# Development of Evaluation Tests for Sensitive Earth Fault Protection

## Protection Applications


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## 1 Abstract

Sensitive Earth Fault (SEF) protection has been employed by Ausgrid (formerly EnergyAustralia) to detect high impedance earth faults on its 11kV system. The SEF protection detects faults which are below the typical earth fault protection i.e. for earth faults in the range of 3 to 250 amps.

Originally SEF relays were developed in house, later electronic relays and recently numerical relays were employed. The following paper presents our present method for testing SEF relays, an explanation of the development of these testing methods and the experience gained from these tests.

Testing includes frequency response of the relay, response to actual high impedance faults (obtained from the Canadian Electricity Association) and transients generated by sympathetic saturation of zone transformers.

Testing ensures that the relay is sensitive to faults and non sensitive to switching transients.

## 2 Introduction

Sensitive earth fault (SEF) protection has been used by EnergyAustralia for at least 48 years. It has provided a means of detecting low magnitude current faults in the range of 3 to 200 amps on overhead 11kV feeders. Such faults as a conductor falling on high resistive surfaces (eg roadways, sand, a timber fence or vehicle) do not provide sufficient current to operate feeder earth fault overcurrent protection, which has a typical primary pick up setting of 220 amps.

A fallen conductor left energised presents the possibility that the public could be exposed to live conductors and step and touch potentials. Hence the aim is to have as low as possible primary pick up and the lowest operating times.

There are limits to how low the SEF pickup can be set. These limitations include unbalanced currents resulting from variation in phase insulation and capacitances. There are also magnetising losses in the current transformers which will raise the primary pickup. The magnetising losses effectively increase the primary pick up between 1.5 to 3 amps. There are additional errors as the SEF relay is connected in the star point of the phase current transformers hence the SEF current is the residual of the addition of the phase currents and the phase current transformers' errors are additive. Hence for a high balanced primary low, there may be spill currents in the secondary neutral due to the current transformer errors.

Over time the operating time has been varied between 60 to 5 seconds. At present the time setting is 10 seconds.

As the SEF relay is measuring a low neutral current, there are several restrictions to operating procedures. The three restrictions are the relay has to be made non auto firstly when paralleling feeders, secondly when switching between zone substations and groups and thirdly when single phase switching underground feeders with a capacitance of more than 2 microfarad (typically a length of 3.5kilometres). To overcome the first restriction the Hunter region has installed an additional relay in the zone transformer's neutral. This relay acts as a check to the feeder SEF relays. For the feeder SEF relay to trip the feeder breaker, the SEF relay and the zone transformer SEF relay have to be picked up. This avoids the necessity of setting the SEF relay to non auto when paralleling 11kV feeders.

As the SEF relays are measuring neutral currents, the 11kV feeders have to be radial and have no earth connected load.

The relay typically has a 3 amp primary pick up and a definite time relay with a time setting of 10 seconds. The SEF relay has undergone several development stages from an in house design and dedicated manufactured relay to presently being incorporated into externally manufactured numerical overcurrent relays.

## 3 First SEF Relay

The first SEF relay (1960s) consisted of an armature relay operated by rectified DC current and a thermal timing element.

The next version (1970s) was developed in house by the then Sydney County Council. The relay consisted of a current sensor and an electronic timer. The current sensor was a reed switch with a 2,000 turns coil wound around it. The AC current flowed through the coil and operated the reed switch. The reed switch contacts in turn operated the timer. The timer consisted of an UJT and an SCR. The SCR's current was interrupted by an auxiliary relay. The relay was tested for accuracy of pick up and timing and subjected to dielectric, impulse and interference tests.

The relay was set at a 50ma pick up and a timing setting of 60 seconds.

In 1984 it was decided to reduce the timer setting to 5 seconds. The 5 seconds was chosen as it was shorter than the expected reaction times of bystanders to help victims in a fallen mains situation and long enough to allow any spurious tripping to system transients.

After the relay's settings were altered numerous trips occurred. The causes of the interrupts were investigated.[1,2] A summary of the causes were:

- Ringing current occurring between the zone transformer inductance and feeder capacitance, as a result of sympathetic inrush.
- Single phase switching between zones having a difference in harmonics levels on the 11kV system
- Phase to Earth faults with high zero sequence voltages producing high out of balance feeder capacitance current as result of a phase to earth fault

The above three causes are explained in more detail below.

### 3.1 Sympathetic Inrush

When a transformer is energised there is an inrush current. This is due to the transformer's magnetising inductance and the non linear nature of the inductance. Following is an explanation.

Assume a circuit which has an inductance is supplied by an AC voltage source. If the point in time of energisation is when a current is flowing, then a decaying DC current will flow. The magnitude of the DC current is opposite to the AC current at the time of switching. The reason the DC current flows is that at the point of switching the current has to be zero. Another way of looking at the problem is that the DC current inrush will flow if the inductor's flux value is not the value that corresponds to the initial voltage of the AC voltage source.

Another form of inrush is Sympathetic Inrush which is due to an additional inductance being switched into a circuit. E.g. Assume 2 transformers are supplied from the one busbar. The busbar is supplied by a feeder. One transformer is energised and supplying load. The second transformer is de-energised. When the second transformer is energised, then an inrush current flows with a DC component. The inrush current flows between the 2 transformers causing both transformers to saturate.

To provide a simple explanation of Sympathetic inrush, I have modelled a network to simply represent a feeder and 2 transformers. See figure 1. R1 and L1 represent the feeder, R2 and L2 represent the de-energised transformer and R3 and L3 represent the energised transformer. S1 represents a circuit breaker. S1 is closed at peak current and the waveform in figure 2 is obtained.

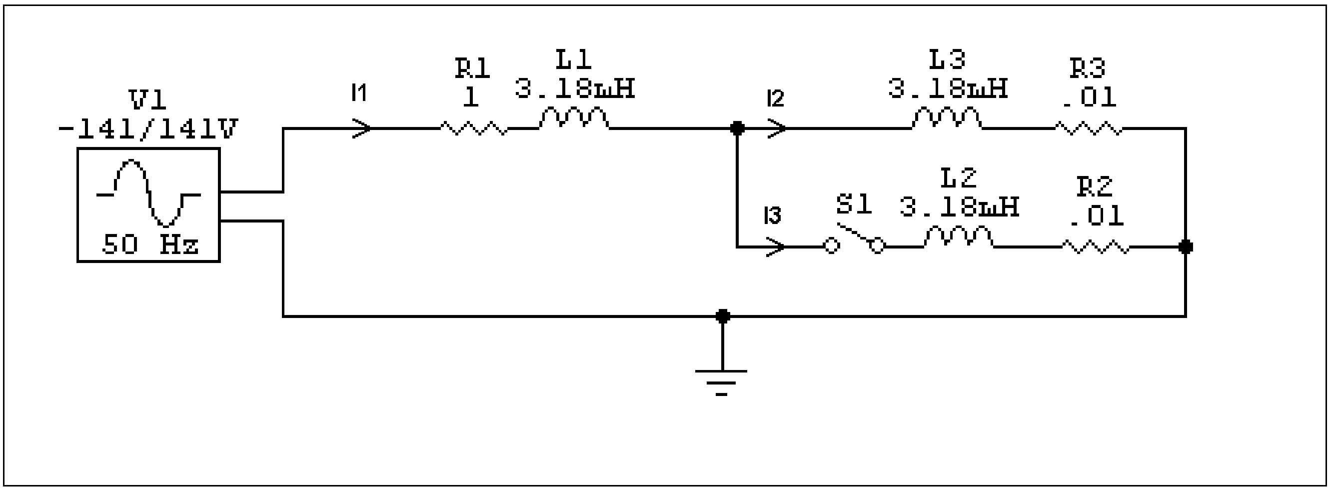



Figure 1 Simplified Circuit to explain Sympathetic Inrush

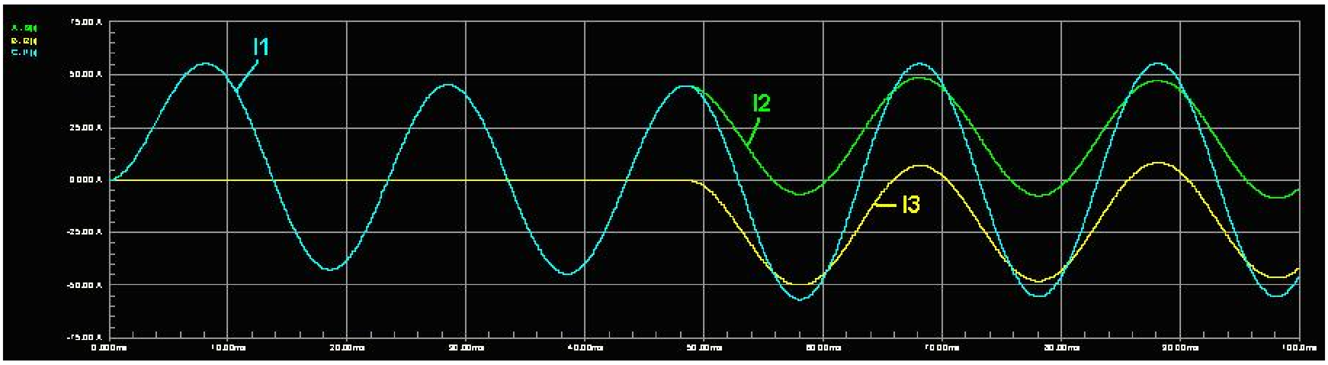



Figure 2 Traces of Sympathetic Inrush Currents

The blue trace I1, is the current through the feeder. The green trace I2, is the current through the continually energised transformer. The yellow trace I3, is the current through the newly energised transformer.

From the traces in Figure 2, you can see that the feeder current increases when the switch S1 is closed (current I1), with the impedance dropping due to the second transformer being in parallel with the first and current I1 has no DC current component. There is a high DC component flowing between the 2 transformers. Note the slow decay time constant.

For power transformers in the real world with non linear magnetic cores the DC current will cause the two transformers to be forced into and out of saturation for an extended period of time. For the loaded transformer, when saturated it does not supply load and when unsaturated it does supply load. Hence for a proportion of the 50Hz cycle the supply voltage dips on one of the secondary phases. Hence it is as if the supply voltage for a short duration is being switched on and off every cycle. On the load side this results in a step change in voltage.

