RMS Measuring Principles in the Application of Protective Relaying and Metering

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Abstract

There are a variety of protective relays using different measuring techniques to provide protection for equipment and lines. These include electro-mechanical, solid state, and numerical relay platforms. Within each group, various types of front-end filtering exists. Protection Engineers should understand how today's and yesterday's relays differ in their approach to protection so they can better provide protection for feeders and other equipment.

Introduction

From our days in college we learned that rms (root mean square) values of voltage and current represent the effective energy transferred to a load by a periodic source compared to the equivalent dc source. Simply stated, the periodic current $\boldsymbol{I}_{p\ (rms)}$ will deliver the same heating on a load as $\boldsymbol{I}_{(dc)}$. This is important to protection engineers because we are often concerned about the damage done to equipment by the heating caused by overcurrent events. We are also concerned with maintaining coordination with fuse links, which respond to ambient heat as well as the heat generated by fault currents. True rms is, simplistically defined as the rms of a waveform that includes all harmonic components [1]. Thus True rms values of voltage and current play a large role in determining the success of the applied protection scheme.

It is also known that any periodic waveform can be described by an infinite series of sine and cosine functions containing integer multiples of a base frequency, called a Fourier Series. These frequency multiples are referred to as *harmonics*, and the base frequency is called the *fundamental frequency.* This concept is important to relay engineers because harmonics appear in non-linear loads and therefore in fault currents.

Protective relay designs vary in the way that they respond to harmonic currents. Electromechanical relays are, essentially, low pass filters. Microprocessor relays are either designed to filter out harmonics, or in rare cases respond to true rms[1] current (and voltage). Which is correct? The answer, as is usually the case in relaying, is neither. In this paper we will give the relay engineer "food for thought", and make some recommendations.

The way that protective relays respond to harmonic distortion is well studied. Many papers have been published dealing with the testing of various types of relays. These analyses are revealing, but don't answer the question "Should relays react to, or filter out harmonic distortion?" Most of today's numerical relays filter out non-fundamental harmonics, therefore not giving an accurate refection of the true rms heating effect the current and voltage is having on the protected equipment. Is this always the preferred practice? As we all know, the vast majority of the historical relay installed based is electromechanical. How do these relays respond to harmonics, and can coordination be maintained with a numerical device?

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[1] Note: Although the definition of True rms includes all harmonics, this paper recognizes a practical limitation of measuring all harmonics due to current transformers and sampling frequency and will simplistically term True rms with common harmonic values seen in the industry (i.e. harmonics of the 13^{th} and less).

We first study the concepts involved in true rms metering of harmonic waveforms. We then discover the types and origins of harmonic distortion in fault currents. In a laboratory setup, electromechanical and numerical relays are subjected to various levels of harmonic currents, and their trip times are examined. From the analysis of the testing we can see the dramatic effect harmonics have on the performance of the relays. From there, the algorithm for a true rms numerical relay is studied to understand the technology that is available today. Finally, conclusions are drawn, answering the questions posed above.

RMS Voltage and Current

What is rms, and what does it mean to us? rms stands for Root Mean Square. It is the effective value of a voltage or current that will produce the same heating effect as the identical dc value of voltage and current. It can be derived from the following.

The amount of energy delivered to a resistor in T seconds for a dc circuit is

$$W = (V^2/R) \bullet T \qquad (1)$$

The amount of energy delivered to a resistor by a sinusoidal voltage is

$$W = \int v^2/R \; dt \qquad (2)$$

Where

$$v = V_m \sin(\omega t + \theta) \qquad (3)$$

In order to have the two energies the same, we therefore have

$$(V^2/R) \bullet T = \int v^2/R \; dt \qquad (4)$$

$$V^2/R = 1/T \int v^2/R \; dt \qquad (5)$$

$$\boldsymbol{V_{eff} = \sqrt{1/T \int v^2 \; dt}} \qquad (6)$$

From the relationship above we can see that the effective voltage of a periodic function is the *square root of the mean value squared,* or abbreviated by the initials “rms”. This is defined as the True rms [1], however, for a single frequency sinusoidal function, this expression reduces to the familiar

$$V_{eff} = V_m/\sqrt{2} \qquad (7)$$

For this paper however, we will be dealing with harmonic frequencies, so this simplified form for the effective voltage or current will not be helpful.

Fourier Series

The basis for this analysis comes from Fourier's discovery that a periodic function can be represented by an infinite sum of sine or cosine functions that are harmonically related [4]. That is, the period of any trigonometric term in the series is an integral multiple, or harmonic, of the fundamental period of the periodic function. The result is the familiar form of the Fourier Series

$$f(t) = a_v + \sum_{n=1}^{\infty} a_n \cos(n\omega_o t) + b_n \sin(n\omega_o t) \qquad (8)$$

Where ω_o is the fundamental frequency, and a_v, a_n, and b_n are the *Fourier coefficients*. The integral multiples of ω_o, 2 ω_o, 3 ω_o, 4 ω_o, and so on are known as the *harmonic frequencies of* $f(t)$. The Fourier coefficients give rise to the *amplitude spectrum* of $f(t)$, which is a useful graphical representation of its harmonic content.

For instance, in Figure 1 below, the periodic function has third and fifth harmonic content.

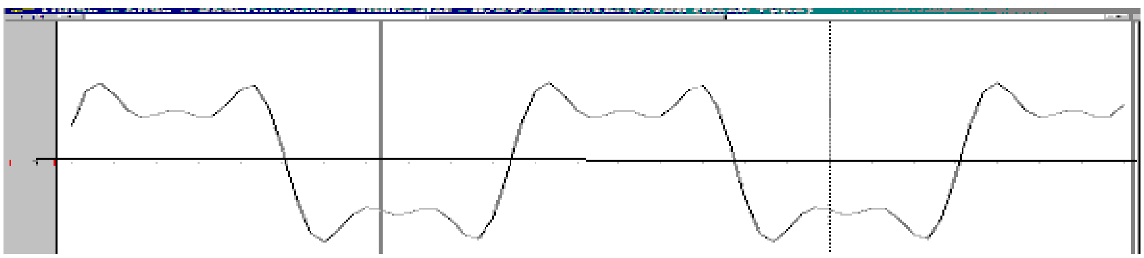

Figure 1

The Fourier coefficients can be read directly from the Fourier spectrum analysis in Figure 2.

Harmonics

Channel Name: (1) IL A

	DFT Peak	DFT RMS	DFT Angle	% of Fundamental	% of TrueRMS
H1	7073.396	5001.646	256.435°	---	87.572%
H2	11.839	8.372	257.171°	0.167%	0.147%
H3	3508.544	2480.915	47.272°	49.602%	43.438%
H4	0.547	0.387	195.141°	0.008%	0.007%
H5	1702.401	1203.779	197.281°	24.068%	21.077%
H6	0.581	0.411	43.727°	0.008%	0.007%
H7	1.920	1.357	229.799°	0.027%	0.024%

True RMS (Samples): 5711.445 Calculated RMS (Harmonics): 5711.441

Figure 2

That is, given the fundamental frequency is 60Hz or 377 radians per second

$$f(t) \approx 0 + 7074 \sin(377t) + 3509 \sin(3 \cdot 377t) + 1702 \sin(5 \cdot 377t) \qquad (9)$$

Charting the coefficients produces the amplitude line spectrum of $f(t)$.

