The Effect of Non-Sinusoidal Current Waveforms on Electro-Mechanical & Solid State Overcurrent Relay Operation

P. M. Donohue **Syed Islam SMIEEE**

Abstract - **Modern day power systems create harmonics within the electrical network that can have an impact upon the associated protection system. This paper has investigated how both an electro mechanical and a solid state protection relay are affected by the non-sinusoidal resulting current within the electrical system. The work was carried out using a commonly used GEC CDG11 overcurrent relay and a Multilin 369 Plus Motor Management Relay. The testing was carried out using a three phase Omicron 256 Plus secondary injection test set.**

The test results showed that harmonic currents are not filtered out by either of the two relays, and that both of the relays tested will operate faster than they are otherwise seen to do due to non-sinusoidal currents.

The work further demonstrated that neither of the relays responded to the simple equivalent RMS summation of the harmonic current in the circuit.

I. INTRODUCTION

Many users of electrical power systems generate harmonic currents within their system from the use of equipment such as variable speed drives, induction furnaces etc. The harmonic currents generated, from this type of equipment, will cause the supply current to become non-sinusoidal if filtering is not present.

A non-sinusoidal electricity supply will increase the losses in power transformers, induction motors and other equipment connected to it [1]. These losses in power are seen as additional heat in the equipment being subjected to the non-sinusoidal supply. It is widely known that the value of insulation is adversely affected by heat and that even a small increase in heat can shorten the life of power equipment such as that described above. This has been well documented by others notably Fuchs and Massoum [2].

Electricity supply authorities in Australia and other countries, seek to regulate the production of harmonics by electricity power users at the point of common coupling. [3] This ensures that the sinusoidal supply provided to other customers, is maintained within preset limits and at the same time ensures that the maximum life and efficiency is obtained from the supply authorities upstream transformers and generators.

The primary purpose, of this paper was to examine the effects of non-sinusoidal currents on two particular power system protection relays. These were the GEC CDG11 IDMT overcurrent relay and the GE Multilin 369 Plus motor management relay.

In 1998 Fuller, Fuchs and Roesler, carried out research supported by the US Department of Energy. The area investigated demonstrated that the pick-up times for a number of both electro-mechanical and electronic relays were affected by non-sinusoidal supplies.

In research centered on the pick-up times of an unspecified electro-mechanical relay with an inverse time curve. As with the work in 1998 this investigation also showed that the pickup times of the protection relays could not be determined when the monitored power was not sinusoidal. [4]

Work by Elmore, W.A. Kramer, C.A. Zocholl, S.E. in 1993 determined that the effects of harmonics currents, at magnitudes less than the fundamental value, had an insignificant effect on the steady state behavior of the protection relay. [5]However this work has shown that under non-sinusoidal conditions at full load levels the relay could produce a trip condition.

This work has not looked at the pickup times for the relays but instead has concentrated on the actual trip times of the relay when subjected to a non-sinusoidal current.

Whilst the GEC CDG protection relays are no longer in production they are still in service today, monitoring medium and high voltage networks around the world.

The GEC CDG relay was brought out at a time well before the common day use of six and twelve pulse variable speed drives used to control motors. Discussion with GEC CDG relay manufacturer revealed that during the development and

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Professor Syed Islam is the Head of the Department of Electrical and Computer Engineering at Curtin University in Western Australia. Professor Islam provided guidance and advice to Paul Donohue for the work described in this paper. A more comprehensive report on this subject was submitted by Paul Donohue in part fulfillment of a Master of Engineering Science degree in Electrical Utility Engineering in November 2008.

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production phases these electro mechanical relays were not tested for operation under non sinusoidal conditions. Therefore the manufacturer had no primary data available to specify how this relay would function under these conditions. However there was some expectation, from a past employee of the company, that the relay would operate based on the equivalent resulting RMS current of the non-sinusoidal current.

The other relay tested for this paper was the GE Multilin 369 Plus Motor Management Relay. This device is an electronic relay that is in production today, as the previously mentioned CDG relay, it is in widespread use throughout the world.

