Effect of Waveform Distortion on Protective Relays

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Introduction

The technical literature is filled with theoretical and empirical references to harmonics in power systems, but few have made an effort to define the influence of these waveform distortions on protective relays. It is felt that one important reason for this omission is that the wide variety of measurement principles used for relays produce different results, and the scope of such an appraisal becomes gargantuan. In spite of this fact, this paper will make an effort to 1. examine several electromechanical, solid state and microprocessor measurement concepts, 2. describe the theoretical expectations of harmonic influence and 3. present laboratory confirmation of these results.

Most waveform distortions (generation of voltages or currents with no useful intent) are generated by non-linear impedances. Classical generators of harmonics are arc furnaces, saturating current transformers, arcing faults, transformer energization, capacitor switching and thyristor switching loads. While protective relays are likely to be subject to one or more of these phenomena, the quantity of difficulties reported that are explicitly attributable to waveform distortion have been few.

Relaying Units

Instantaneous Overcurrent Measurements

Instantaneous overcurrent measurements are being accomplished in many ways. There are plunger, clapper, fundamental, RMS and average methods. The first two, discussed here, are electromechanical flux-responsive devices. The instantaneous force applied to the moving element is dependent on instantaneous flux and thus instantaneous current. If the force on the moving armature, in excess of pickup force, persists for a long enough time within the cycle, the plunger or clapper unit will operate. A very high frequency current or current with harmonic content applied to the unit will operate the relay, if of sufficient magnitude.

Theoretically, the average force on the moving element is proportional to the integral of the current squared.

$$\int_0^{2\pi} i^2 dt = \frac{I_m{}^2}{2} + \frac{I_{3m}{}^2}{2} \quad \cdots \quad + \frac{I_{nm}{}^2}{2} \qquad (1)$$

where I_{nm} = maximum current value of the fundamental component of the sinewave.

I_{nm} = maximum current value of the n*th* harmonic.

Through a consideration of the fundamentals, it would appear that average force is dependent only upon the sum of the squares of the peak magnitudes of the various harmonic components. This ignores any influence by a dc component in the current.

Based on this, each frequency component would produce an independent and cumulative effect, causing the pickup value to decrease for an increase in harmonic content. However, this overlooks a very important influence. The pole of a relay of this type is equipped with a shading ring to produce a shifted component of pole flux. The effect of higher frequency is such as to cause the two fluxes in the pole structure to become more nearly in phase and for each to become smaller for a given current input. This causes the pickup to increase as frequency increases, with some chatter at very high frequencies.

Induction Disc Overcurrent

This type of relay consists, in one implementation (CO), of a 3-pole electromagnet. All of the operating energy for the relay is applied to the center pole coil. One outer pole is equipped with a lag coil. The remaining pole has no coil but receives flux as influenced by the other two poles.

With fundamental pickup current applied, torque is produced of sufficient magnitude to overcome the spring restraint and to cause the disc to just begin to move. This torque results from interaction between disc currents produced by each pole flux and the other two pole fluxes. All of these torques are in the same direction.

Increasing the frequency of the input current results in little change in the current that is produced in the lag coil circuit. The flux in this pole will decrease in inverse proportion to the frequency increase, maintaining the behavior of the electromagnet as the equivalent of a current transformer. Similarly the flux in the other outer pole decreases because of the lowered magnetomotive force across it. Since the flux in the center pole is the sum of the two outer pole fluxes, it also is reduced.

With decreasing magnetizing current for increasing frequency and constant lag coil circuit current, the net effect is for the center pole and the unlagged pole fluxes to draw closer in phase. This causes pickup to increase, slows the disc rotation and ultimately causes the efficiency of the electromagnet to deteriorate to the point of non-operation. Harmonics combined with the fundamental would have little effect on operation of this unit.

Induction Disc Phase Balance

One type of phase balance relay (CM) uses two pair of identical 3-pole electromagnets with two independent discs. Torque is generated by current fed into each of the four center pole coils in an identical fashion to that described for the induction disc overcurrent relay. Phase current is passed through a center pole coil on an electromagnet on each of the discs.

With the electromagnets arranged to produce torque in opposite directions on each of the discs (phase A opposite phase B, phase C opposite phase B), current comparison results. Phase angle separation between the phase currents has no influence on the operation of this relay. However, if the magnitude of one current exceeds the other by an appropriate amount, the disc moves in the direction dictated by the predominant torque, and the relay contacts close.

With no current in one electromagnet input coil, the phase balance relay behaves as a simple overcurrent relay, with similar response to harmonic influence. Because of the nature of its construction, equal harmonics in each phase produce no net effect. With a harmonic frequency present having different magnitudes in the two phases but with the two currents having equal fundamental magnitudes, the relay becomes a harmonic phase balance relay. It will operate or not depending on the relative magnitudes of the harmonics and the weighting factor of the torque produced by the particular harmonic.

The construction of this relay is such that the lag coil circuits are interconnected in series across a tapped parallel resistor to provide a balance adjustment at 60 hertz. This produces a slight frequency dependency of pickup. The pickup will decrease with 180 hertz current alone applied, compared to the 60 hertz pickup. However it rises as expected as frequency is raised farther.

Negative-Sequence Overcurrent

This type relay is intended to recognize negative-sequence current and ignore positive-sequence current. At 60 hertz it does. At any other frequency, the relay ceases to be a negative-sequence-only device. One form of this relay (COQ) contains a reactor-resistor circuit to "filter out" the positive-sequence effect at rated frequency. The influence of frequency on the reactance of these reactors is significant, and the single frequency pickup varies widely. With moderate harmonic currents superimposed on a predominate negative sequence fundamental, little influence of the harmonic is evident.