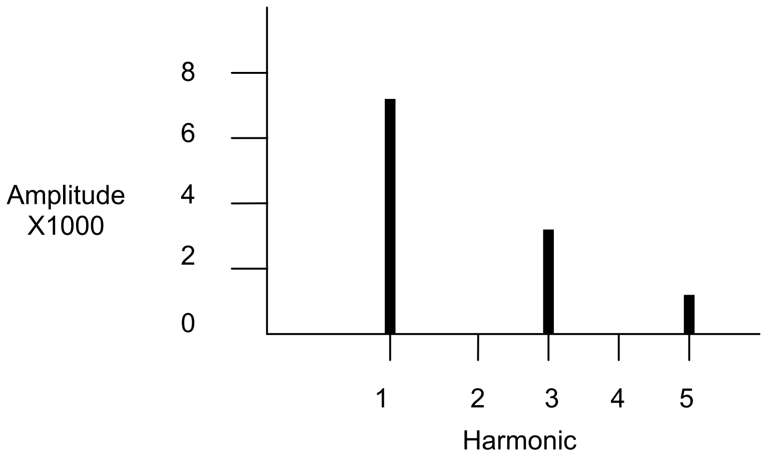

Figure 3

By charting the envelope of the line spectrum, we have the familiar phase spectra plot below. This plot is useful in determining the locus of points that make up the harmonic content of *f(t)*.

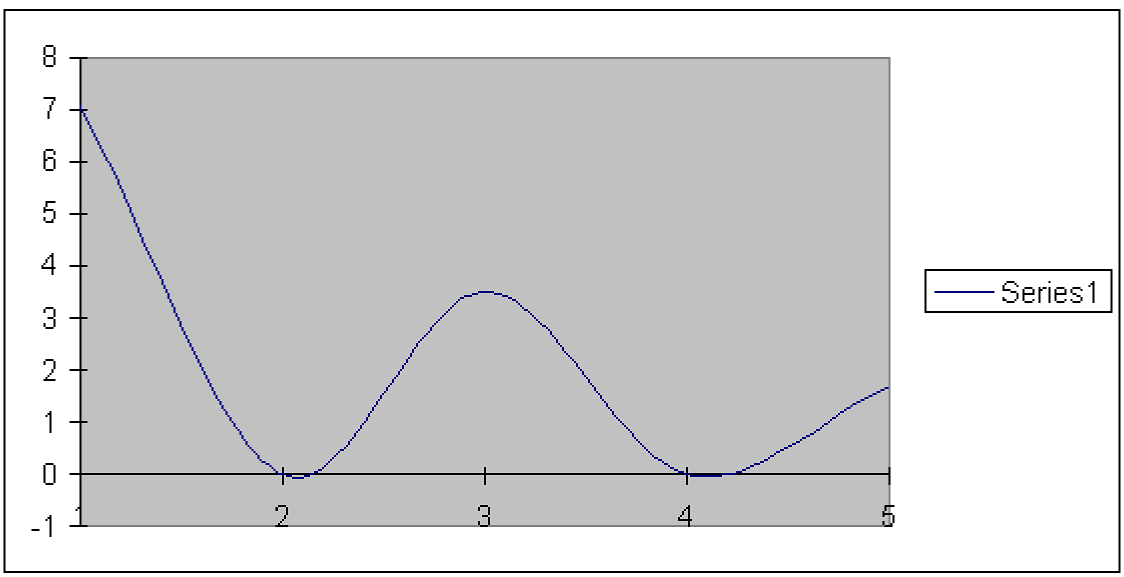

Figure 4

Harmonics in Power Systems

It is well known that harmonics exist in power systems. These can be classified into two categories, those present in loads, and those present during faults. The protective relays in the affected circuit are connected to the power system at all times. It therefore experiences the effects of both load and fault harmonic currents and voltages. This paper deals with overcurrent conditions, and thus the subject of harmonic frequencies in voltages won't be discussed in depth here. That is not to say that they are insignificant, rather that the analysis of such, will be saved for future research.

It is the job of the relay engineer to protect equipment from damage. But, damage from what? It may seem trivial, but the answer is heat. Heat caused by overcurrent conditions damages transformers, conductors, generators, and capacitors. In fact, the IEEE publishes guidelines for protecting such equipment in the form of transformer damage curves, conductor annealing curves, and generator overload withstand curves. We will not discuss these documents here, except to say that for the most part they are based on the ability of the equipment to withstand heat.

The heat produced in an electric device is given by

$$P = I^2_{rms} R \tag{10}$$

The current, I, is given as the rms value, or effective value of the magnitude of the applied current. In power systems, the circuits generally include inductive components, so the R in the above relationship denotes the real part of the impedance triangle. It is noted here, however, that the current component is the **magnitude** of the combined real and imaginary parts of the applied current.

Below is a diagram showing one half cycle of distorted waveform superimposed onto a perfect sine wave.

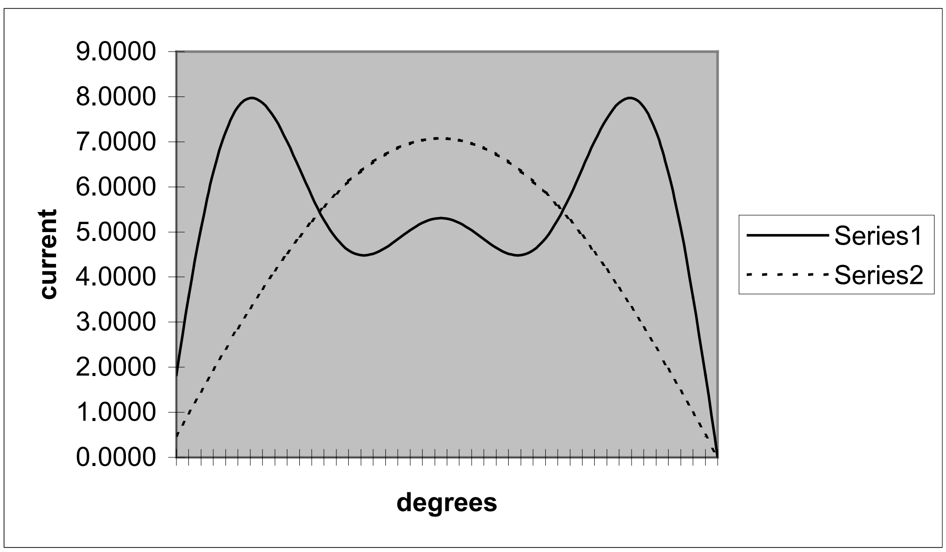

Figure 5

The dashed line is,

$$f(t) = 7.07\ sin(\omega t)$$

where the rms value is 5.0 amps. The solid line is the graph of

$$f(t) = 7.07\ sin(\omega t) + 3.54\ sin\ (3\omega t) + 1.77\ sin\ (5\omega t)$$

It is obvious from the graph that the area under the solid curve is greater than that of the dashed line. The true rms value of this current is approximately 5.73 amps, 14.6% higher than the fundamental. This added current would produce 24% more heating than the fundamental.