This Multilin relay comes with a large user manual that specifies the range of fundamental frequencies under which the relay will operate. Unfortunately the user manual does not specify how the relay will function under non-sinusoidal conditions. The local suppliers of this relay “believed” that 369 plus would filter out the harmonic currents and operate on the RMS values of the fundamental frequency alone.

The lack of information as to how these two commonly used, but very different, relays would function under non-sinusoidal conditions made them an important and yet obvious choice for further investigation.

The testing was carried out using an Omicron CMC256 Plus three phase secondary injection test set. This equipment allows the user to produce a fundamental current and simultaneously up to three harmonic currents. The magnitude of the harmonic currents can be adjusted to be a percentage of the fundamental current or at a pre-determined magnitude. The harmonic currents, produced in this way, can also be set to a required phase angle to lag or lead the fundamental current. The resultant current is thus non-sinusoidal and for the purposes of this work was then fed directly from the test set into the protection relay under test.

The testing for this paper was carried out at the fundamental frequency of 50Hz as employed in Australia. The magnitude and frequency of the component currents used are as shown below in Table 1

Table 1
Magnitude & Frequency of Current Used for Testing

Frequency	Harmonic Order	Percentage of Fundamental Current
50Hz	Fundamental	100%
150Hz	3rd	33.33%
250Hz	5th	20%
350Hz	7th	14.3%

The work for this paper has shown that neither of the two relays tested:

1. Filter out the harmonic currents to operate on the current at the fundamental frequency alone.
2. Operate on the equivalent RMS current of the non-sinusoidal current

The work further demonstrated that at very low levels of non-sinusoidal overcurrent the relays could now operate some 60% faster than it would otherwise do if no harmonics were present in the system.

Electrical power users often employ equipment that shunts the harmonic currents away before it reaches the point of common coupling. This paper highlights the importance of knowing how the different protection relays employed at different levels within the electrical network will operate under non-sinusoidal current conditions. Failure to take into account the effects of non-sinusoidal conditions and the correct placing of harmonic filters may give rise to unexpected tripping of circuits, especially at low overload type conditions.

II. The Effects of Frequency on an Induction Disc Relay

The relay, investigated for this paper, was the GEC CDG11 with a Standard Inverse Definite Minimum Time (IDMT) curve. This relay, although not in present day production, is still widely used today throughout the world.

One element of the induction relay was injected with current from the test at varying the frequencies in steps from 25Hz up to 300Hz. The time taken for the relay to produce a trip signal at each step was recorded and plotted as shown in Figure 1.

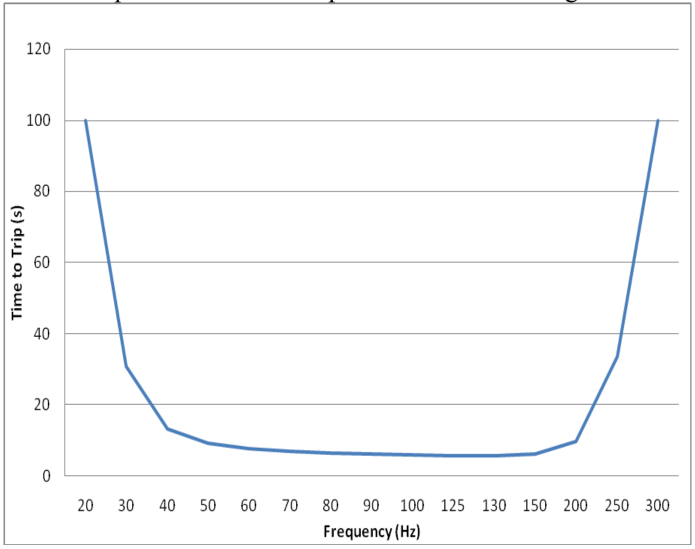

Figure 1 - Effect of Varying Frequency on an Induction Relay

The current injected into the relay was at an RMS current equivalent to two times the full load current. The time to trip method was adopted in preference to the pickup method as it produced an unarguable result.