The step change results in a ringing of the neutral current due to the transformer's leakage inductance and the 11kV feeder's capacitance. The 2 reactive components form a series RLC circuit. As shown in Figure 3. The voltage source can be considered as a short duration step of magnitude E. The step is occurring every 20 milliseconds.

Only transformers with star connected 11kV windings were affected. 132/11kV transformers which have a delta connected 11kV winding (earthed by a zig zag earthing transformer) produced no trips. This is due to the dips due to Sympathetic Inrush produced dips in phase to phase voltages and not phase to earth.

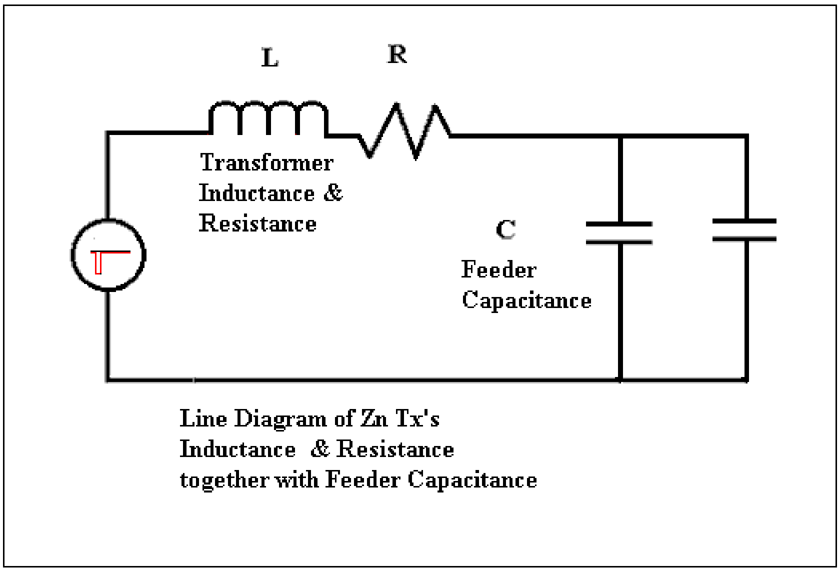



Figure 3 Transformer and Feeder Sympathetic Inrush Model

The following expressions describe the transformer's neutral current. The magnitude of current that flows through the individual SEF relays is dependant on the ratio of the feeder capacitance to the total capacitance.

Current magnitude = $E * \sqrt{\dfrac{C}{L}}$

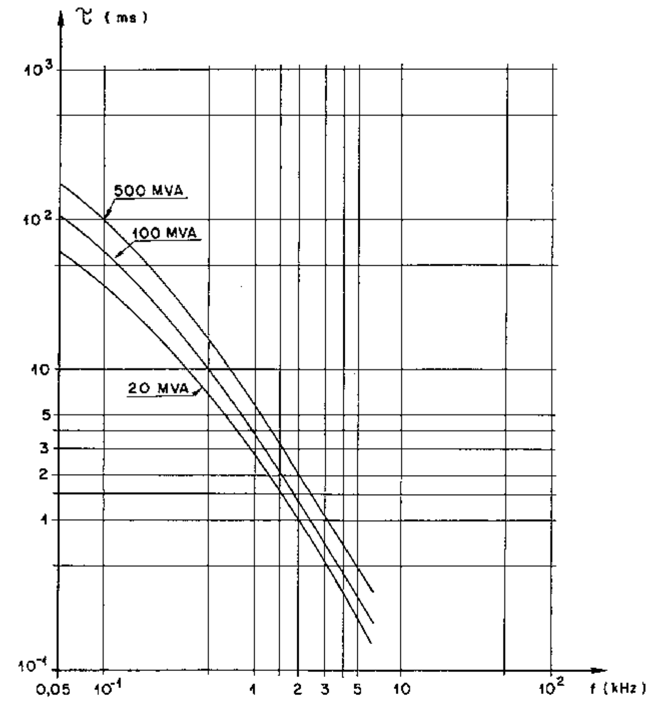
Frequency is $\approx \dfrac{1}{2\pi\sqrt{LC}}$

The magnitudes of inductance and capacitance are assumed to be frequency independent. However the transformer resistance R is frequency dependant hence the transformer's time constant is also frequency dependant. This is due to the effects of eddy currents. To determine the transformer's time constant L/R, first calculate the frequency and using Figure 4 the time constant can be determined.[3]

Time Constant = $\dfrac{2L}{R}$

Equation of the current waveform is given by the following expression:-

$$i(t) = E\sqrt{\frac{C}{L}}\exp(-\frac{rt}{2L}) \times \sin(\frac{t}{\sqrt{LC}})$$




*Time Constant ($\tau = L/R$) of Leakage Reactance of Transformers (typical values) [inductance assumed to be constant].*

Figure 4 Time Constant of Zone Transformer Leakage Reactance. Tranformer Inductance is assumed to be independent of frequency.[3]

Given the same voltage dip E due to sympathetic inrush, as the capacitance increases, the frequency decreases and the current magnitude increases. Hence for larger values of capacitance the SEF relay will be more susceptible to Sympathetic Inrush currents and conversely for smaller values of capacitance the relay response will be less.

Typical values for L, C and R are

| Zone | Tx Type | Tx Ind (mH) | Tx L/R (ms) | Cable Cap (uf) |
|---|---|---|---|---|
| Noraville | 33/11kV 10/12MVA | 3.6 | 2.8 | 9.6 |
| Kirrawee | 33/11kV 10/12MVA | 2.4 | 1.0 | 3.2 |

Comparing the calculated figures from the modelled network with the recorded results there is a good correlation.

| Zone | Cal. Freq (Hz) | Meas. Freq (Hz) | Cal. L/R (ms) | Meas. L/R (ms) |
|---|---|---|---|---|
| Noraville | 856 | 800 | 5.6 | 5 |
| Kirrawee | 33/1816 | 1850 | 2 | 2 |

### 3.2 Single Phase Switching Between Zones and Harmonic Voltages

This is another cause of SEF maloperation. In order to transfer load between zones without interruption the two zones are required to be connected. Normally this is achieved by closure of a 3 phase switch but occasionally a switch that is operated one phase at a time is employed. Such an operating function was conducted between Epping and Pennant Hills zones. The SEF protection at both zones on the switched feeder were made non auto. When the first phase was closed SEF protection on other feeders operated at Pennant Hills Zone. The cause of the maloperation was due to a combination of factors i.e. a difference in harmonic voltages at the 2 zones, the single phase switching and the high zero sequence impedance at Pennant Hills zone.

Harmonic voltages were measured at the 2 zones and found to be in the order of 2.5% for the fifth and 1.6% for the seventh. Other harmonic voltage magnitudes were insignificant. At Epping zone the zone transformer has 66/11kV delta star connections and at Pennant Hills Zone the zone transformers has 132/11kV star delta connections with an earthing transformer providing the earthing on the 11kV.

Following is an extract from Terry Fagan's paper explaining how the harmonic voltages result in zero sequence current flows in other feeders.

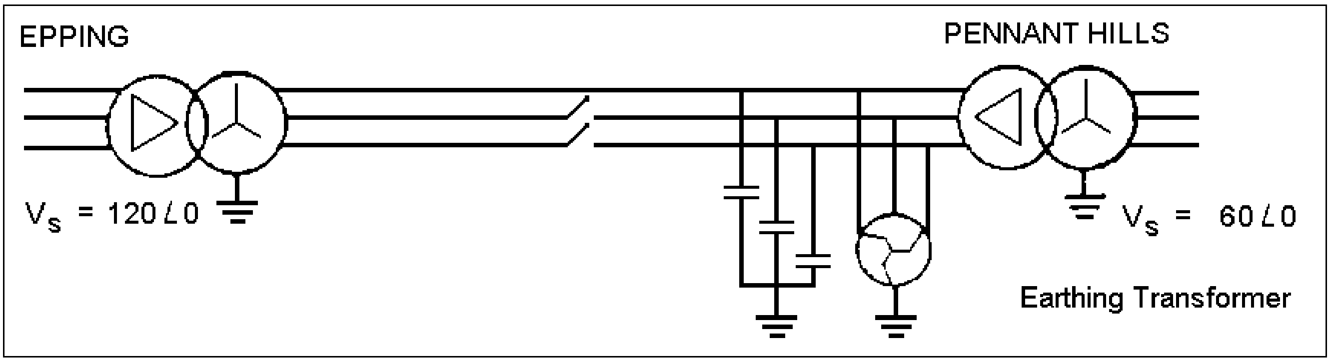



Figure 5 Line diagram showing the single phase connection between Epping and Pennant Hills Zones[2]

The above diagram consists of two zone transformers one at Epping zone and one at Pennant Hills zone and an interconnecting feeder. The system impedances at 250Hz are as follows:

Epping transformer Zone impedance details, $Z_{1TX} = Z_{2TX} = Z_{0TX} = j3.5\Omega$

Interconnecting feeder impedance details, $Z_{1FD} = Z_{2FD} = Z_{0FD} = j2.8\Omega$

Pennant Hills Zone transformer impedance details, $Z_{1TX} = Z_{2TX} = j4.0\Omega$

Pennant Hills Zone earthing transformer impedance details, $Z_{0ETX} = j26.7\Omega$

Pennant Hills Zone feeder cable capacitance impedance details,
$Z_{1CC} = Z_{2CC} = Z_{0CC} = -j13.75\Omega$

The sequence impedance for a single phase connection is as follows:

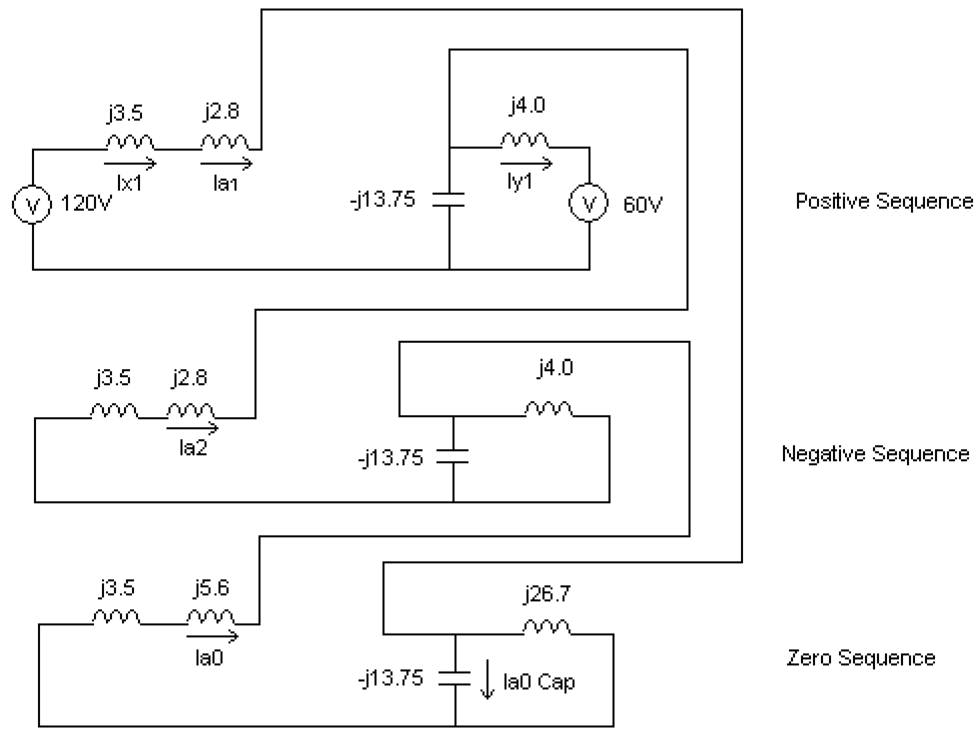



Figure 6 Sequence diagram of the single phase connection between Epping and Pennant Hills zones[2]

The above sequence network can be reduced to the following.

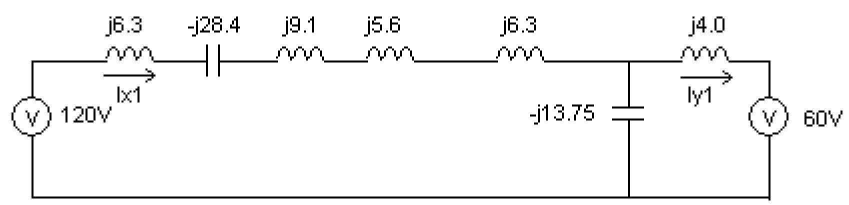



Figure 7 Reduced Sequence diagram of the single phase connection between Epping and Pennant Hills zones[2]

Looking at the above circuit, there are 2 mesh currents Ix1 and Iy1. The 2 mesh equations are:

$$120 = (j6.3 - j28.4 + j9.1 + j5.6 + j6.3 - j13.75)I_{x1} - j13.75I_{y1}$$
$$60 = -j13.75I_{x1} + (j13.75 - j4)I_{y1}$$

These equations reduce down to:

$$120 = -j14.85I_{x1} + j13.75I_{y1}$$

$$60 = -j13.75I_{x1} + j9.75I_{y1}$$

The solution to the above is $I_{x1} = -j7.8$ and $I_{y1} = -j17.1$

The current we are interested in is the Iaocap's value. This is given by

$$I_{a0cap} = \frac{I_{x1}j26.7}{j26.7 - j13.75} = -j16.1$$

The neutral current through the feeder cable's capacitor is a total of 48.3 amps at 250Hz. The individual feeder current is proportional to its feeder capacitance compared to the total capacitance.

## 3.3 Single Phase High Impedance Faults

Consider if a high impedance phase to earth fault occurs which takes a long time to be cleared by the feeder earth fault protection i.e. greater than 10 seconds, then the resulting zero sequence voltages will cause zero sequence currents to flow into the feeder cable capacitances. Following is a calculation which Terry Fagan did to show the likely scenario.

The 11kv system is modelled as a single 132/11kV zone star/delta transformer and feeder capacitance.

The 50Hz impedances of the components are

Pennant Hills Zone transformer impedance details, $Z_{1TX} = Z_{2TX} = j0.8\Omega$

Pennant Hills Zone earthing transformer impedance details, $Z_{0ETX} = j5.3\Omega$

Pennant Hills Zone feeder 42.2 microfarad cable capacitance impedance details, $Z_{1CC} = Z_{2CC} = Z_{0CC} = -j75.4\Omega$

The sequence impedance for a single phase connection is as follows:

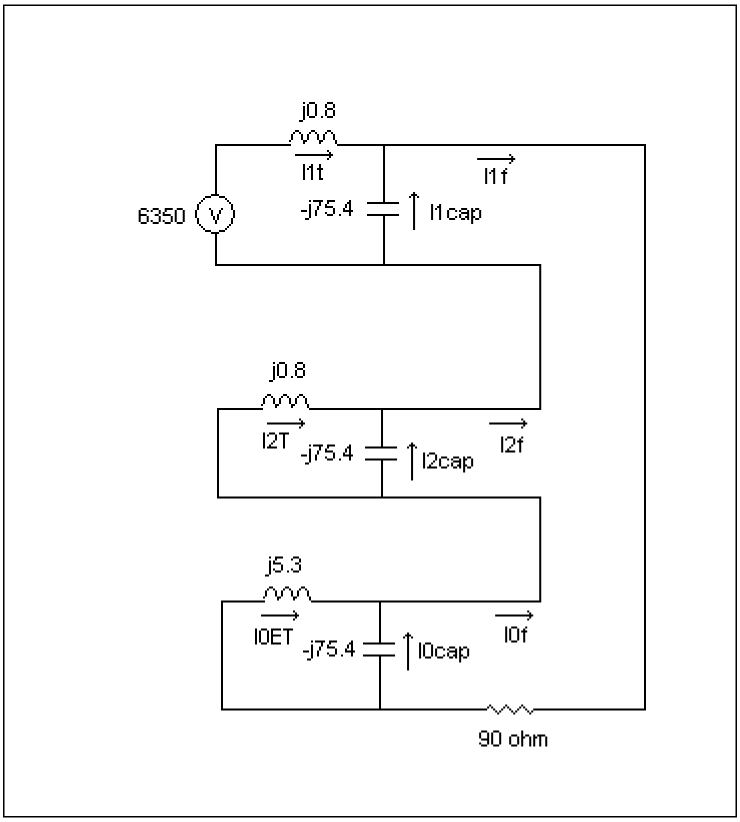



Figure 8 Sequence diagram of phase to earth fault2[2]

In the real world the arc is not a simple linear resistance but rather a non linear device that produces harmonics as well as 50 Hz voltages & currents. The resulting higher frequency currents would be impeded by the earthing transformer's impedance and cable capacitance would sink the harmonics thus adding to the capacitor's neutral current. The 50 Hz currents that will flow are shown in Figure 9 below.

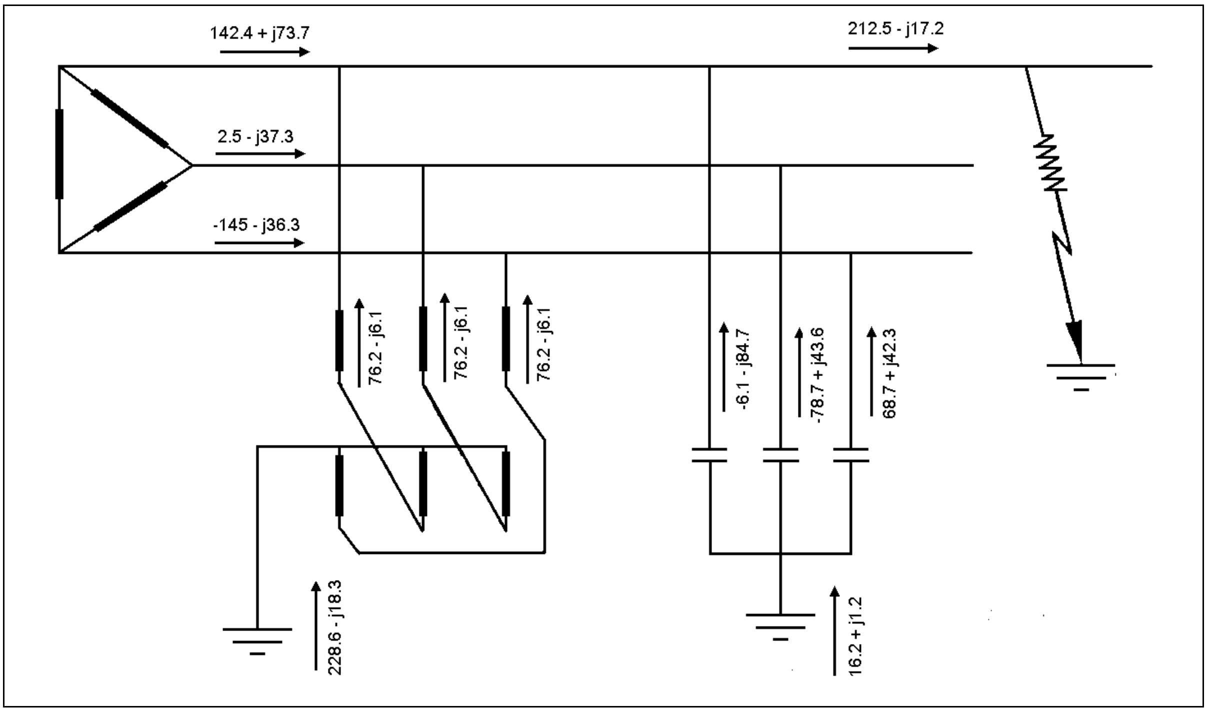



Figure 9 Capacitor and transformer currents for a phase to earth fault[2]

## 4 Redesigning the SEF Relay

Due to the findings of the investigation, filtering was added to the relay. A manufacturer supply of filtered relays was sourced. To test the new relay's suitability a 50hz current was passed through the SEF relay and the relay picked up at the correct value. A higher frequency current was passed through the relay and the relay did not respond. The new filtered relays were installed and there were no further false trips. The relay's filtering was based on analogue techniques.