Causes of Harmonics in Power Systems

We summarize below some of the ways that harmonic currents (and voltages) creep into distribution networks. The relay engineer is concerned with load and fault related causes, as both have an effect on the performance of the protective relays.

Loads

Harmonics occur as the result of non-linear consumption of power by the connected load. Industrial loads such as arching furnaces in steel mills, computer equipment in call centers, or six pulse rectifiers in motor drives are common contributors of harmonic distortion. The effect on the power equipment is to cause heating in transformers, reactors, fuses, and conductors. In transformers and conductors, this ambient heating causes the damage curves to shift downward, effectively reducing the amount of time the equipment can withstand an overcurrent condition. Load also preheats fuses, reducing their operating time, and therefore complicating coordination with protective relays.

A typical Kansas distribution feeder was modeled by Wichita State University in [7]. A six pulse rectifier was modeled at the end of the feeder representing a three phase rectifier supplying an adjustable speed drive. A line to ground fault was initiated near the substation, and the results are shown below [5]. Note fifth harmonic currents exceed 26% of fundamental, with 7th order harmonic exceeding 18%. This experiment clearly shows that relays and reclosers can be subjected to significant current and voltage distortion due to non-linear loads.

HARMONIC NUMBER	FAULT DISTORTION AT					
	BUS 1		BUS 8		BUS 17	
	I %	V %	I %	V %	I %	V %
5	0.00	2.10	26.43	8.64	15.26	20.08
7	0.00	1.49	18.78	7.58	12.09	16.78
11	0.00	0.11	1.42	0.82	2.64	1.34
13	0.00	0.09	1.17	0.78	2.92	0.98

Figure 6

Capacitor banks are more susceptible to overvoltage than overcurrent [4]. Traditionally, capacitor overvoltage settings are based on a pickup 110% of rms voltage. If the protective device filters out all but the fundamental voltage, then the bank is clearly under protected. Newer capacitor designs have higher withstand capabilities, but the retrofit with these newer units cannot be counted on when protection is considered. Shunt capacitor banks absorb harmonics, causing eventual failure due to overloads. If protected by overcurrent relays that are insensitive to harmonics, the relays may not adequately protect the bank [5].

Geomagnetically Induced Currents (GIC)

GIC can cause high levels of harmonic distortion in power systems, providing the risk that a conventional protection system may not be adequate to protect transformers, capacitors, or generators. Geomagnetic disturbances (GMD) give rise to the GIC phenomena, and are tracked in the US by the Space Environmental Service Center[4]. This agency assigns indices to GMD events corresponding to the severity of magnetic fluctuations. In the six years from 1988 to 1993, there were 14 GMD events that created major disturbances on the North American power system. This is not a high number, but many US and Canadian utilities are installing GIC monitoring sites to keep records of the events.

Distortion levels are significant. Measured levels by Hydo-Quebec and BC Hydro exceeded 40%, while simulated levels have exceeded 44%. A more complete discussion of GIC is contained in [4].

Arcing Faults

Arcing faults occur when a fault arc is extinguished at the zero crossing, but restrikes as the voltage recovers in each half cycle [6] . The speed of the recovery voltage is dependant upon the X/R ratio. The actual true rms value of the fault will be less, with the fundamental component being reduced by up to 20%. Figure 6 shows a typical line-to-ground arcing fault [6].

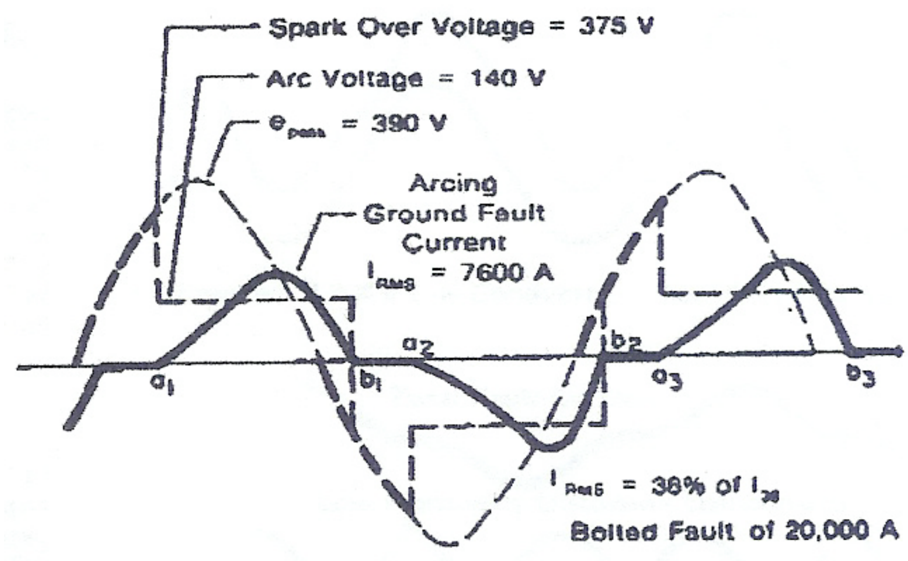

Figure 7
Arcing Fault [6]

Recovery Inrush

Recovery inrush occurs after a permanent fault is interrupted and then re-energized by circuit auto-reclosing. A fault on a feeder will cause one or more phase voltages to collapse. This causes the station transformer to partially de-energize one or more windings. When the breaker is reclosed by the action of the feeder relay, the station transformer will be re-energized, producing an inrush condition on the transformer. The resulting current becomes distorted with high 2nd and 3rd harmonic.

The figures below show a recovery inrush event at a NW utility. The current shown has a true rms value of 2300 amps. The sampling rate of the recording device is 32 samples per cycle. It can be seen that the waveform is rich in second harmonic (38%), as well as a lower value of 3rd (20%). This phenomenon is documented in [8] as well, but it is not specifically referenced as "recovery inrush".