The results from this test demonstrate that this induction relay will operate as expected at fundamental frequencies in the range of ~40 to 200Hz.

III. THE EFFECTS OF NON-SINUSOIDAL CURRENT ON AN INDUCTION DISC RELAY

The electro mechanical relay used for this testing was a used piece of equipment, it was thus decided to first test the relay using the fundamental 50Hz supply only. The data obtained from this set of tests would then be used as a yardstick against which the results of the non-sinusoidal injection tests could be judged.

The 1A relay was set to a pick up value of 100%, with a time delay of 1. A series of timing tests were then carried out at various levels of current injected into the relay under test using the Omicron CMC 256 Plus. This accurately timed and recorded both the time taken to trip and at the same time the RMS value of the current input into the relay under test.

Table 1 demonstrates the tabulated results as recorded for the actual trip time of the CDG IDMT relay under test. These results were later used to compare the difference in relay time to trip due to the additional effects of a non-sinusoidal current.

Table 2 - Induction Relay Test Results @ 50Hz

Injected Current (A)	Actual time for 50Hz (sec)
1.05	Never
1.3	28.405
1.5	16.785
1.75	11.746
2	9.332
2.25	7.944
2.5	7.024
2.75	6.369
3	5.887
3.25	5.509
3.5	5.204
3.75	4.951
4	4.73
4.5	4.41
5	4.185
5.5	4.023
6	3.883
6.5	3.751
7	3.643
7.5	3.543
8	3.45

.The formula for an IEC inverse definite minimum time (IDMT) standard inverse curve is given in GEC's documentation for the CDG relay as:

$$t = T * \left(\frac{K}{\left(\frac{I}{I_s}\right)^{\propto} - 1}\right) + L$$

Where: [6]

t = Trip Time
T = Time Multiplier
K = .14 for a standard inverse curve
$\propto$ = .02 for a standard inverse curve
I = Injected Current
Is = Pick Up Current
L = 0 for a standard inverse Curve

The preceding formula was first used to determine the expected trip times for the CDG 11 relay under test. The calculated trip times are shown in Table 3 along with the previously shown actual trip times in Table 1. The speed of operation was calculated to determine whether the relay was operating faster or slower than the required margin of operation.

Table 3 - Comparison of Trip Time at 50Hz with Trip Time and at 50Hz Plus 3rd, 5th & 7th Harmonics

Injected Current Times FLC	Actual time for 50Hz Current Only (sec)	Actual Time @ 50Hz & 3rd,5th & 7th (sec)	% Fast
1.05	Never	41.59	!!!
1.3	28.405	13.062	-50%
1.5	16.785	9.562	-40%
1.75	11.746	7.682	-31%
2	9.332	6.65	-24%
2.25	7.944	6.003	-19%
2.5	7.024	5.551	-15%
2.75	6.369	5.223	-13%
3	5.887	4.978	-11%
3.25	5.509	4.771	-10%
3.5	5.204	4.603	-9%
3.75	4.951	4.463	-8%
4	4.73	4.332	-7%
4.5	4.41	4.131	-6%
5	4.185	3.963	-5%
5.5	4.023	3.843	-4%
6	3.883	3.711	-4%
6.5	3.751	3.603	-3%
7	3.643	3.503	-3%
7.5	3.543	3.411	-3%
8	3.45	3.33	-3%

Comparison of all data obtained from the electro mechanical relay, whilst subjected to non-sinusoidal currents, was now made against the results shown in Table 2.This ensured that any variance between the actual trip times of the relay and the

Table 4 – Calculated and Actual Trip Times at 50Hz and at 50Hz Plus 3rd, 5th & 7th Harmonics