However in 2002 as part of an evaluation of numerical overcurrent relays, tests were conducted to determine if the relays were suitable for application of SEF protection. The numerical relays offered the opportunity to incorporate the feeder overcurrent, earth and sensitive earth fault protection into one relay, thus reducing costs. Numerical relays are designed to operate for 50Hz but, depending on the digital signalling process technique can have mixed responses to higher frequency currents. Also with a mixed signal of fundamental and harmonics the result can be varied. The relay may also "chatter", i.e. quickly picking up and dropping out. One of the main causes for this is that the numerical relay has a short sampling window of one cycle.

As part of the evaluation and to provide a bench mark, one of the existing present analogue relays was tested. Unlike previous test methods which involved conducting 2 separate current injection tests of (a) solely fundamental (b) and solely harmonics, a mixed current signal consisting of a fundamental current above pick up and varying magnitudes of harmonics where injected into the relay. In summary the test results indicated that with no harmonics present, the relay picked up at the setting value. As the harmonic current was increased the relay ceased being picked up. The ratio at which dropout occurred was frequency dependant. The higher the frequency, the ratio of harmonic current required to cause dropout decreased. See Figure 10 below.

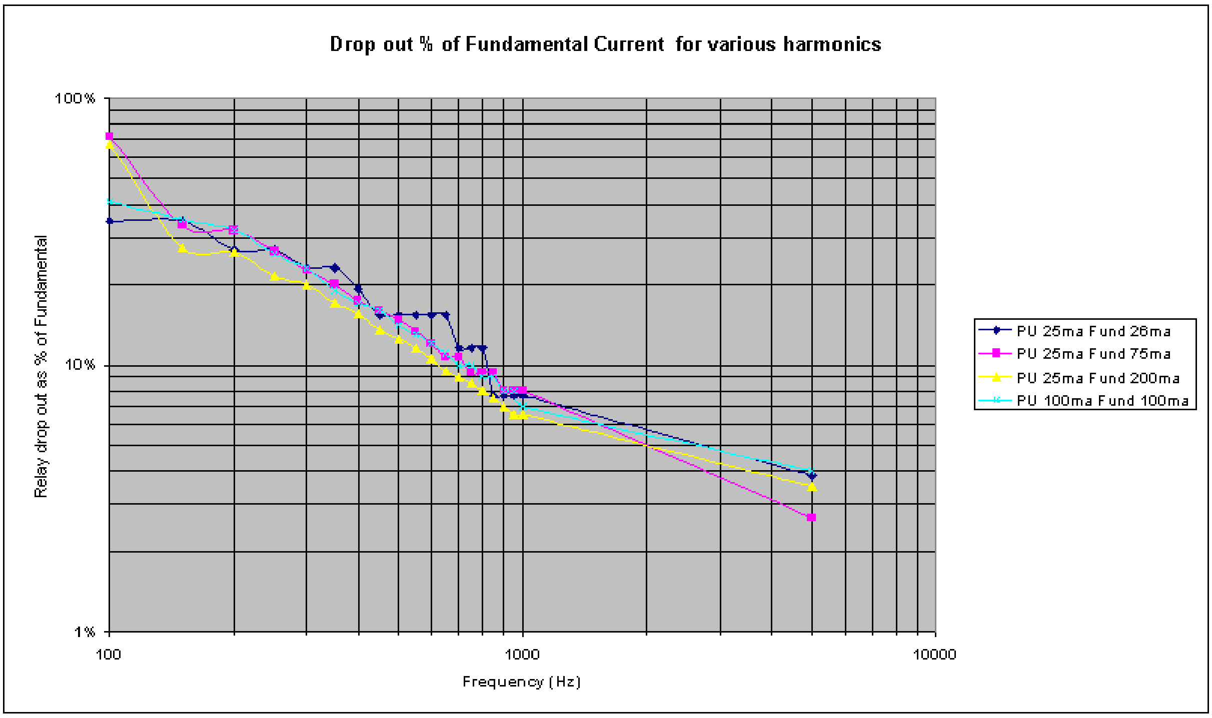



Figure 10 Older SEF relay drop out due to harmonic, level as percentage of fundamental

As a result of these observations we became aware that we had in-service SEF relays which may not respond to high impedance faults. Hence the expected levels for harmonics in high impedance faults needed to be determined. If the expected harmonic levels are high e.g. 30% at 150Hz ,the relays will require replacement. Further investigation was begun to determine the harmonic levels.

## 5 Development of test waveforms.

With modern test equipment it is possible to generate current waveforms of complex shapes using COMTRADE[4] files. COMTRADE[4] files can either be in a binary format or in an ASCII format. The ASCII format is easily constructed using mathematical tools in Excel or other such programs. COMTRADE[4] files can also be obtained by relays capturing current wave shapes passing through relays or oscilloscopes. Wave shapes stored in other formats can be translated to the COMTRADE[4] format.

Generally there are two groups of files (a) wave shapes which SEF relays need not respond to, i.e. currents due to sympathetic inrush and harmonics such as the 5$^{th}$ and (b) wave shapes which SEF relays need to respond to i.e. high impedance arc faults.

### 5.1 Sympathetic inrush wave shapes

Sympathetic inrush wave shapes were easily constructed due to excellent work done by Steve Hodginkson[1] and Terry Fagan[2]. With their investigation wave shapes were recorded by ultra violet light recorders. The results agreed closely with predicted values and formulas. The following formula was used to develop the COMTRADE4 files. The wave shape is repeated every 20 milliseconds.

$$i(t) = E\sqrt{\frac{C}{L}}\exp(-\frac{rt}{2L}) \times \sin(\frac{t}{\sqrt{LC}})$$

Below are 2 of the generated wave shapes

Wave shape 1 (below) is an 800 hertz wave shape with a time constant of 5 millisecond. The peak of the waveform is 1.67 amps. The burst is repeated every 20 milliseconds i.e. every 50Hz cycle. See Figure 11 below.

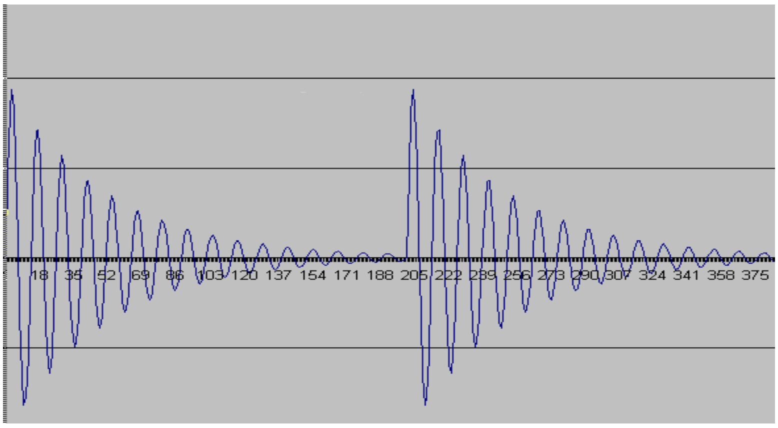



Figure 11 wave shape 1 modelled SEF current resulting from sympathetic inrush 800Hz, 5 millisecond time constant

Wave shape 2 (below) is a 1850 hertz wave shape with a time constant of 1 millisecond. The peak of the waveform is again 1.67 amps. The burst is repeated every 20 milliseconds ie every 50Hz cycle. See Figure 12 below.

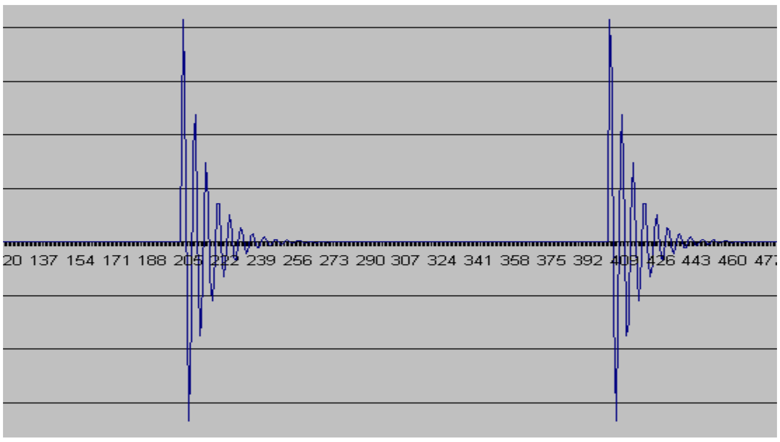



Figure 12 wave shape 2 modelled SEF current resulting from sympathetic inrush 18500Hz, 1 millisecond time constant

The above 2 wave shapes were converted into COMTRADE[4] format. The peaks for both waveforms were adjusted to be 1.67 amps, which corresponds to 100 amps primary for a CT ratio of 300/5. 100 amps peak was the highest current measured during field measurements. The relay pickup is set at 50ma and the time setting is at the relay's lowest definite time setting. Note if the relay responds then the time setting is to be altered to 10 seconds and the test is repeated. Ideally the SEF relay is not to respond to the wave shape at the lowest definite time setting.

The following two figures show the peak magnitudes of the harmonics for the 800Hz and 1850Hz waveforms.

For the 800Hz wave form the maximum harmonic is at 800Hz with a peak value of 0.44 amps. The 50Hz (fundamental) peak component is a high 0.035 amps i.e. 49% of the 50 milliamp RMS (71 milliamp peak) pick up setting. See Figure 13 below. Most SEF relays incorrectly tripped in response to this waveform.