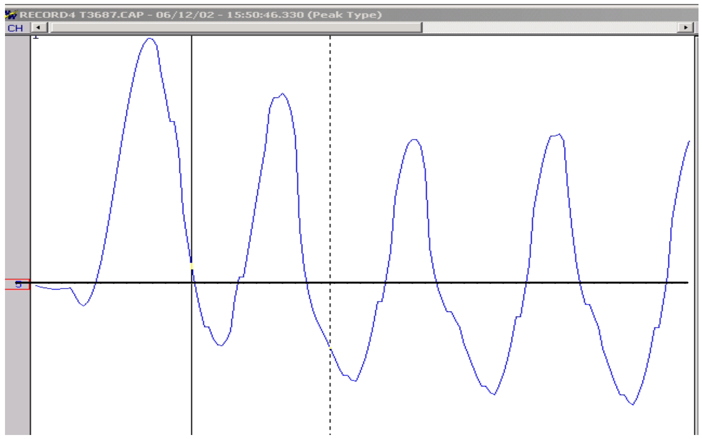

Figure 8
Recovery inrush

Harmonics

Channel Name: (5) W2 Ia

	DFT Peak	DFT RMS	DFT Angle	% of Fundamental	% of TrueRMS
H1	7938.324	5613.243	227.169°	---	84.335%
H2	3013.310	2130.732	8.766°	37.959%	32.013%
H3	1579.761	1117.060	64.241°	19.900%	16.783%
H4	425.700	301.015	80.005°	5.363%	4.523%
H5	199.247	140.889	197.261°	2.510%	2.117%
H6	443.256	313.429	16.090°	5.584%	4.709%
H7	695.094	491.506	42.422°	8.756%	7.385%

True RMS (Samples): 6655.879   Calculated RMS (Harmonics): 6143.827

Figure 9
Recovery Inrush Harmonic Content

Harmonic Resonance

Harmonic resonance is a condition that produces high currents during line to ground faults on impedance grounded systems [7]. Capacitive reactance is given by

$$X_C = 1/(2\pi f C) \qquad (11)$$

It can be seen that Xc will decrease with increasing frequency. Any impedance that is capacitively coupled to ground will decrease as frequency increases. Resonance will occur at a specific distance from the source, causing fault currents to be maximum. It's been shown that 5th and 7th harmonic currents of magnitude up 60% can be expected during resonance. A very complete discussion of harmonic resonance is given in [9].

Operating Principles of Some Common Relays

Electromechanical Overcurrent Relay

Probably the most prevalent relay in existence today is the electromechanical overcurrent relay. The principle operation is that of a shaded pole motor [10],[11]. An aluminum disk is caused to rotate by the changing flux produced in the stator pole. Its motion is restrained by an adjustable spring, whose resistance must be overcome by the flux induced torque. When the disk reaches the limits of its travel, a contact is closed to trip a circuit breaker, thereby interrupting the fault. The basic time overcurrent unit can be seen in Figure 10 below.

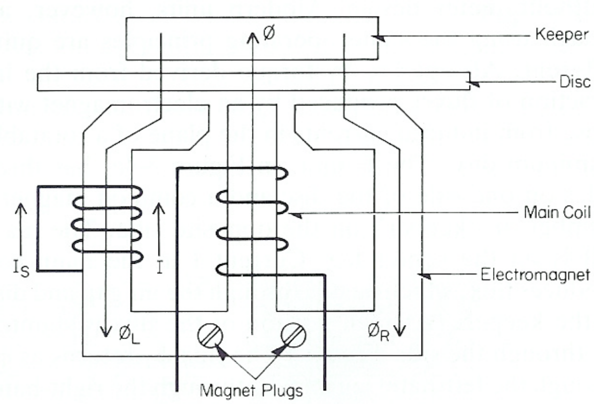

Figure 10
Induction Disk Unit

The flux induced in the main coil from the operating current passes through the air gap and into the keeper. The total flux returns through the left and right hand legs. A short circuited lag coil in the left hand leg causes Φ_L to lag both Φ_R and Φ_T producing a split-phase motor action on the induction disk. The amount of torque produced is proportional to the magnitude, but the time it takes the disk to complete its rotation is inversely proportional to the magnitude of the operating current.

The effect of increasing harmonic current on this unit is to cause the flux to decrease. With decreasing magnetizing current for increasing frequency, the net effect is to cause the disk rotation to slow [12]. This is verified in the testing that was done as part of the research for this paper.

Microprocessor Based Numerical Feeder Protection Relay

The microprocessor relay accepts sampled voltage and current and stores it for use in protection and metering algorithms [10]. Most relays available today have sampling rates of 32 samples / cycle or higher. The way that the sampled data produces an input waveform for protection and metering algorithms varies with manufactures. Some relays filter out all but the fundamental frequencies, some produce a true rms value, and some do both.

Relays that produce rms values of voltage and current for protection and metering use the following simple relationship (assuming 32 samples / cycle)

$$I_{rms} = \sqrt{1/32 \sum_{n=1}^{32} I^2_n} \qquad (12)$$

The choice of measurement principle rests with the relay engineer. Time overcurrent devices that coordinate with equipment that experience I² R heating effects (such as fuses, conductors, and transformers) should have a True rms response [10].

Relays Tested

Two relays were tested in laboratory conditions for this report. They were, an electromechanical time overcurrent relay, and a numerical feeder relay that has an True rms and fundamental mode of operation. The choice operating principle is made by the relay engineer in the settings. Much has been written on the harmonic response of electromechanical relays, but little work has been done with very modern rms measuring units. Older rms such devices had minimal sampling rates and 8 bit processors, making them somewhat slow with a limited frequency response.

The relay selected for this test uses a up out to the 11th harmonic. The sampling rate of this device is 32 samples per cycle. The rms calculation is done in the DSP and then made available to the main CPU for processing. This unburdens the CPU and speeds up the decision making time of the relay.

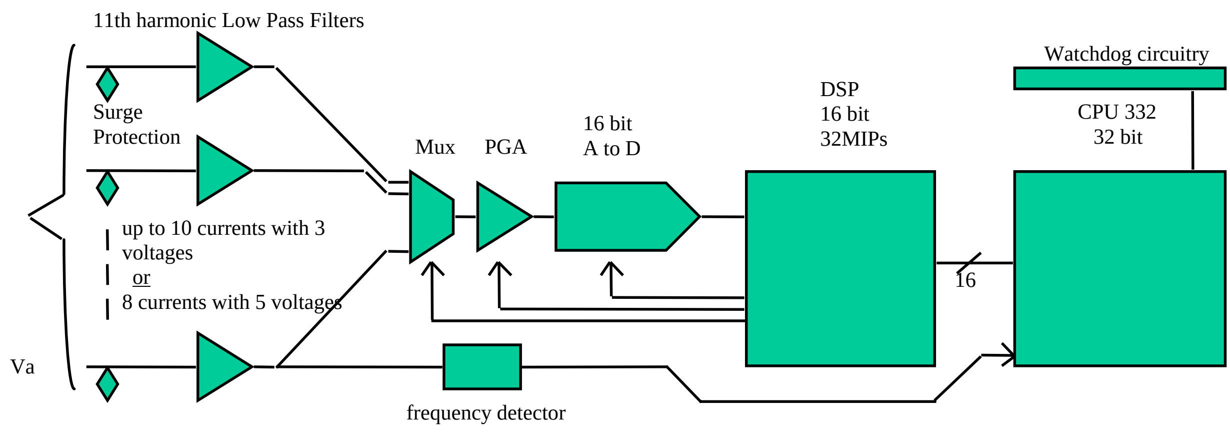

Figure 11
Typical Numerical Relay with DSP

Electromechanical Time Overcurrent Relay

The electromechanical relay was tested with secondary current injection from a modern relay test instrument. The relay was subjected to a variety of harmonic waveforms and the trip times were compared to the manufacturers curves for accuracy.