Product Type Relays

An element often used in directional control, distance and voltage control relays is the product-type induction cylinder unit. It is composed of 2 series connected polarizing coils mounted opposite one another on 2 poles of an electromagnet assembly, and 2 series-connected operating coils mounted opposite one another on the other 2 poles of the electromagnet.

The interaction of the operating circuit flux and the polarizing circuit flux produces a torque on a moving cylinder, to which a contact is attached, located in the center of the 4 poles. Torque is proportional to the product of the operating input, the polarizing input and is dependent upon the phase angle between them. Maximum torque occurs when the two fluxes are 90° apart. The influence of a change in frequency, or addition of harmonics to the fundamental, changes the impedance and phase angle relationship of the operating and polarizing circuits. This influence tends to decrease the torque on the cylinder, causing pickup to increase. This effect will vary depending on the frequency, amount of harmonic content and configuration of the cylinder unit coil circuits.

Transformer Differential

It is now virtually universally accepted that the proper quantity to use for inrush restraint in a transformer differential relay is second harmonic (as a percentage of the fundamental). For a 60 hertz relay, 120 hertz is the key frequency. In an analog relay (HU), a parallel resonant filter is provided to block second harmonic from the operating circuit and a series tuned parallel resonant circuit shunts second harmonic current through a restraint winding. The higher harmonic currents, to a degree, then flow through the operating coil circuit. This is mollified by the fact that the currents described above are differential currents. Through-currents only influence restraint in a second measuring unit.

As would be expected with this relay, single frequency current input will have a vastly different effect depending upon which frequency is involved. Current of 120 hertz alone is incapable of operating the harmonic restraint unit. This type of unit will operate with current of 180 hertz alone but at a much higher input than that required at 60 hertz. Though unrealistic from the standpoint of the conditions expected on a power system, this unit is capable of operating with no 60 hertz but is restrained by 120 hertz, irrespective of the frequency of the current producing operation. The principle of operation of the microprocessor relay is different from this.

In the microprocessor relay the second harmonic current is extracted from the waveform. The 60 hertz current is also. The magnitude of the 120 hertz component is compared to the 60 hertz component. If this magnitude exceeds 7 to 15%, depending on the sensitivity chosen, the differential algorithm is restrained from producing an output. No acknowledgement nor influence of other harmonics is given in the basic differential scheme unless fifth harmonic (as percentage of fundamental) is used to block tripping on overvoltage.

Thus a microprocessor transformer differential relay using the concept described is incapable of operating on third harmonic alone. In the analog relay, harmonic components cannot be simply thrown away, though they can be diverted. In the microprocessor relay, harmonics may be selectively chosen and used in an appropriate fashion, or ignored.

Microprocessor Overcurrent Relays

Microprocessor overcurrent relays utilize various measurement techniques - digital sampling, digital filtering, asynchronous sampling, RMS measurement. Two such relays, discussed here, use digital filtering techniques and asynchronous sampling, both of which can accommodate harmonic influences.

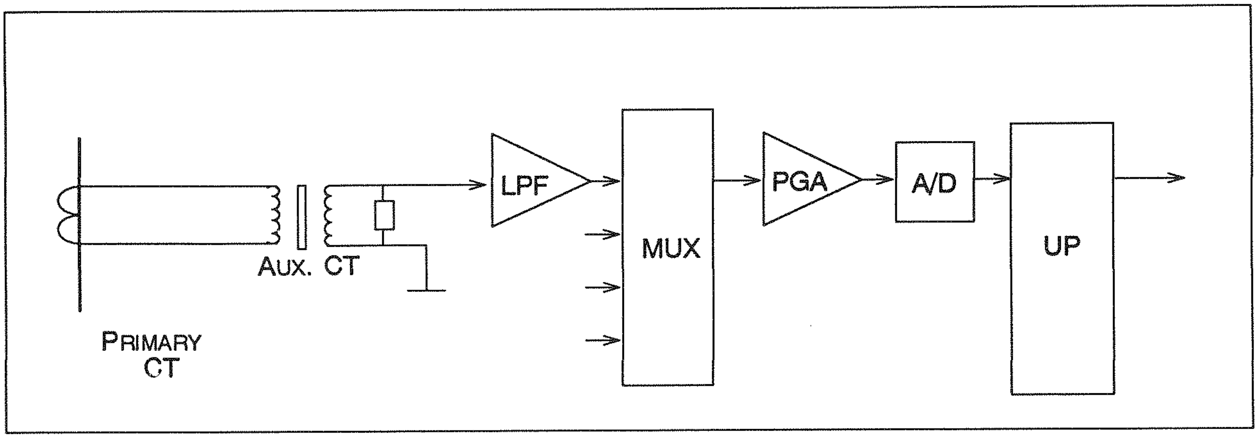

Figure 1. Microprocessor Overcurrent Relay (IMPRS).

- **Digital Sampling and Anti-Aliasing Filter.** Figure 1 is a schematic diagram ot the major elements of a microprocessor overcurrent relay. The diagram shows a primary ct connection to the circuit of the relay. In the relay an input transformer feeds secondary current to a burden resistor. The voltage signal developed across the burden feeds a low-pass anti-aliasing filter (LPF). The filter output is then routed in sequence to a programmable gain amplifier (PGA) (or equivalent) along with the other phase and ground current signals (not shown) by means of the multiplexer (MUX). The PGA provides software control of the relay tap setting. The A/D converter then converts the PGA analog output to the digital quantity.

The input for this digital relay is obtained by sampling sinewave currents and/or voltages at discrete time intervals. A fixed number of instantaneous samples per cycle are converted to digital quantities by an A/D converter and stored in memory for processing. Digital filtering is the simple process of combining the successive samples to obtain the quantities representing the phasor components of the input. For example, a first sample taken at an arbitrary time on a current sinewave is a dc value representing I sin (xt + u) where u is an arbitrary phase angle. The sample taken 90 degrees later in time is I cos (xt + u). Consequently, taking just two samples 90 degrees apart extracts the real and imaginary components of the phasor.