Injected 50Hz Current (A)	Calculated Equivalent RMS Current (A)	Actual time for 50Hz Current Only (sec)	Calculated Trip Time @ 50Hz plus 3rd, 5th & 7th (sec)	Actual Time to Trip @ 50Hz & 3rd,5th & 7th (sec)
1.05	1.134	Never	55.60	41.59
1.3	1.404	28.405	20.56	13.062
1.5	1.62	16.785	14.44	9.562
1.75	1.89	11.746	10.93	7.682
2	2.16	9.332	9.02	6.65
2.25	2.43	7.944	7.81	6.003
2.5	2.7	7.024	6.98	5.551
2.75	2.97	6.369	6.36	5.223
3	3.24	5.887	5.88	4.978
3.25	3.51	5.509	5.51	4.771
3.5	3.78	5.204	5.19	4.603
3.75	4.05	4.951	4.93	4.463
4	4.32	4.73	4.71	4.332
4.5	4.86	4.41	4.36	4.131
5	5.4	4.185	4.08	3.963
5.5	5.94	4.023	3.86	3.843
6	6.48	3.883	3.68	3.711
6.5	7.02	3.751	3.52	3.603
7	7.56	3.643	3.39	3.503
7.5	8.1	3.543	3.28	3.411
8	8.64	3.45	3.18	3.33

Manufacturer's published trip times, for the same GEC CDG protection relay, was taken into account.

The following series of tests were carried out with the same 1A RMS 50Hz fundamental current as before, but this time with the addition of harmonic currents of the third, fifth and seventh order at values previously shown in Table 1.

As can be seen from Table 3, with the addition of harmonic currents at RMS values shown in Table 1, this protection relay will now operate for an overload situation at just 1.05 times the full load current. This magnitude of purely fundamental current was previously found to be insufficient to cause the relay to operate.

Table 3 clearly shows how the operational speed of the relay is increased as the level of overload current is decreased. This demonstrates that for low overload situations the relay will operate much faster under the presence of non-sinusoidal currents than it would otherwise be expected to do.

As the manufacturer had indicated that this relay would operate as a function of the equivalent RMS current a check was made in this area.

The equivalent RMS current for the circuit containing third fifth and seventh harmonic current at the magnitudes previously discussed and at a zero phase shift can now be seen to be:

$$I = \sqrt{(I_1^2 + I_2^2 + \ldots I_n^2)}$$

Where:

$$I_1 = \frac{I_{1max}}{\sqrt{2}} \quad [7]$$

For a fundamental 50Hz current of 1A and with the addition of harmonic current that are as specified in Table 5 the equivalent RMS current becomes.

$$I = \sqrt{(1^2 + .333^2 + .2^2 + .143^2)}$$

$$= 1.0823A$$

[7]

This shows that 1.0823A is the equivalent RMS current for the complex wave with a zero phase shift consisting of

- 1 A @ 50Hz
- 0.333A @ 150Hz
- 0.2A @ 250Hz
- 0.143A @ 350Hz

Calculated trip times, using the equivalent RMS current, for the GEC CDG 11 relay equivalent RMS currents were now compared against the actual trip times.

Column one in Table 4 shows the actual 50Hz fundamental current injected into the relay. Column two shows the calculated equivalent RMS current with the addition of third, fifth and seventh harmonic currents as described above. Columns four and five of this table show the calculated and actual time taken to trip under these harmonic conditions.

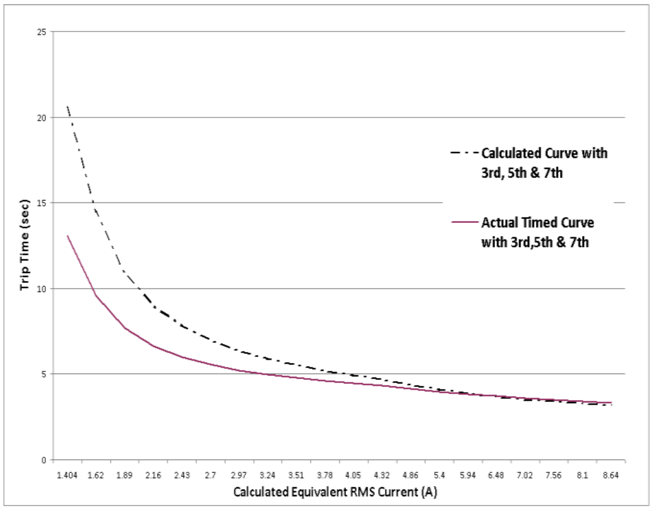

Figure 2 - Comparison of Constructed Trip Curve with Actual Curve

As can be seen in Figure 2 the calculated value of the trip curve subjected to third, fifth and seventh harmonic current was found to produce a slower trip time than was actually seen to occur.