Test 1

Bench Test	Iteration	Actual Time	% Error
PU = 1.0 Amps	1	0.4606	0.130
Time Dial = 2	2	0.4605	0.109
Operating Time = 0.46	3	0.4603	0.065
I = 5.0 Amps	4	0.4603	0.065
	5	0.4593	0.152

This test shows that the relay is calibrated properly, and that the trip times are repeatable.

Test 2
50% Harmonic Current Distortion

Test 2	Harmonic	Actual Time	% Error
f(t) = 7.07 sin(wt) + 3.54 sin(3nwt), n=3 - 15	3	0.5288	18.68
Tap = 1	5	0.649	33.74
Time Dial = 2	7	0.6833	37.07
I rms = 5.59 Amps	9	0.6569	34.54
T expected = 0.43 seconds	11	0.6476	33.60
	13	0.6274	31.46
	15	0.6147	30.05

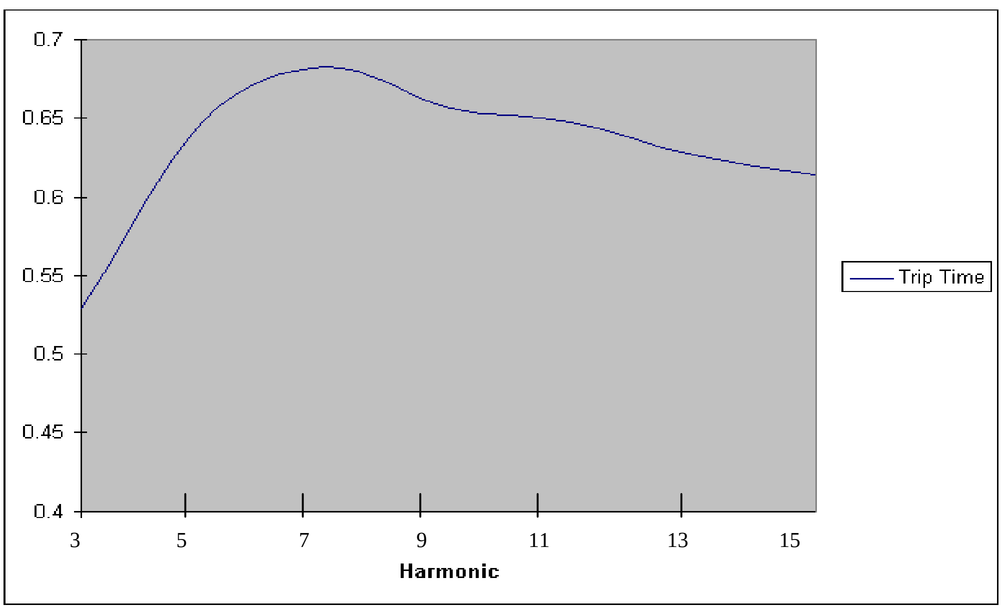

Figure 12

The low pass filter effect can be seen from the trip time characteristic. The shape of this curve agrees well with the test results found in [7], [11], [12], and [13]. Note the maximum error is 37% for this test.

Test 3

25% Harmonic Current Distortion

Test 3	Harmonic	Actual Time	% Error
f(t) = 7.07 sin(wt) + 1.77 sin(nwt), n=3 - 15	3	0.4962	8.30
Tap = 1	5	0.5201	12.52
Time Dial = 2	7	0.5477	16.93
I rms = 5.154 Amps	9	0.5284	13.89
T expected = 0.455 seconds	11	0.5148	11.62
	13	0.509	10.61
	15	0.5085	10.52

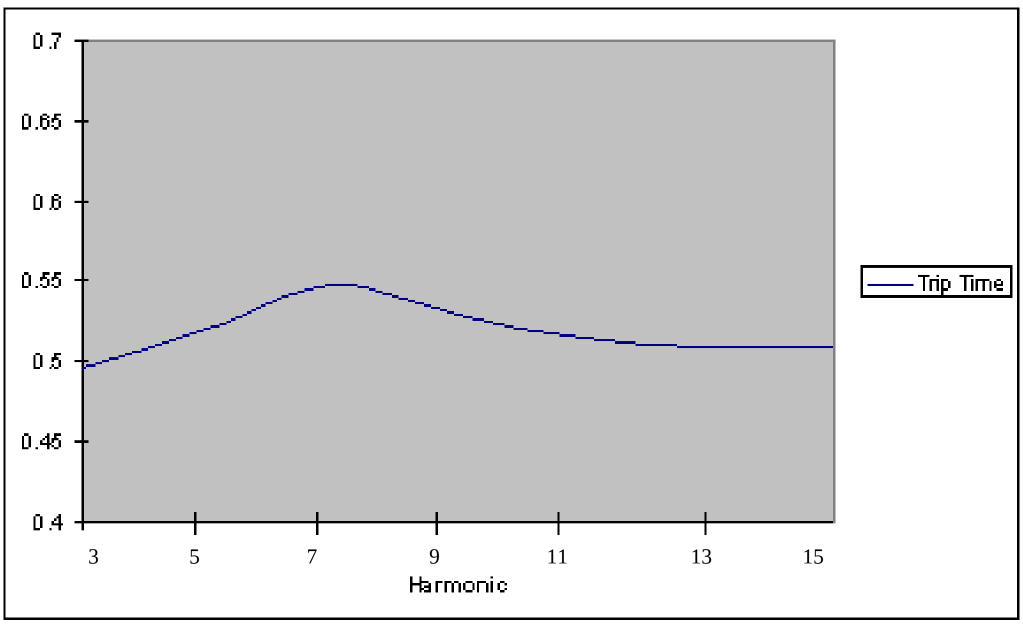

Figure 13

Note from the test results at this relatively low THD that the error reaches 17%.