The term "filtering" is used because the magnitude of the components change when the sampling intervals remain fixed and the frequency of the input is varied. The result then varies in magnitude and phase as a function of input frequency. Consequently, more than two samples can be combined to obtain a more favorable frequency response. For example, Figure 2 shows a sinewave sampled at a 240 hertz rate or four times per cycle. The five consecutive samples (S1 through S5) enter a register and are combined as follows:

$$S1 - S2 - S3 + S4 = 2\sqrt{2}\,\sin(\omega t + \phi - 45) \qquad (2)$$

$$S2 - S3 - S4 + S5 = 2\sqrt{2}\,\cos(\omega t + \phi - 45) \qquad (3)$$

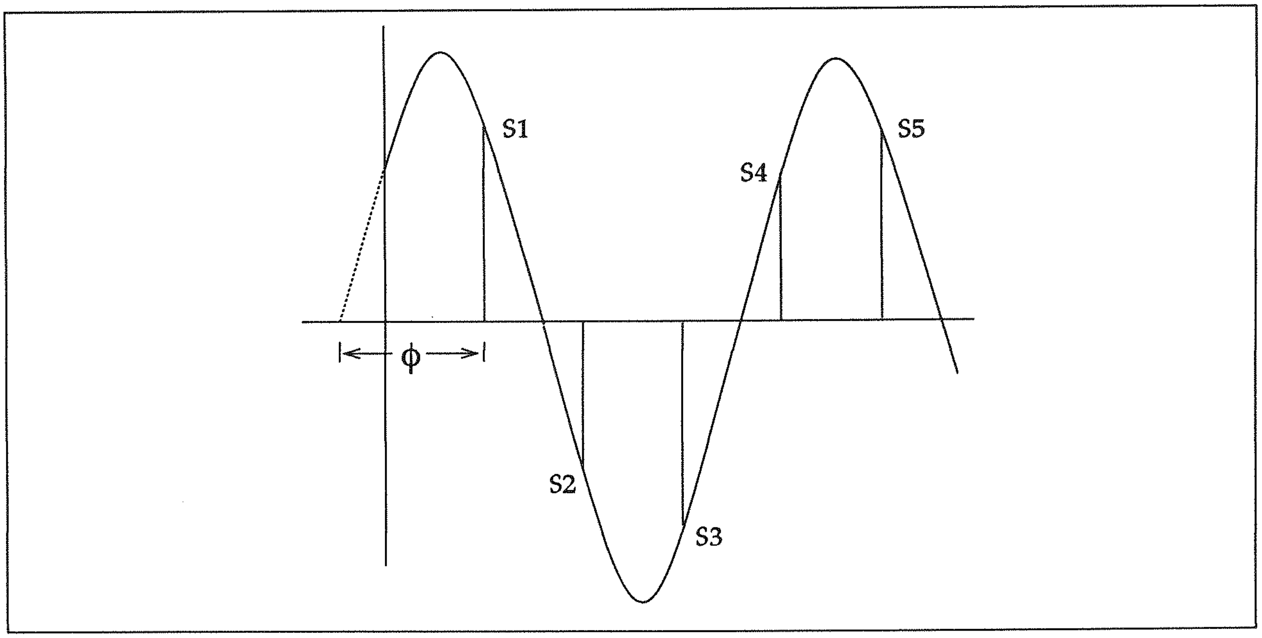

Figure 2. Sampling the current signals.

The first set of four samples gives a result proportional to the imaginary component of the measured phasor as shown by equation (2). The same combination of samples taken 90 degrees later in time gives the real part, equation (3). This simple algorithm has proved ideal for protective relay applications because it has little response to dc offset and has no response to second harmonic and other even harmonics. To illustrate, it can be seen that if the input were a one per unit dc signal, either set of samples would add to zero as follows:

$$1 - 1 - 1 + 1 = 0$$

Likewise, a ramp, (I=t), would also produce no response:

$$1 - 2 - 3 + 4 = 0$$

Since a negative ramp plus a dc signal approximates an exponential, it can be seen that the filter has little response to the decrement when used to measure fault current. The filter also responds to odd harmonics which would corrupt the measurement of the fundamental. Consequently, a low pass analog anti-aliasing filter is used preceding the A/D converter to eliminate the higher frequencies from the measurement.

By definition, a digital filter extracts the phasor components of the analog current or voltage input. By definition, what is being measured is the fundamental, and a low pass analog filter preceding the A/D converter is required to eliminate aliasing which would corrupt the intended measurement. Consequently, a microprocessor relay using the digital filter is immune to the effect of harmonics in the sense that it extracts the fundamental from the waveform.

Figure 3 shows the response of such a digital filter to the typical current waveform of a 6-pulse rectifier. The figure shows the rectifier waveform, the output of the anti-aliasing filter, and the output of the digital filter. The digital output returns the magnitude of the fundamental.