This clearly demonstrates that the additional torque on the induction disc, of the relay, due to a non-sinusoidal current is not simply proportional to the magnitude of the additional equivalent RMS current.

IV. THE EFFECTS OF FREQUENCY ON THE ELECTRONIC RELAY

As with the induction relay, a test was first carried out varying the frequency of the supply at two times the full load fundamental 50Hz current.

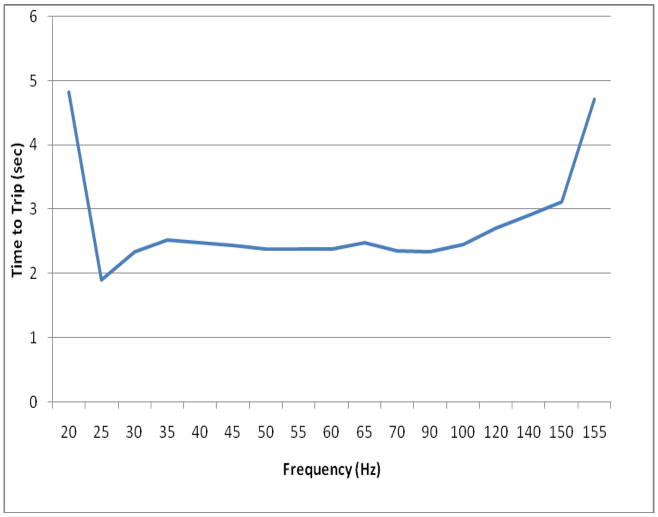

Figure 3 - Effect on Trip Time at 2 x FLC with Varying Frequency

The graph obtained from the testing did not fully correspond with the specification given by the manufacturer of the relay. The manufacturer’s data stated that this relay would operate over range of 20Hz to 100Hz. The data obtained from the testing showed that the operation of the relay will remain reliable at a magnitude of two times the full load RMS current over the range of 35Hz to ~100Hz.

V. THE EFFECTS OF NON-SINUSOIDAL CURRENT ON THE ELECTRONIC RELAY

The maximum error for the Multlin 369 Plus relay is given in the manufacturer’s technical data as +/-2%. The relay was found to be operating within these limits, with the exception of the seven times full load current test. These results were again checked to ensure that they were repeatable and very similar results were obtained. It was assumed that the slight discrepancy in the seven times test is due to the error in the test equipment.

As the calculated results and the actual results for the relay were very similar, it was decided to use the calculated values when making comparisons for trip times under non-sinusoidal conditions.

The Multilin 369 Plus relay displayed an “expected time to trip” message that decremented to zero as the relay trip time approached. Where the Omicron test set was unable to meet the required duration of trip current the value of expected time to trip was taken from the protection relay. These trip times are shown in the following tables with the letters Est after them to signify that they are not actual trip times but estimated trip times obtained from the protection relay itself.

In this test harmonic current of the third, fifth and seventh order was added to the fundamental current. The time taken for the relay to trip under these non-sinusoidal conditions is shown below in table 5.

Table 5. The Multilin Published Test Results at the Fundamental 50Hz Current and the Actual Recorded Trip Time at 50Hz Plus 3^{rd}, 5th & 7^{th} Harmonic.

Times FLC	Expected Time at 50Hz Only (sec)	Actual Time with 3rd,5th & 7th Harmonic (sec)	% Fast
1.05	5122.3 Est	2107	-59%
1.3	760.82	610	-20%
1.5	419.94	353.046	-16%
1.75	254.49	215.384	-15%
2	174.95	143.788	-18%
2.25	129.18	107.369	-17%
2.5	99.96	85.369	-15%
2.75	79.96	67.977	-15%
3	65.59	54.962	-16%
3.25	54.87	46.156	-16%
3.5	46.64	39.573	-15%
3.75	40.17	33.548	-16%
4	34.98	29.339	-16%
4.5	27.25	23.18	-15%
5	21.86	17.94	-18%
5.5	17.94	14.563	-19%
6	14.99	12.151	-19%
6.5	12.72	10.152	-20%
7	10.93	8.937	-18%
7.5	9.49	7.972	-16%
8	8.33	7.954	-5%

The magnitude of the harmonic currents used in this series of tests is the same as the values previously used when carrying out similar testing on the induction relay and was shown in Table 1.