Test 4

25% 3^{rd} plus 15% 5^{th} – 15^{th}

Test 4	Harmonic	Actual Time	% Error
f(t) = 7.07 sin(wt) + 1.77 sin(3nwt) + 1.061 sin(nwt), n=5 - 15	5	0.4924	8.31
Tap = 1	7	0.5373	15.97
Time Dial = 2	9	0.539	16.23
I rms = 5.208 Amps	11	0.5297	14.76
T expected = 0.4515 seconds	13	0.5117	11.76
	15	0.51	11.47

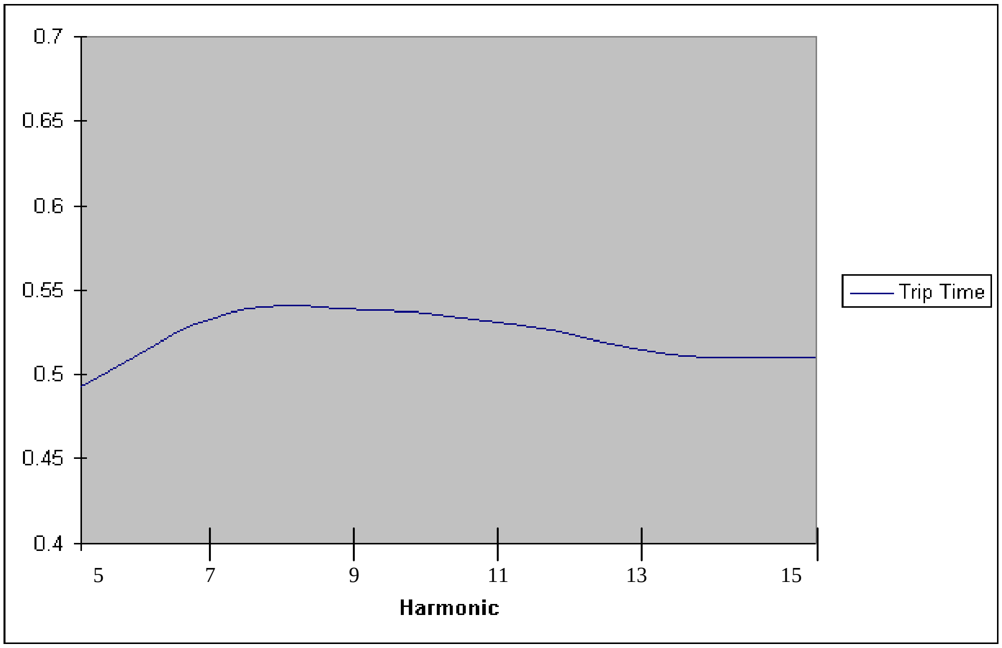

Figure 14

The added 15% 5th – 15th harmonic adds to the average error but reduces the maximum error.

The electromechanical relay didn't get into its published rating of ±10% until the THD dropped to 15%.

Numerical Feeder Protection Relay

This relay was subjected to the identical tests as the electromechanical unit. The (True) rms mode of protection was chosen for these tests.

Test 1

50% harmonic distortion

Test 1	Harmonic	Actual Time	% Error
f(t) = 7.07 sin(wt) + 3.54 sin(nwt), n=3 - 15	3	0.4289	1.33
Tap = 1	5	0.4328	2.22
Time Dial = 2	7	0.4413	4.10
I rms = 5.59 Amps	9	0.45	5.96
T expected = 0.4232 seconds	11	0.4618	8.36
	13	0.4706	10.07
	15	0.4747	10.85

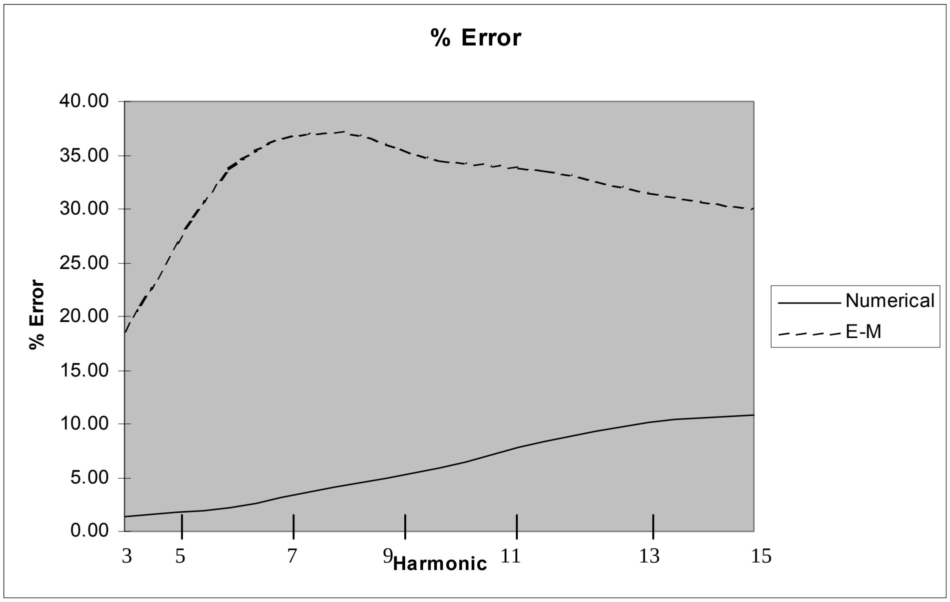

Figure 15

Figure 14 above shows the comparison of percent error for the numerical and electromechanical relays. Note the huge discrepancy between the electromechanical and True rms relays near the 7th harmonic. The published accuracy for the time overcurrent element is ± 7%.

Test 2

25% Harmonic Distortion

Test 2	Harmonic	Actual Time	% Error
f(t) = 7.07 sin(wt) + 1.77 sin(3nwt), n=3 - 15	3	0.4737	1.33
Tap = 1	5	0.4747	1.54
Time Dial = 2	7	0.4745	1.50
I rms = 5.154 Amps	9	0.4788	2.38
T expected = 0.455 seconds	11	0.4831	3.25
	13	0.4871	4.04
	15	0.4872	4.06