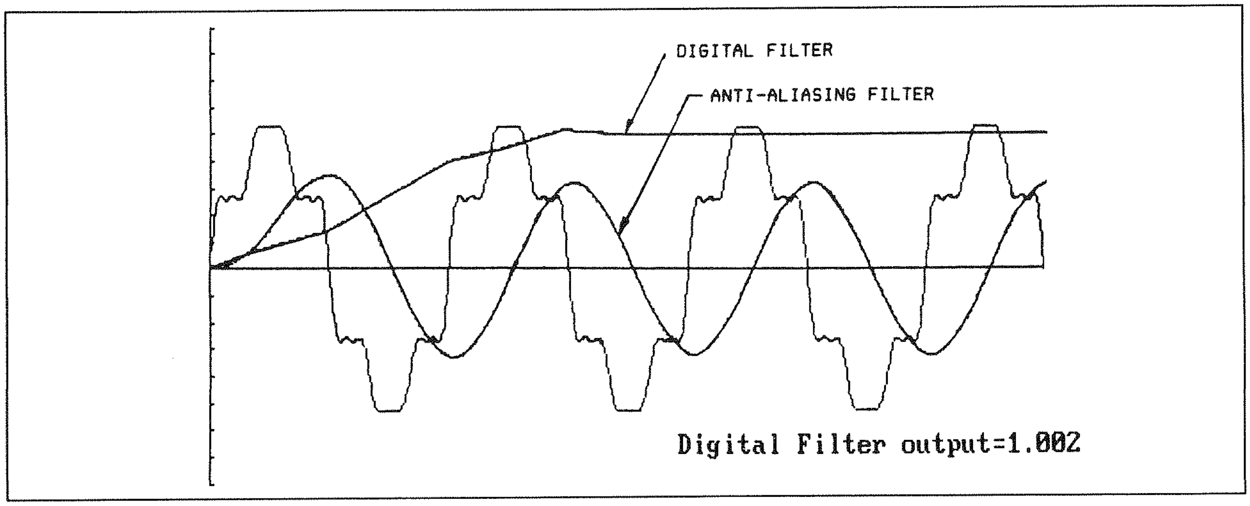

Figure 3. Response of a digital overcurrent relay (IMPRS) to 6-pulse rectifier current waveform with 1.0 pu 1st, 0.22 pu 5th, 0.13 pu 7th, 0.04 pu 11th, and 0.03 pu 13th harmonic.

Figure 4 shows the response of the same digital filter input circuit to a 6-pulse rectifier current with 5th and 7th harmonic amplification. [1] Again the digital filter suppresses the harmonics and returns the magnitude of the fundamental. Harmonic amplification in this context means that inherent characteristics of the power system produce amplified values of certain frequencies.

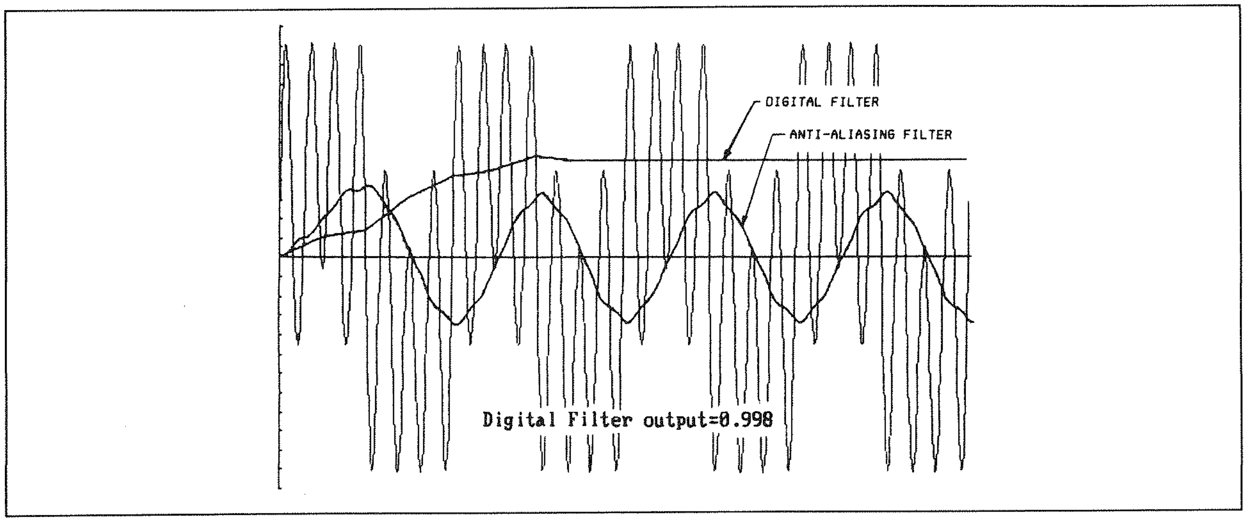

Figure 4. Response of digital overcurrent relay (IMPRS) to 6-pulse rectifier current waveform with 1.0 pu 1st, 0.45 pu 5th, 1.50 pu 7th, 0.09 pu 11th, and 0.05 pu 13th harmonic.

- **RMS Measurement with Asynchronous Sampling.** Another technique used in a microprocessor based overcurrent (MCO) relay measures the RMS value of the current input directly and uses it as an operating quantity. This approach uses no filtering, and the waveform is sampled a sufficient number of times to account for the high frequencies. Each sample is squared and summed, and the average of the square root of the sum over the number of samples per cycle is taken as the RMS value.

This synchronous sampling process would have a high computational burden, and the processing time between samples is limited by the number of samples required per cycle. Adequate sampling requires a sampling frequency at least twice that of the highest frequency to be measured. For example, sampling the 13th harmonic requires a 1560 hertz sampling frequency or 27 samples to execute the relay algorithm. However, the asynchronous sampling technique allows more efficient use of processing time by using fewer samples per cycle and accumulating the necessary number of samples over a number of cycles. Each sample is taken after a delay time of 2.0833 milliseconds (8-samples per cycle), except that a millisecond is added to the 7th sample. This skew causes the RMS value calculated from the 8 samples each cycle to undulate around the true RMS value. However, the average taken over time quickly approaches the true RMS value. For example, Figure 5 shows the typical 6-pulse rectifier waveform sampled 8 times per cycle.