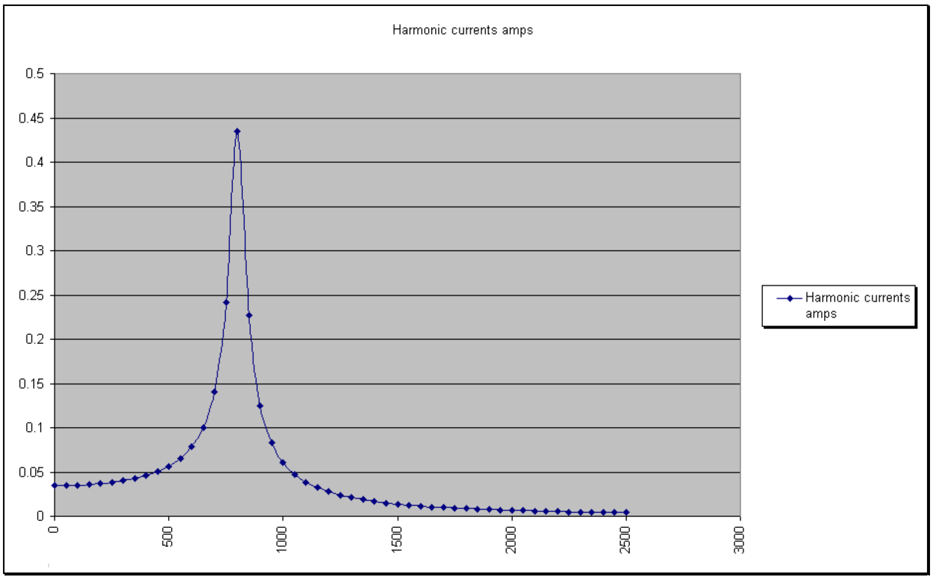



Figure 13 Harmonic content of 800Hz, 5 millisecond sympathetic inrush waveform

For the 1850Hz wave form the maximum harmonic is at 1850Hz with a peak value of 0.096 amps. The 50Hz (fundamental) peak component is a low 0.016 amps i.e. 23% of the 50 milliamp RMS (71 milliamp peak) pick up setting. See Figure 14 below. Most SEF relays had no difficulty not operating in response to this waveform.

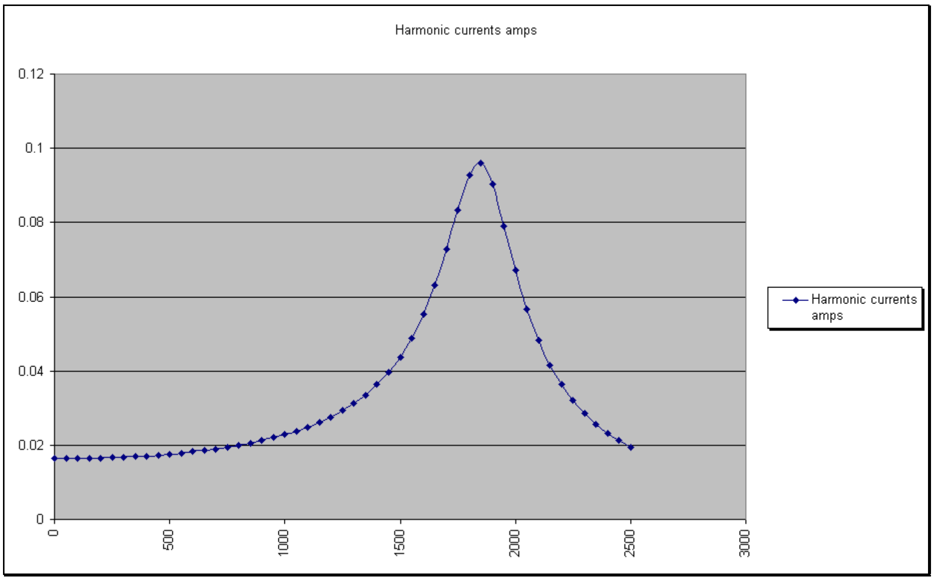



Figure 14 Harmonic content of 1850Hz, 1 millisecond sympathetic inrush waveform

## 5.2 Frequency response Tests

To determine the relay's frequency response, a number of tests were conducted. The relay was set at its lowest pick up setting and definite time setting. The tests were as follows:

1. A single frequency current was applied to the relay. The magnitude of the current was increased until the relay picked up or the relay's thermal limit was reached.
2. A mixed signal of a 50Hz current at 90% of the relay's pick up and a harmonic at varying frequencies was applied to the relay. The magnitude of the harmonic was increased until the relay picked up or the relay's thermal limit was reached.
3. A mixed signal of a 50Hz current at 110% of the relay's pick up and a harmonic at varying frequencies was applied to the relay. The magnitude of the harmonic is increased until the relay dropped out or the relay's thermal limit was reached

## 5.3 Detection of arc faults

Generally the desired requirements for a SEF relay include:

- Responds to currents with frequencies between 50Hz and 150Hz and does not respond to currents with frequencies of 250Hz and above.
- There is a possibility that higher harmonics 3 kilohertz and above could be acceptable, but further research is required.
- Responds to high impedance faults.

Our concerns were, was it possible to purchase such a relay and would limiting the relay's frequency response to higher harmonics decrease the relay's response to low current arc faults.

What was needed was data on such faults and especially if available COMTRADE4 files of the actual faults?

## 5.4 Sandy Soil Arc Model

Two overseas groups were approached for data but they declined to supply the data. Hence a literature search was begun. Our aim was to construct mathematically some arcing faults or gain an appreciation of the arc fault's harmonic content. One promising article was "High Impedance Fault Arcing on Sandy Soil in 15kv Distribution Feeders"[5]. In this article a simple model was proposed. The arc was represented as a resistance, with two diodes and two DC voltages. The inductance represents the supply inductance. See Figure 15 below.

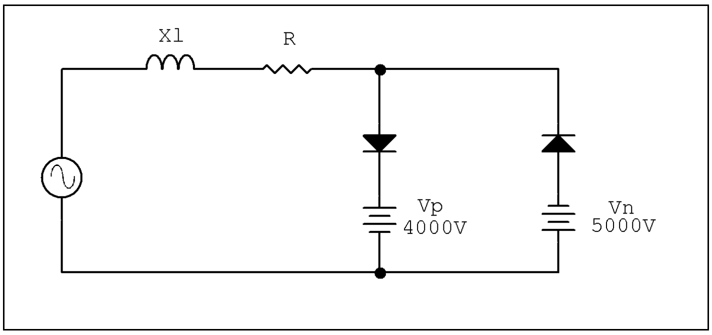



Figure 15 Schematic of the Sandy Soil Arc model[5]

Conclusions arising from the report of the work done indicate the fundamental and the third harmonic are dominant. The above circuit was modelled using Spice and Excel VBA. The wave shapes obtained by using both programs matched. A listing of the harmonic content and arc current waveform is tabled below in table 1. Note the third harmonic is approx 30% of the fundamental. The high percentage of third harmonic would indicate that the existing relays required replacement. Although the Sandy Soil Arc model is a simple model it does produce current waveforms similar to those described in the literature.

Table 1 Harmonic content of currents produced by the Sandy Soil arc model

| Frequency (hertz) | Harmonic Magnitude (amps) | Harmonic Phase (degrees) |
|---|---|---|
| 0.00 | 0.00 | 0.00 |
| 60.00 | 9.66 | 90.10 |
| 120.00 | 0.00 | 0.00 |
| 180.00 | 2.88 | -89.69 |
| 240.00 | 0.00 | 0.00 |
| 300.00 | 0.82 | -89.48 |
| 360.00 | 0.00 | 0.00 |
| 420.00 | 0.00 | 0.00 |
| 480.00 | 0.00 | 0.00 |
| 540.00 | 0.38 | 90.94 |
| 600.00 | 0.10 | 1.05 |
| 660.00 | 0.37 | 91.15 |
| 720.00 | 0.09 | 1.25 |

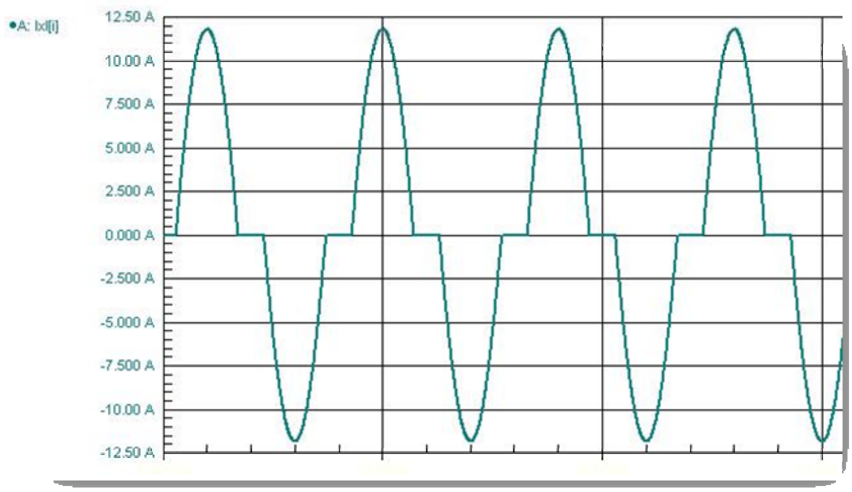



Figure 16 Sandy Soil Model Current Waveform

The frequency was altered to 50 Hertz and converted into a COMTRADE[4] file. Other methods were attempted to develop arc fault wave shapes, but were unsuccessful due to mathematical instability. And authorisation was not forthcoming to conduct staged high impedance faults testing at Lane Cove Testing Station.

During 2007 David Hughes[6] completed his university treatise on this particular topic. It was advantageous to have the assistance of David and his Sydney University co supervisor A/Prof Stephen Simpson. A/Prof Simpson has extensive knowledge in welding and has developed an automatic welding quality checking process called Weldprint.

David extended on work done previously with modelling arcs using fluorescent tubes and Cassie and Mayr models.

## 5.5 Fluorescent Tube Testing and Modelling

Tests were conducted with cold cathode 300mm fluorescent tubes and domestic 1200mm fluorescent tubes. The aim of these tests was to determine the harmonic content and the parameters of Cassie and Mayr models. The following test circuit was employed.