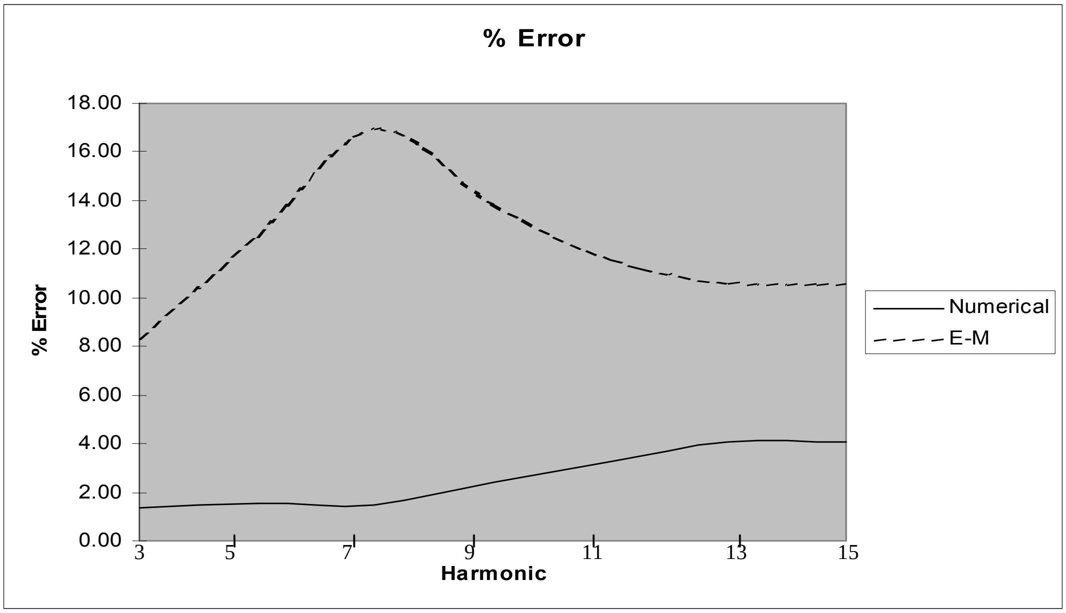

Figure 16

<u>Test 3</u>

25% 3rd plus 15% 5th – 15th

Test 3	Harmonic	Actual Time	% Error
f(t) = 7.07 sin(wt) + 1.77 sin(3nwt) + 1.061 sin(nwt), n=5 - 15	5	0.465	0.81
Tap = 1	7	0.4662	1.07
Time Dial = 2	9	0.4706	1.99
I rms = 5.208 Amps	11	0.4707	2.01
T expected = 0.46123 seconds	13	0.4703	1.93
	15	0.4703	1.93

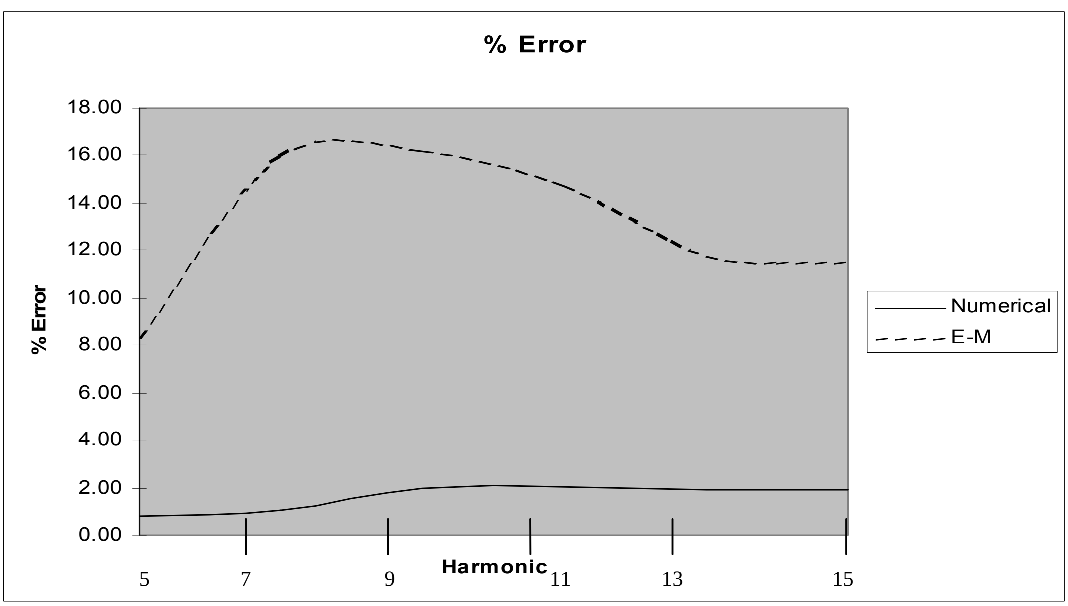

Figure 17

The data from these tests show that the numerical True rms relay clearly out performs the electromechanical relay at all harmonic levels. Coordination between the two relays is nearly impossible at distortion levels above 25%. An EM relay, such as the one tested, would not adequately protect equipment that is sensitive to heat damage.

A Utility Perspective on True RMS Measurements

The application of True rms measurements began for the City during the commissioning of newly installed IED revenue meters and then again later during the commissioning of newly installed multi-function protective relays. From these tests, there was observed a discrepancy of current readings compared to other equipment measuring the same feeders.

The residential and commercial connected loads and resulting harmonic content on the distribution feeders is typical of other utilities. The slight differences in current readings were confusing and a concern, particularly when the relays would be integrated into a new SCADA system. Previous indicating equipment utilized both thermal and instantaneous, from average responding ammeters of various manufacturers and accuracies. These were replaced and standardized with an IED revenue meter displaying True rms values. SCADA automation economically justified the replacement of electromechanical IAC and CO overcurrent relays. Previous papers have described an electromechanical relay as rms responding [2]. As such, the installation of an overcurrent relay that filters all but the fundamental would respond to faults differently than previous relays and indicate different current readings to personnel than the feeder True rms revenue meters. However, the installation of feeder protective relays utilizing True rms protection would more closely follow the behavior of existing electromechanical relays while also indicating actual loads to local and remote personnel through the SCADA system.

Coordination curves have historically been graphed at the fundamental frequency. When the coordination is to be done with fuses, the fundamental coordination neglects to account for the heating effects of current harmonics. A protective relay that filters all but the fundamental may not coordinate with fuses when subjected to the heating effects of all current harmonics. The heating effects of harmonics have been described earlier in this paper. However, a True rms responding protective relay can account for the heating effects and coordinate more accurately to distribution power fuses.

The City of Richland, a municipal utility in the NW, has an electrical distribution which includes sixty feeders served from a 115 kV wye – 12.47 kV grounded wye with a delta tertiary. The high side wye is only surge grounded through lightning arresters. A typical feeder serves sections of overhead conductors (four wire) and underground cable (four wire). Each feeder has an intelligent electronic device (IED) revenue meter and multi-function IED protective relay with phase and residual overcurrents, in addition, to a reclosing relay. Feeder coordination is necessary with substation transformer multifunction relays and distribution system power fuses. The protection is a “fuse saving” scheme with instantaneous disabled after the first trip, a 0.8 second open followed by a reclose with only time overcurrents active, a 10 second open (if necessary) followed by a second reclose. Another trip by time overcurrent will lockout the feeder.

The key is that instantaneous overcurrents are disabled after the first trip until the reclose reset time, typically 60 seconds.

A line to ground fault on CØ occurred on 5/19/03 at 08:33:13 with the graph shown in Figure 16[2]. Phase time overcurrent pickup was set for 600A using an extremely inverse curve and a time dial of 3; Phase instantaneous was set for 1800A; Residual time overcurrent pickup was set for 240A, using an extremely inverse curve and a time dial of 2; Residual instantaneous was set for 888A.