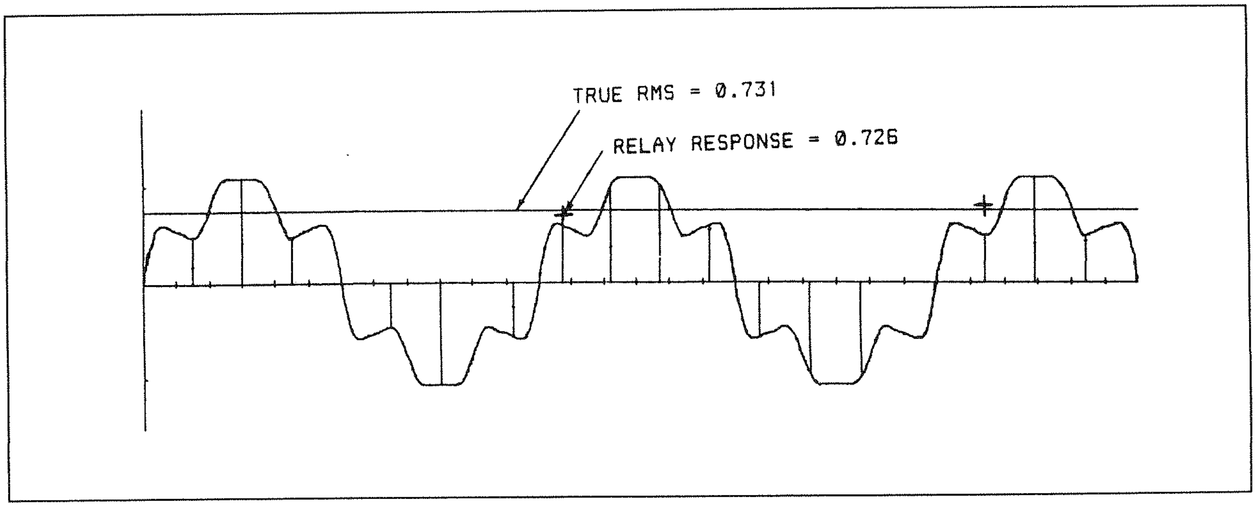

Figure 5. 8-sample asynchronous sampling of 6-pulse rectifier waveform.

The harmonics in a nominal current waveform of 6-pulse rectifier load has RMS only three percent above the RMS of its fundamental and hence has little effect on relay settings or operation. The 6-pulse rectifier waveform with 5th and 7th harmonic amplification can have an RMS value 30 to 40 percent higher than the fundamental. [1] These severely distorted waveforms must be tolerated until remedial system changes can be made. The distortion must therefore be considered as a temporary steady state conditions. Consequently, a relay set for overload protection, regardless of operating principle, must be set to allow operation.

Summary of Test Results

To completely analyze the effects of waveform distortions on the measurement units discussed here, a wide variety of relays was tested using single frequency, mixed frequency, saturated and dc offset inputs. Single harmonic inputs were applied from the fundamental (60 Hz) to the 9th order (540 Hz). Mixed frequencies included the 2nd and the odd harmonics (3rd to 9th) superimposed on the fundamental.

The magnitudes of the mixed frequency inputs applied were a function of the order of harmonic. With a fundamental magnitude of 1 per-unit, a given frequency was added at a magnitude of 1/n of the fundamental, where n is the order of harmonic. For example, at 180Hz,

$$I_{input} = I_{60} + I_{180} \text{ where } I_{180} = \frac{I_{60}}{n}$$

Instantaneous Overcurrent Unit

A clapper type instantaneous unit (IIT) was tested. This unit consists of a coil wound around a magnetic core and a moving armature to which contacts are attached. The 60 Hz pickup value was set to 5 amps. Higher order pickup values are as follows:

f	RMS
120 Hz	7.3 Amps
180	9.3
300	12.6
420	14.2
540	14.8

As previously described, an increase in frequency increases pickup. Chatter was also evident at the higher frequencies. For the mixed frequency inputs, the RMS values of pickup varied from 5.1 (60 Hz + 540 Hz) to 5.7 amps (60 Hz + 120 Hz).

Induction Disc Relays

The induction disc unit is applied in many protective functions, generally overcurrent, and the effect of harmonics is similar in all of them with the exception of the phase balance relay. As frequency is increased from the fundamental to the odd harmonics up to the 9th, the torque produced on the disc by the electromagnet decreases, for a given RMS current, hence producing a higher minimum pickup. The extreme case was observed with the single phase overcurrent relay (CO). Inadequate torque was produced to cause the disc to move for frequencies higher than the 5th order, with current as high as 10 multiples of pickup.

Applying mixed frequency inputs (harmonic superimposed on the fundamental), a less pronounced effect was seen. The induction disc relays operated within 5% of the fundamental pickup value. The pickup response of the induction disc overcurrent relay set at 1.0 amp tap, where

$$I_{input} = I_{60} + I_{60n}, \quad \text{where } I_{60n} = \frac{I_{60}}{n},$$

is shown in the following table.

f	n	I_{60}Hz	$\frac{1}{n} I_{60}$	RMS Pickup
60Hz	1	1.00A	-	1.0
120	2	.92	.46	1.03
180	3	.99	.33	1.04
300	5	1.02	.20	1.04
420	7	1.02	.145	1.03
540	9	1.00	.11	1.01

The time curves for the induction disc relay are shifted up as the relay becomes less efficient for increasing frequency. Mixed frequency inputs caused the time curves to vary only slightly.

The phase balance induction disc relay (CM) also operated similarly for mixed frequencies. However, unlike the overcurrent induction disc relays with single frequency input, torque did not constantly decrease for a given input current with an increase of the order of harmonic. At 120 Hz and 180 Hz, torque actually increased, and the pickup quantity was approximately 15% less than that of the fundamental value.