Table 5 clearly shows how the trip time for the Multilin 369 Plus Motor Protection relay is dramatically effected at 1.05

times the full load current. At this value of over load the relay is seen to operate almost 60% faster than it would do so without the presence of harmonic currents in the circuit.

At overload values between 1.3 times full load current and eight times the full load current the relay is seen to still operate much faster than it would otherwise do without the presence of these harmonic currents. Over this range of overload the relay is seen to operate around 15% to 20% fast. For comparison purposes, a check on the Multilin 369 Plus to determine how this relay would operate with respect to the equivalent RMS current in the circuit.

The speed of operation for a standard curve multiplier of six as used in this series of tests with the GE Multilin relay is given by the formula

$$time\ to\ trip = \frac{6 * 2.2116623}{\left(.02530337 * (FLC-1)^2\right) + \left(.05054758 * (FLC-1)\right)}$$

From the above formula and the equivalent RMS current, as previously calculated, the calculated times to trip were calculated as shown in Table 6 below.

Table 6 - Multilin - Calculated Speed of Operation with Harmonics v Actual Speed of Operation under Non-Sinusoidal Conditions

Times FLC	Calculated Equivalent Harmonic Current x FLC (A)	Calculated Time for Equivalent Calculated Harmonic Current (sec)	Actual Trip Time (sec)	% Fast/Slow
1.05	1.136415	1801.44	2107	-17%
1.3	1.40699	535.87	610	-14%
1.5	1.62345	320.93	353.046	-10%
1.75	1.894025	202.86	215.384	-6%
2	2.1646	142.40	143.788	-1%
2.25	2.435175	106.45	107.369	-1%
2.5	2.70575	83.02	85.369	-3%
2.75	2.976325	66.77	67.977	-2%
3	3.2469	54.99	54.962	0%
3.25	3.517475	46.14	46.156	0%
3.5	3.78805	39.30	39.573	-1%
3.75	4.058625	33.91	33.548	1%
4	4.3292	29.57	29.339	1%
4.5	4.87035	23.09	23.18	0%
5	5.4115	18.55	17.94	3%
5.5	5.95265	15.24	14.563	4%
6	6.4938	12.74	12.151	5%
6.5	7.03495	10.82	10.152	6%
7	7.5761	9.30	8.937	4%
7.5	8	8.33	7.972	4%
8	8	8.33	7.954	4%

Table 6 demonstrates that the Multilin is not simply reacting to the equivalent RMS current of a complex waveform. The speed of operation is now seen to change from acting 17% slow at low over load currents to 6% fast at 6.5 times the FLC The trip curve for the Multilin 369 Plus with a 50Hz current plus third, fifth and seventh harmonics is seen to follow a different curve from the equivalent RMS current of a complex wave form.

VI CONCLUSION

This paper has shown that harmonic currents are not filtered out by the modern day electronic relay tested as was claimed by the agents supplying the Multilin 369 Plus Motor Management Relay.

It has been shown that the both types of protection relays tested here provided a change in speed of operation that is inconsistent with the simple equivalent RMS value of the current.

This change in speed of operation due to the presence of a non-sinusoidal current could lead to a discrimination problem within a power network. The non-coordination of the protection equipment within a power system would be most noticeable at low overload conditions.

Research carried out in this paper has shown that others have looked at various aspects of this problem and that all have concluded that different relays react in different ways to non-sinusoidal conditions. 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. However the work has found that harmonics cannot be simply ignored as to do so could give rise to inaccurate grading within the system leading to the unnecessary loss of some or part of that network.

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