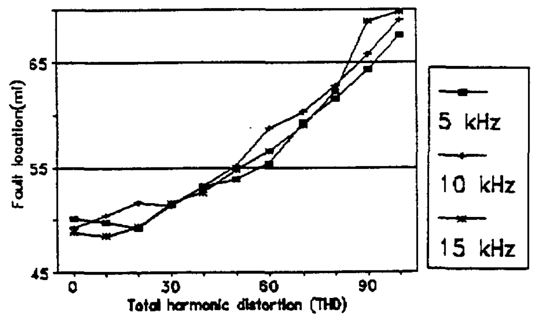


Figure 15. Fault location with varying V & I THD.

A. Current Distortion

**Total Harmonic Distortion Effects**

Significant changes from manufacturer's specifications in fault location can occur with 30% or greater THD in current waveform. This is for all frequencies.

**Frequency Effects**

Distortion at any frequency can affect the fault location reported by the relay.

**Phase Effects**

When only current is distorted, the phase angle between the fundamental current and harmonic current does not affect the fault location reported by the relay.

B. Voltage Distortion

**Total Harmonic Distortion Effects**

A slight change of $\pm 3$ mile from the manufacturer's specifications in fault location reported by the relay. This is for all frequencies.

**Frequency Effects**

Voltage distortion at any frequency has a slight change on fault location reported by the relay.

**Phase Effects**

When only voltage is distorted, the phase angle between the fundamental voltage and harmonic voltage does not affect the fault location reported by the relay.

C. Voltage and Current Distortion

**Total Harmonic Distortion Effects**

Significant changes from manufacturer's specifications in fault location reported by the relay, can occur with 40% THD or greater.

**Frequency Effects**

Distortion at any frequency can significantly change the fault location reported by the relay.

**Phase Effects**

The phase between fundamental and harmonic waveforms affects the fault location reported by the relay, when the frequency is at 180 Hz or 300 Hz only. This effect is a random effect, and does not follow a certain pattern.

## VI APPLICATION OF RELAY IN DISTORTED ENVIRONMENT

A. Current Distortion Only

**Constant THD, 30% or less:** Relay will trip as specified by manufacturer. Therefore changes in the settings are not required.

**Constant THD, 40% or greater:** Fault location will increase from the manufacturer's specifications. New locations can be calculated from Figures 6, 7, 8, and 9.

**Varying THD:** Variations in fault locations will occur as shown in Figures 7, 8, and 9. If these variations cannot be tolerated, the relay should not be used.

**Distortion at multiple frequencies:** When distortion is present at multiple frequencies, the THD value for all frequencies combined, and the single frequency at which the largest change in trip time occurs, should be used in evaluating the application.

B. Voltage Distortion Only

**Constant THD:** Relay will trip as specified by the manufacturer's. No changes in trip setting required.

**Varying THD:** No variations in fault location occurs.

**Distortion at multiple frequencies:** When distortion is present at multiple frequencies, the THD value for all frequencies combined, and the single frequency at which the largest change in trip time occurs, should be used in evaluating the application.

C. Voltage and Current Distortion

**Constant THD, current and voltage 40% or less:** Relay will report the fault location as specified by the manufacturer's. No changes in trip settings required.

**Constant THD, current and voltage 50% or more:** Relay report the fault at different location from the manufacturer's specification.

**Varying THD:** Variations in trip impedance will occur as shown in Figures 10, 11, and 12.

**Distortion at multiple frequencies:** When distortion is present at multiple frequencies, the THD value for all frequencies combined, and the single frequency at which the largest change in trip time occurs, should be used in evaluating the application.

## CONCLUSION

The operation of this relay is effected by the presence of the harmonic distortion. Test results show that the relay will report the wrong fault location. The relay is frequency sensitive up to 20 kHz, the highest testing frequency, and it is not phase sensitive when voltage and current are distorted. When distortion is present at multiple frequencies, the THD value for all frequencies combined, and the single frequency at which the largest change in fault location occurs, should be used in evaluating the application.

The results presented in this paper apply only to the one relay tested. A number of other relays have been tested at WSU, and it has been found that each responds differently. Detailed results are available for each relay tested, and testing continues on other relays.

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