As the frequency was then increased from the 3rd to the 9th harmonic, the relay operated like the overcurrent relay. Torque decreased and pickup values increased.

Negative Sequence Overcurrent

The negative sequence overcurrent relay (COQ) is influenced by a change in single frequency input due to the change in reactance of the negative sequence filter circuit. This circuit begins to respond to positive sequence as well. For increasing single frequency inputs, the sequence filter output decreased and the minimum pickup of the relay increased as approximately $\sqrt{f}$. Applying a combined fundamental and harmonic input had little effect on relay operation.

Product Type Relays

The effect of harmonics on the induction cylinder unit, product type relays was examined. These included directional overcurrent, loss-of-field, voltage controlled and bus differential relays.

In a directional unit application, such as a loss-of-field relay (KLF) or directional overcurrent relay (CR), the operating quantity is current, and the polarizing quantity is voltage, with a given maximum torque angle. For pure n*th* order harmonic inputs, at the given torque angle, the pickup value of the directional unit increased as frequency increased, by approximately the order of the harmonic.

The maximum torque angle of the unit at the fundamental frequency is 30° leading, with the zero torque line at 120° and 300°. See Figure 6. Maximum torque angle occurs when the operating circuit and the polarizing circuit fluxes are 90° apart, for a 60 hertz input. As frequency is increased, the phase relationship of the polarizing circuit and operating circuit fluxes is such that maximum torque applied to the cylinder occurs at points other than 90° between the fluxes. The result is that n maximum torque angles are produced for n*th* order harmonic inputs. See Figure 7.

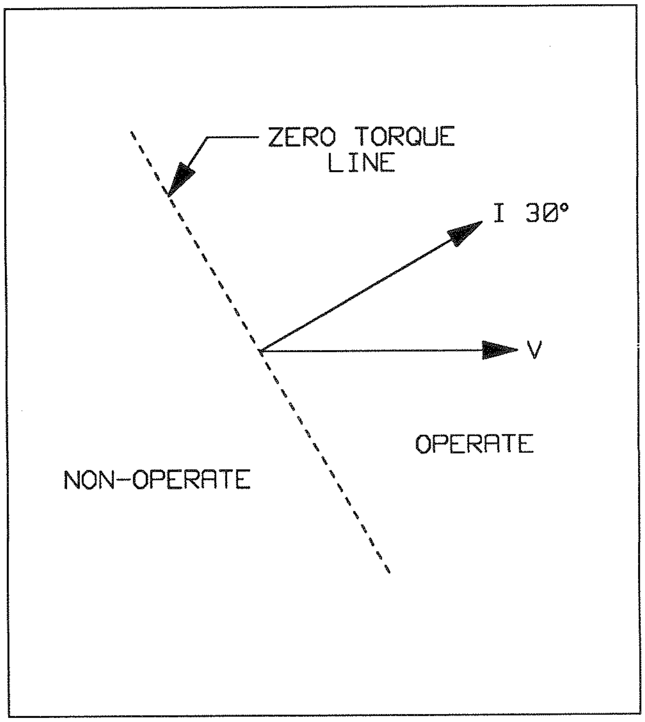

Figure 6. Maximum torque angle at 30° leading at 60 Hz current and voltage.

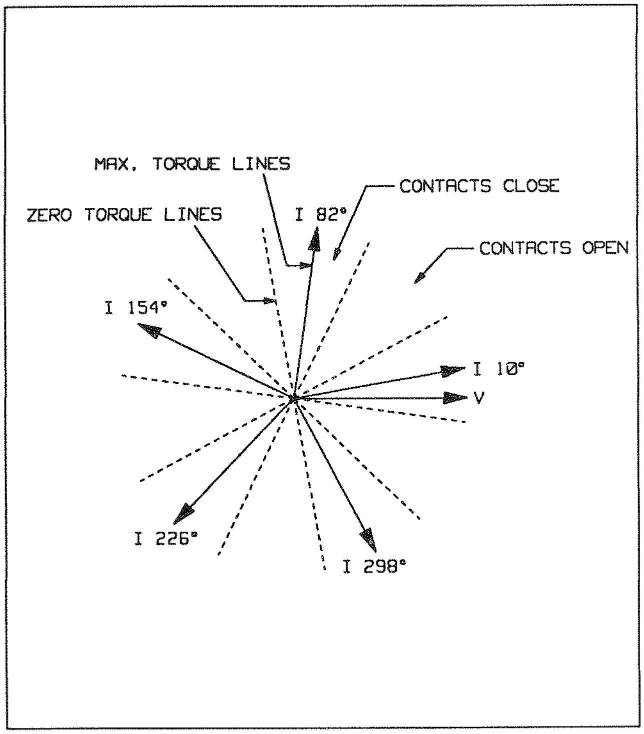

Figure 7. Maximum torque angles at 5th order harmonic current and voltage.

For mixed frequency inputs (n*th* order superimposed on the fundamental), the induction cylinder directional unit pickup value varied within 7% of the fundamental value. Maximum torque angle changed less than 1° from the fundamental value.

The induction cylinder unit is also used as a voltage unit in loss-of-field (KLF) and voltage controlled overcurrent relays (COV). In these applications the operating and polarizing circuits are interconnected in the relay and the unit operates on a single voltage input. Similar to the directional relays, operating torque decreased and the pickup value increased for an increase in frequency. Also, mixed frequency inputs had little effect on the pickup value.

High Impedance Bus Differential

A cylinder unit voltage element is also used in a "high impedance" differential relay (KAB). It is connected across the two junction points formed by paralleling all of the ct's associated with circuits for each phase on the protected bus. It has in series with it a 60 hertz tuned circuit.