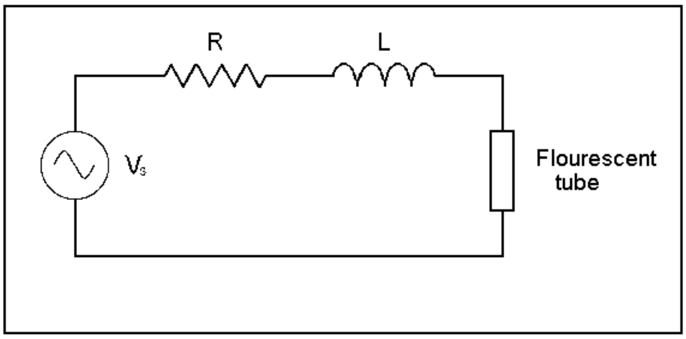


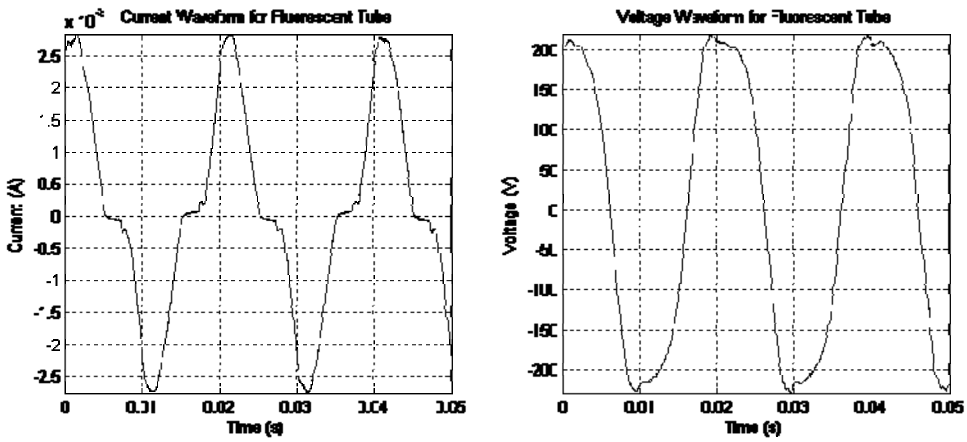

Figure 17 Schematic of the cicuit employed to record fluorescent tube currents

The following fluorescent tube testing results have been copied from David Hughes treatise (not all recordings are shown). The following parameters were varied:

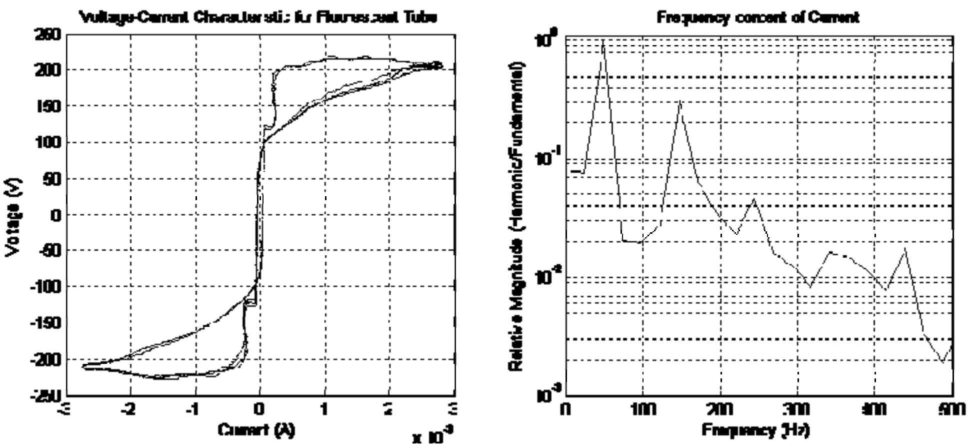
- supply voltage magnitude and frequency
- resistance and inductance magnitude and
- the length of the fluorescent tube 300, 800 and 1200 mm

- ### Medium Level Harmonic Content

The 240V, 47kΩ, 0H, 50Hz produced a current waveform with a medium level of harmonic content as observed below, see Figure 18:




(a) (b)



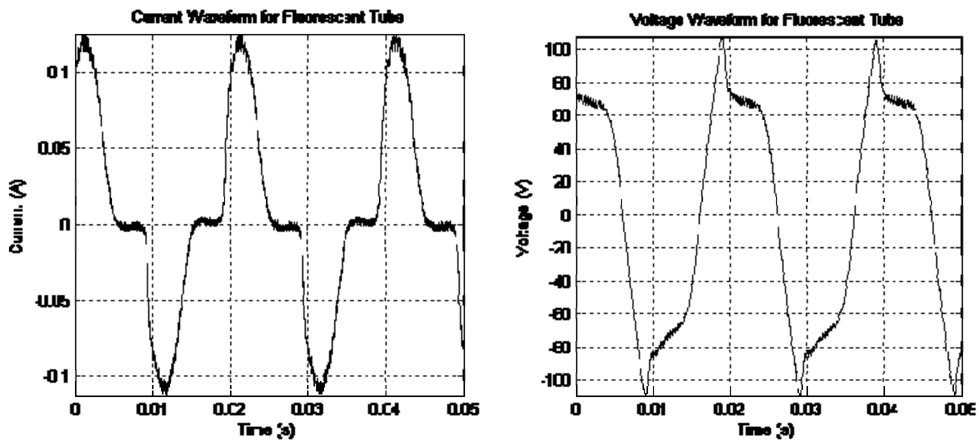

(c) (d)

Figure 18 – Measured and Calculated Waveforms for fluorescent tube experiment with Vs=240V, R=47kΩ, L=0H, frequency=50Hz (a) Current Waveform; (b) Voltage Waveform; (c) VI-Characteristic; (d) FFT for Current Waveform.[6]

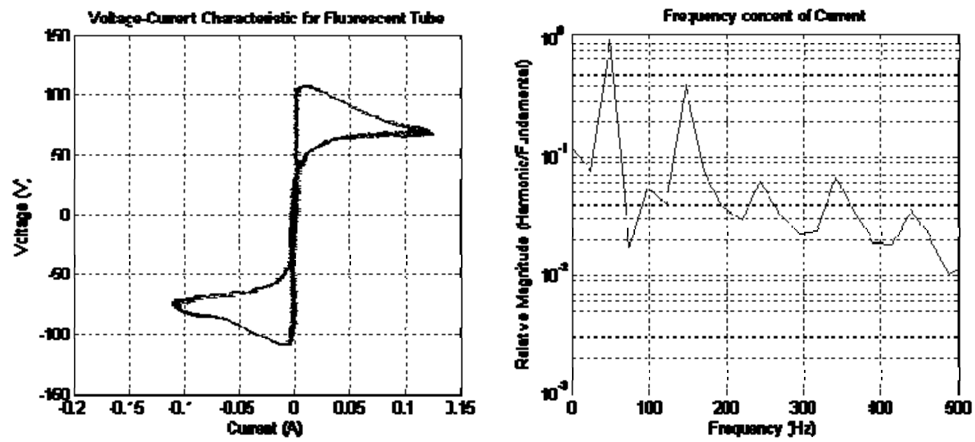
This current waveform is observed to have more significant third harmonic 30% and slight fifth harmonic 4.2% components.

- **Relatively High Harmonic Levels**

The 100V, 600Ω, 0H, 50Hz produced a current waveform with relatively high significant harmonic content as observed below, Figure 19:




(a) (b)




(c) (d)

Figure 19 – Measured and Calculated Waveforms for fluorescent tube experiment with Vs=100V, R=600Ω, L=0H, frequency=50Hz (a) Current Waveform; (b) Voltage Waveform; (c) VI-Characteristic; (d) FFT for Current Waveform.[6]

The above waveform diagram has a significant third harmonic component 40%, as well as small second, fifth, seventh and ninth harmonic components.

These waveforms could be used as part of the testing procedure for Sensitive Earth Fault relays. Current waveforms from these results would be scaled so that they contained 50 ma rms fundamental.

The fluorescent waveforms are of a similar shape to that of high impedance faults discussed in the Sandy Soil Arc Model.

## 5.6 Cassie and Mayr Modelling

The fluorescent tubes electrical behaviour was modelled by David Hughes using Cassie and Mayr formulas. The fluorescent circuit was modelled as displayed in Figure 20.

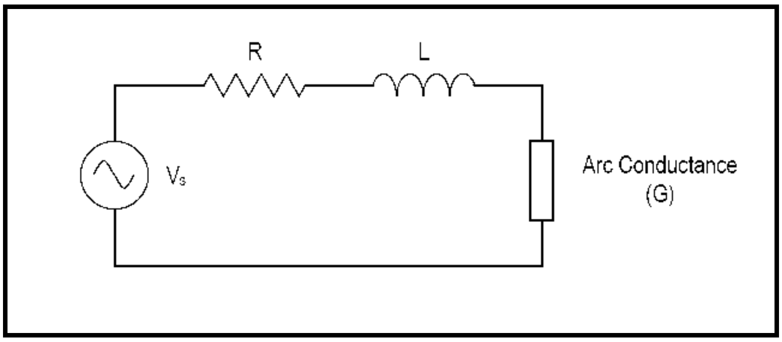



**Figure 20** – Circuit model used for calculating the modified Cassie-Mayr model[6]

Note the following is reproduced from his treatise. The Arc conductance G is determined using the following formulas:

**Modified Cassie and Mayr models of the arc**

The model used is a modified Cassie Mayr model. It is a combination of the two models Cassie and Mayr.[7]

$$G = \begin{cases} \dfrac{vi}{E_0^2} - \theta\dfrac{dG}{dt}, i > I_0 & \text{Cassie Model for high current region} \\ \dfrac{i^2}{P_0} - \theta\dfrac{dG}{dt}, i \le I_0 & \text{Mayr Model for current zero (low current) region} \end{cases}$$

To maintain differential continuity of this equation, a current dependent weighting factor is used to combine the two equations.

$$G = [1 - \sigma(i)].G_C + \sigma(i).G_M$$

where $G_C$ is the arc conductance calculated from the Cassie model of an arc, $G_M$ is the arc conductance calculated from the Mayr model of an arc and σ(i) is the current dependent weighting factor defined as:

$$\sigma(i) = \exp\left(-\frac{i^2}{I_0^2}\right)$$

Combining the above three equations results in the arc model equation below.

$$G = G_{\min} + \left[1 - \exp\left(-\frac{i^2}{I_0^2}\right)\right]\cdot\frac{vi}{E_0^2} + \left[\exp\left(-\frac{i^2}{I_0^2}\right)\right]\cdot\frac{i^2}{P_0} - \theta\frac{dG}{dt}$$

Where the time constant $\theta$ is given by $\theta = \theta_0 + \theta_1.\exp(-\alpha.|i|)$,

$\alpha \rangle 0 \, and \; \theta_1 \rangle\rangle \, \theta_0$

G = arc conductance (S), v = arc voltage (V), i = arc current (A), t = time (s), $I_0$ is the current threshold for determining the transition between the two models. Other constant parameters of the arc include:

$G_{min}$ – the impedance of the arc gap when not ignited.