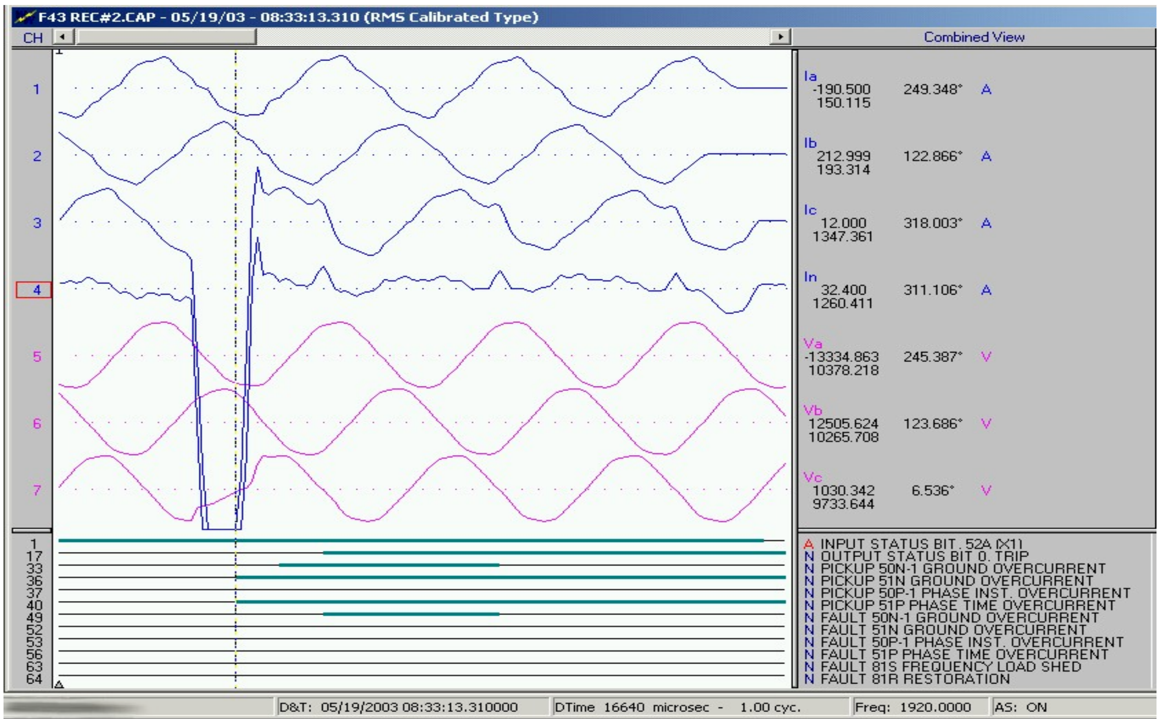

Figure 18

One cycle of data prior to pickup indicated 149.549 amps AØ (60Hz), 150.115 amps AØ (True rms), 192.606 amps BØ (60Hz), 193.314 amps BØ (True rms), 864.593 amps CØ (60Hz), 1347.361 amps CØ (True rms), 734.588 amps residual (60Hz), and 1260.411 amps residual (True rms). Details of the first cycle harmonics are shown in Figures 19, 20, 21, and 22. As the rms calculations were performed over one cycle and the initial CØ included fault current, non-fault fundamental to rms load comparisons shouldn't be used on CØ.

[2] Note: CØ and the residual scales were made such that the majority of the waveform could be visible. The "flat topping" was due to exceeding the screen frame and not to CT saturation.

Harmonics

Channel Name: (1) Ia

	DFT Peak	DFT RMS	DFT Angle	% of Fundamental	% of TrueRMS
H1	211.494	149.549	0.000°	---	99.623%
H2	2.289	1.619	128.862°	1.082%	1.078%
H3	6.050	4.278	321.656°	2.861%	2.850%
H4	0.469	0.331	237.522°	0.222%	0.221%
H5	14.020	9.914	168.590°	6.629%	6.604%
H6	1.067	0.754	131.611°	0.504%	0.502%
H7	5.985	4.232	154.279°	2.830%	2.819%

True RMS (Samples): 150.115 Calculated RMS (Harmonics): 150.009

Figure 19

Harmonics

Channel Name: (2) Ib

	DFT Peak	DFT RMS	DFT Angle	% of Fundamental	% of TrueRMS
H1	272.386	192.606	0.000°	---	99.634%
H2	4.222	2.986	352.279°	1.550%	1.544%
H3	10.715	7.576	68.129°	3.934%	3.919%
H4	4.839	3.422	70.186°	1.777%	1.770%
H5	17.586	12.435	64.119°	6.456%	6.433%
H6	2.519	1.781	163.608°	0.925%	0.921%
H7	4.688	3.315	148.656°	1.721%	1.715%

True RMS (Samples): 193.314 Calculated RMS (Harmonics): 193.245

Figure 20

Harmonics

Channel Name: (3) Ic

	DFT Peak	DFT RMS	DFT Angle	% of Fundamental	% of TrueRMS
H1	1222.719	864.593	360.000°	---	64.169%
H2	882.628	624.112	26.992°	72.186%	46.321%
H3	621.703	439.610	61.607°	50.846%	32.628%
H4	367.507	259.867	89.159°	30.057%	19.287%
H5	164.855	116.570	91.123°	13.483%	8.652%
H6	141.936	100.364	69.296°	11.608%	7.449%
H7	175.320	123.970	76.824°	14.339%	9.201%

True RMS (Samples): 1347.361 Calculated RMS (Harmonics): 1198.689

Figure 21

Harmonics

Channel Name: (4) In

	DFT Peak	DFT RMS	DFT Angle	% of Fundamental	% of TrueRMS
H1	1038.864	734.588	0.000°	---	58.282%
H2	879.121	621.633	34.190°	84.623%	49.320%
H3	603.610	426.817	68.530°	58.103%	33.863%
H4	362.838	256.565	96.649°	34.926%	20.356%
H5	164.942	116.632	103.175°	15.877%	9.253%
H6	142.725	100.922	75.198°	13.739%	8.007%
H7	176.700	124.946	82.708°	17.009%	9.913%

True RMS (Samples): 1260.411 Calculated RMS (Harmonics): 1101.564

Figure 22

As can be seen, the first cycle of fundamental current for instantaneous phase and residual was below the pickup value, including when factoring in a ±7% instantaneous tolerance, while the fundamental current for phase time overcurrent did pickup. The True rms value of residual (1260A) exceeded the instantaneous pickup value (888A) and successfully caused the feeder breaker to trip. If True rms protection had not been utilized, the fault would have been present until the fundamental phase overcurrent timed out, resulting in more extensive damage and undue strain on the distribution system.

Conclusions

- Significant levels of harmonic distortion can exist during fault conditions.
- The installed base of electromechanical relays cannot adequately protect equipment that is sensitive to heat damage.
- Modern relays that operate on a true rms principle are available.
- rms measurements, that include more than the fundamental frequency in protective relays:
    - Can reduce fault damage by utilizing the harmonic current to trip quicker.
    - Can coordinate more accurately with passive fuses and conductors due to the harmonic heating effects.
- Protective relays that utilize fundamental frequency only and used for ammeter display to operator personnel or integrated into SCADA systems, can cause confusion as they do not provide an accurate system loading in the presence of any harmonics.
- Confusion to engineers and operating personnel can be minimized if more accurate units and terms are used to describe indications (e.g. “Amps, 60Hz”, or “Amps, True rms”).

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