A combination effect occurs with a single elevated frequency applied to this relay. The cylinder unit pickup is inherently higher at higher frequencies, and this condition is exaggerated by the presence of the tuned circuit. Thus the single-frequency pickup increases markedly with frequency.

With mixed frequencies applied, the fundamental voltage is the overwhelming influence. The presence of moderate harmonic voltages has little effect on the behavior of the high impedance bus differential relay.

Transformer Differential Relay

One type of transformer differential relay tested consists of a differential unit and a harmonic restraint unit (HU). The operating elements used in this relay are polar-type units consisting of two coils, operate and restraint, wound on a magnetic core of a frame which is polarized by a permanent magnet. An armature is mounted to the core and is free to move in the air gap of the frame. The armature is polarized by the resultant flux from the coils and will operate (close) or restrain (open) depending on the relative quantities applied to the unit. Harmonic testing was performed on each unit in the relay.

With pure n^{th} order harmonics applied to the differential unit, an increase in frequency results in a higher pickup value than that of the fundamental pickup value because of the greater influence of the air gap transformer in the restraint circuit. Mixed frequency harmonics were applied at a magnitude of the fundamental plus the n^{th} order of harmonic superimposed at a magnitude of 1/n of the fundamental. The pickup of the differential unit was within 3% of the 60 Hz pickup value.

The harmonic restraint unit of the relay is tuned to block on 120 Hz current. This was verified in testing such that with increasing magnitude at 120 Hz, the polar type element produced increasing restraint. For higher than 2nd order frequencies, the harmonic restraint unit pickup increased, reaching a point of non-operation at 9th order input.

Microprocessor Overcurrent Relays

The microprocessor relay used in these tests operates on the asynchronous sampling technique described earlier. This results in an overcurrent relay that is responsive to RMS.

The variance of pickup from the fundamental to the 9th order harmonic was 7%, compared to the electromechanical equivalent relay as shown in Figure 8. Mixed frequency inputs caused the microprocessor relay's pickup to remain within 4% of the fundamental pickup value.

The instantaneous function of this microprocessor relay also takes advantage of digital sampling techniques, and yielded similar results at variable frequency inputs. The instantaneous pickup value was within 4% with pure harmonic inputs, as compared to the fundamental. Mixed frequency inputs had little effect on instantaneous pickup.

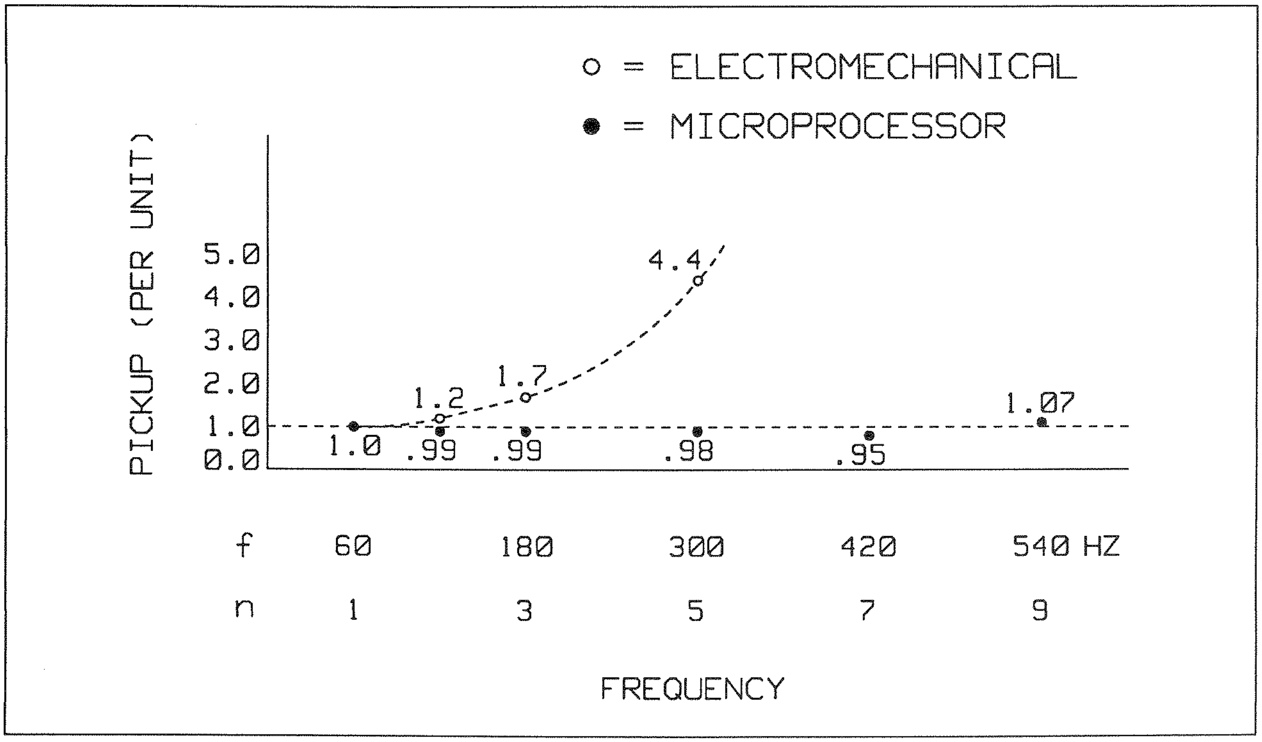

Figure 8. Comparison of electromechanical and microprocessor overcurrent relays frequency response.

Other System Conditions

In addition to harmonic influences, relay performance was tested in response to other system conditions, specifically dc offset and ct saturation.

Transient reach characteristics due to dc offset are shown in Figure 9 for the microprocessor asynchronous sampling (MCO) and the electromechanical (IIT) instantaneous units.