$E_0$ – controls the steady state voltage level of the arc.

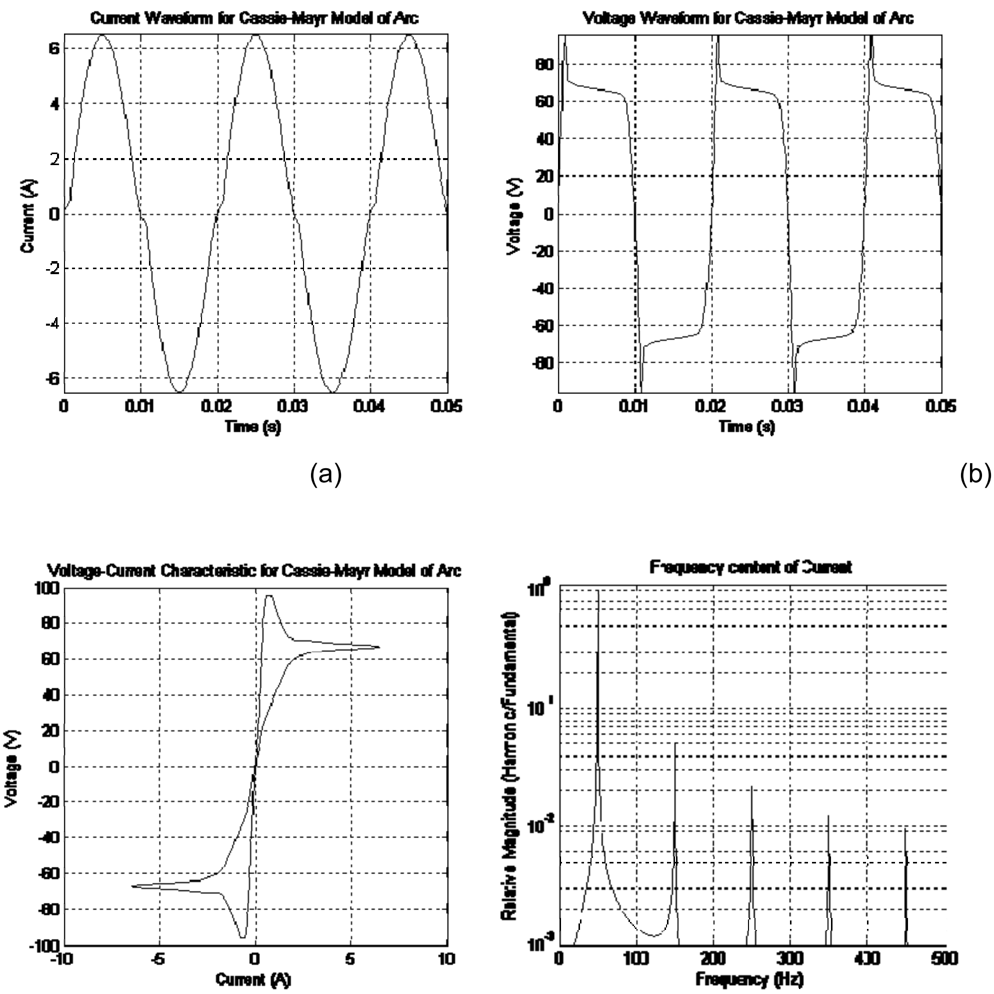
$P_0$ combines with $I_0$ and α to control the peak voltage level (low current region of the arc).

$\theta_0$ and $\theta_1$ – time constants for the low and high current regions of the arc.

By means of a trial and error process the following parameters were obtained for the fluorescent tubes waveforms. See results below, Figures 21, 22 and 22.

### Low Harmonic Content

Parameter Set: $E_0$=67; $I_0$=1.0; $\alpha$=$I_0$; $P_0$=26; $G_{min}$=1e-8; $\theta_0$=9e-5; $\theta_1$=5e-4;
R=80; L=1e-6; $V_s$=415V (rms, 50Hz);



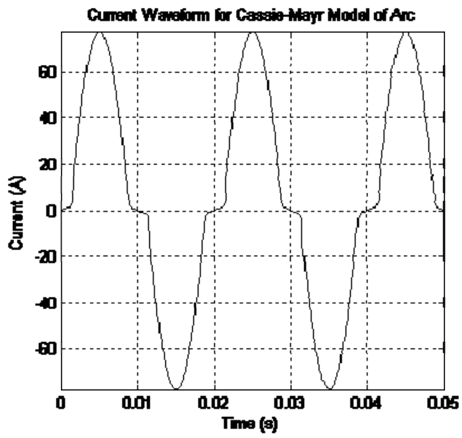

(a) (b)

(c) (d)

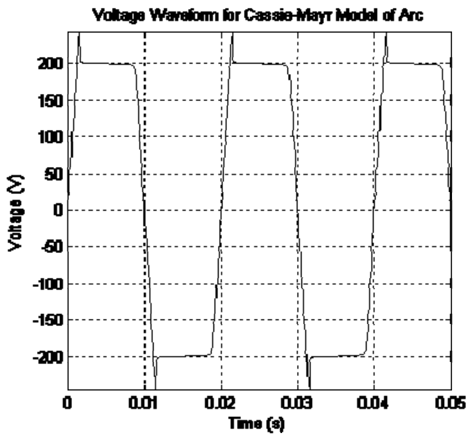
**Figure 21 –**Calculated waveforms for the modified Cassie-Mayr model of arc with low harmonic content. (a) Current Waveform; (b) Voltage Waveform; (c) VI-Characteristic; (d) FFT for Current Waveform. [6]

### Medium Harmonic Content

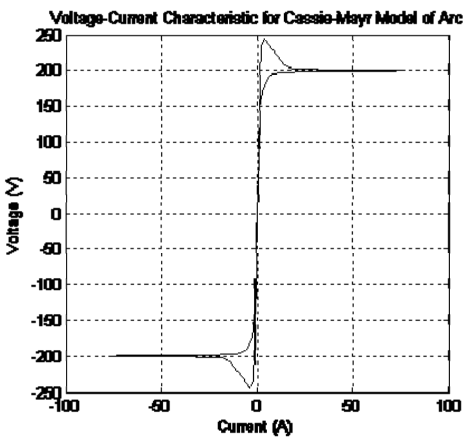
Parameter Set: $E_0$=200; $I_0$=0.5; $\alpha$=$I_0$; $P_0$=5; $G_{min}$=1e-8; $\theta_0$=7e-6; $\theta_1$=3e-4; R=5; L=0; $V_s$=415V (rms, 50Hz);



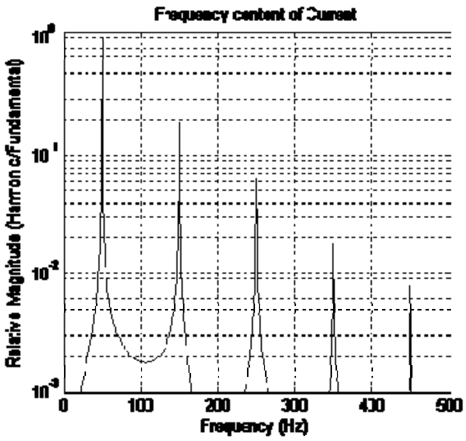

(a)




(b)




(c)

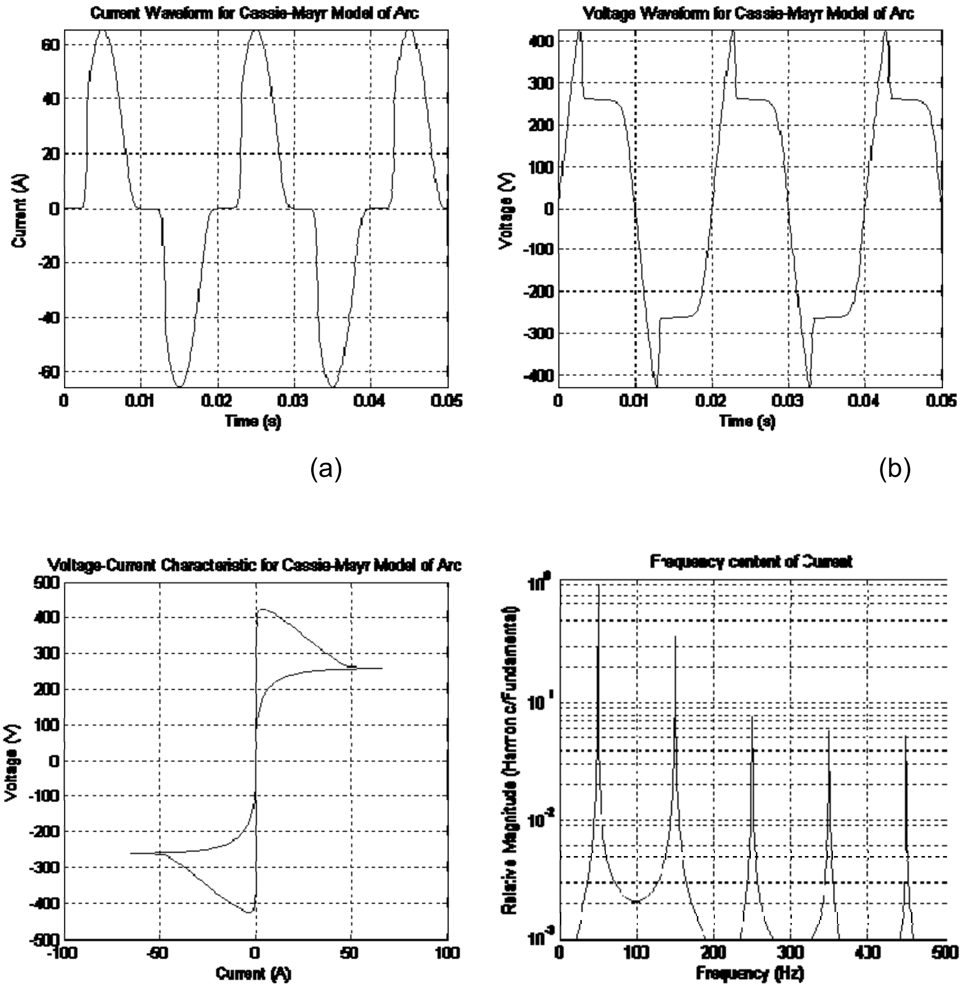



(d)