The effect on the microprocessor unit is less than the electromechanical as the circuit angle approaches 90°. Conversely, the electromechanical unit is nearer to 100% reach, approaching unity power factor.

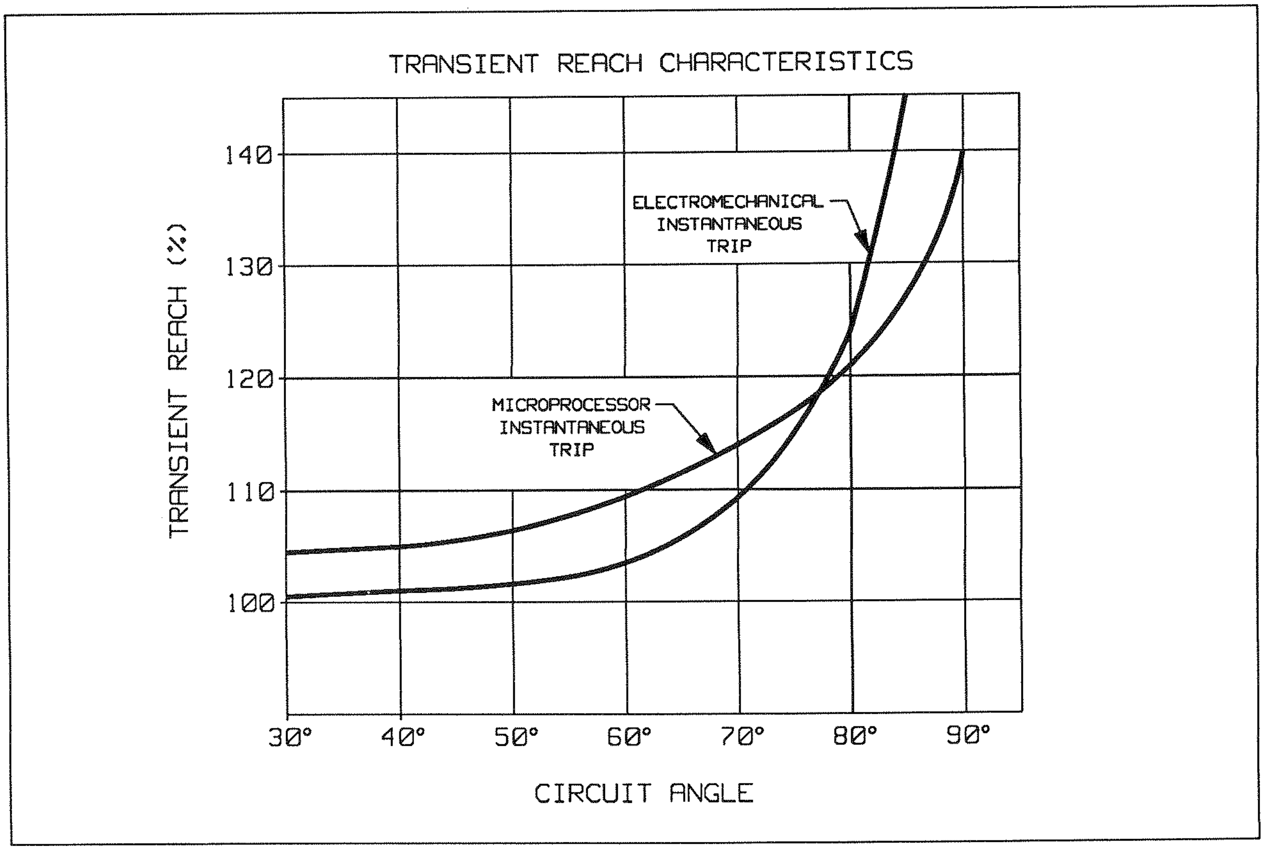

Figure 9. Transient Reach Characteristics.

Both units were also tested under saturated ct conditions. Pick up response time increased approximately 7% in both cases with a severely saturated waveform input as compared to an unsaturated sinewave input.

From this series of tests, it is evident that the influence of harmonics (with magnitude decreasing with order) on the steady state behavior of the protective relays studied is minor and insignificant. For faults containing a substantial dc component, the performance of various relaying units will vary markedly depending upon the duration of the dc and more importantly on the nature of the measuring concept.

TABLE 1 - TEST RESULTS

MEASURING UNIT	APPROXIMATE PICKUP FOR SINGLE FREQUENCY INPUTS	PICKUP WITH MIXED FREQUENCY INPUTS
Clapper	$\alpha \sqrt{f}$ (may chatter)	slightly higher RMS pickup
Induction disc (overcurrent)	higher	essentially unchanged
Induction disc (phase unbalance)	15% lower at 120, 180 Hz. 15% - 30% higher up to 540 Hz.	essentially unchanged
Negative Sequence Overcurrent	$\alpha \sqrt{f}$	essentially unchanged
Cylinder (directional)	α f	slightly higher
Cylinder (bus differential)	αf^2	slightly higher
Cylinder (undervoltage)	$\alpha f^{.85}$ α f 0.85	same fundamental pickup
Polar (transformer differential)	$\alpha f^{0.25}$ α f 0.25	slightly higher
Polar (harmonic restraint)	blocks at 2nd, decreases beyond 2nd.	blocks at 2nd
Microprocessor (asynchronous sampling)	no change	RMS responsive

Conclusions

This paper has attempted to show, theoretically and by laboratory tests, the influence of harmonics on protective relays. Representative relays using various operating principles were tested using fundamental currents and/or voltages. They were then tested using single frequency inputs that were multiples of the fundamental frequency. Finally, tests were made using realistic combinations of fundamental and harmonics.

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