**Figure 22** –Calculated waveforms for the modified Cassie-Mayr model of arc with medium level harmonic content. (a) Current Waveform; (b) Voltage Waveform; (c) VI-Characteristic; (d) FFT for Current Waveform. [6]

### Significant Harmonic Content

Parameter Set: $E_0$=260; $I_0$=0.05; $\alpha$=$I_0$; $P_0$=5; $G_{min}$=1e-8; $\theta_0$=7e-6; $\theta_1$=3e-4; R=5; L=0; $V_s$=415V (rms, 50Hz);




(a) (b)

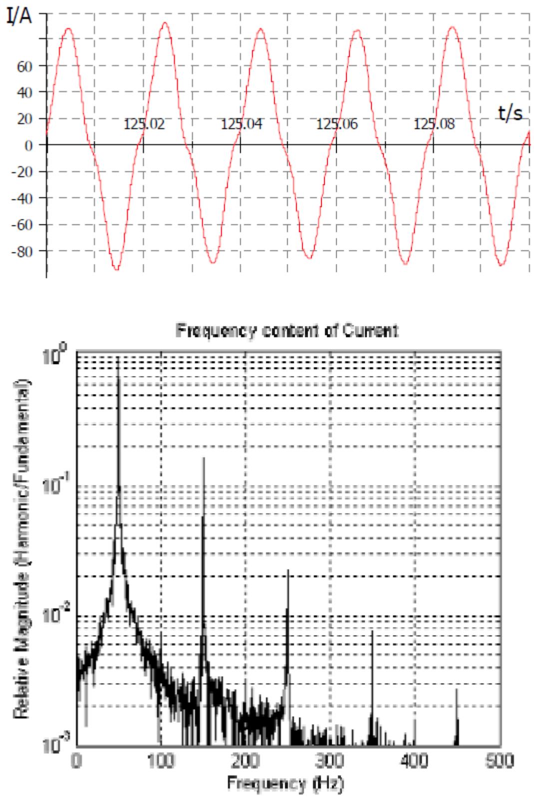
(c) (d)

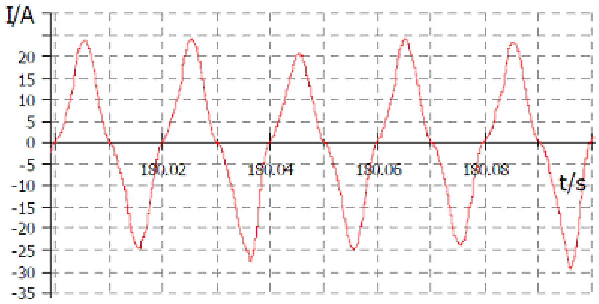
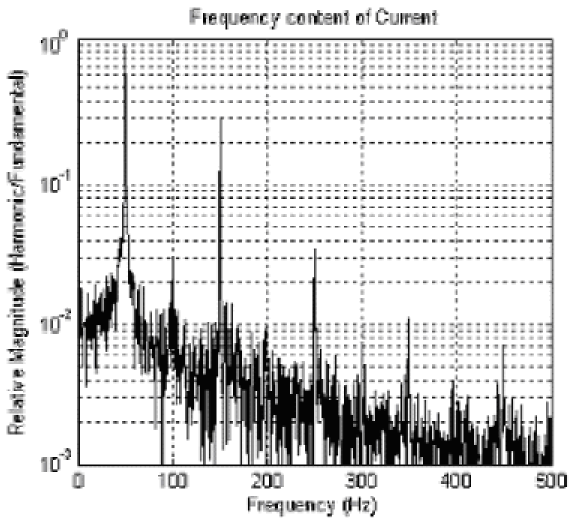
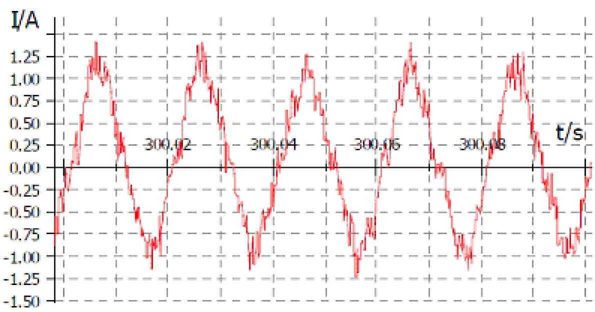
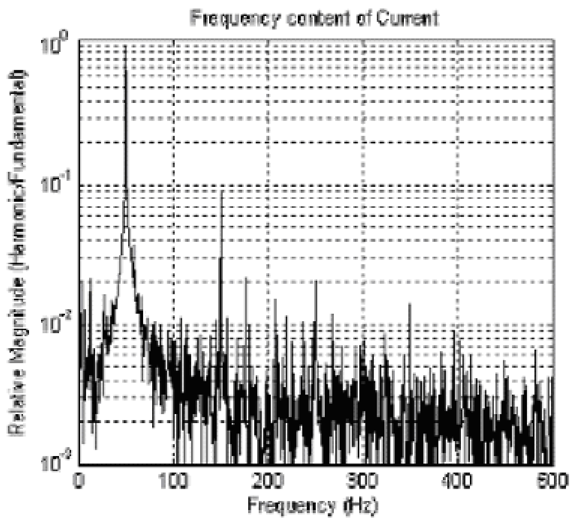
**Figure 23** – Calculated waveforms for the modified Cassie-Mayr model of arc with significant harmonic content.
(a) Current Waveform; (b) Voltage Waveform; (c) VI-Characteristic; (d) FFT for Current Waveform. [6]

## 5.7 CEATI waveforms

The search for high impedance fault testing data was ongoing. Towards the end of 2007, it was discovered that the Canadian Electricity Association Technologies Inc. (CEATI)[8] had conducted high impedance fault testing. CEATI produced 9CDs of test results. The data was purchased and the most promising files were converted from a binary 60Hz 20,000 samples per second file into an ASCII COMTRADE[4] 50Hz 10,000 samples per second file. As part of the conversion the waveforms were filtered to remove any high frequency components. The relays were tested using the converted waveforms. Following is a small extract from David Hughes' treatise showing the wave shapes and harmonic content. See files F02, F06 and F13 below. [6, 8]

Note in file F06 there is a high percentage of third harmonic 30% of the fundamental. I have also included file F13 to show that some high impedance faults will not be detected by the present SEF relays. This is due to the low current levels. When these faults and other faults were passed through the many makes of SEF relays and the fundamental current was above the relay's pick up setting, the relays responded correctly.

<table>
<tr><th>File #</th><th>Surface Type (+ Amplitude)</th><th>Surface Condition</th><th>Waveform</th></tr>
<tr><td rowspan="2">F03</td><td>Subsoil (50-150A)</td><td>Snow</td><td rowspan="2">
</td></tr>
<tr><td colspan="2">Figure C.1 – Test waveform F03 (Subsoil, snow) fault current waveform (top) and frequency content (bottom).</td></tr>
</table>

| File # | Surface Type (+ Amplitude) | Surface Condition | Waveform |
| --- | --- | --- | --- |
| F06 | Sand (0-80A) | Damp, raining | <br> |
| | *Figure C.2 – Test waveform F06 (Sand, damp and raining) fault current waveform (top) and frequency content (bottom).* | | |
| F13 | Gravel | Damp, sunny | <br> |
| | *Figure C.6 – Test waveform F13 (Gravel, damp and sunny) fault current waveform (top) and frequency content (bottom).* | | |

## 6 Conclusion

As a result of the foregoing work it can be concluded that testing relays with switching transients and observing relay response to staged faults provides the most realistic measure of performance. The effects of harmonics on various SEF relays were also observed. The most onerous test being the wave produced by Sympathetic Inrush with the 800Hz, 1 millisecond, which resulted in most SEF relays falsely operating.

High Arc Waveforms were developed using various models such as “Sandy Soil Arc”, Fluorescent tubes and Modified Cassie Mayr equations. Actual waveforms were obtained from CEATI and converted from 60Hz to 50Hz waveforms. These waveforms confirmed the validity of the arc models and the majority of SEF relays operated correctly to them.

Mathematical modelling and the recorded waveforms highlighted the inadequacies of the original SEF relays. Their failure to operate in the presence of high impedance arc faults (i.e. 30% at 150Hz) indicated they be removed from service.

Work is ongoing to produce arc models for low voltage faults. Low voltage arc faults expose Ausgrid personnel to the greatest risk as protection response is slow.

## 7 References

List any references here

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8. Canadian Electricity Association Technologies Inc. (CEATI), ‘Testing of High Impedance Fault Relays’, Report Number: CEA 038-D-1000, Mukesh Nagpal, Powertech Labs Inc,1995.

## Biography

Presenter: John Dowsett B.Eng. Elec. (1st Class Hons)

John Dowsett is a Senior Engineer in the Plant Engineering and Procurement Division, section of Ausgrid (formerly EnergyAustralia). His particular area of interest is procurement and evaluation of protection and secondary systems and load control systems in substations.

John started his career in the power utility industry by gaining a cadetship with the then Sydney County Council in 1973. He received his B. Eng (Elec.) degree from the New South Wales Institute of Technology (now called the University of Technology Sydney) in 1977.

John has worked in many roles within Ausgrid mainly in Protection and Voltage Regulation both in sub transmission and distribution roles. For 6.5 years John was responsible for the training of substation personnel and conducted theoretical and practical courses on Protection and Voltage Regulation both within Ausgrid and with other utilities.

John is an Ausgrid corresponding member on CIGRE's B5.45 Acceptance, Commissioning and Field Testing Techniques for Protection and Automation Systems working group.

Co Author David Hughes - B.E. Elec (1st Class Honours & University Medal)

David is currently a Design Engineer with Realtime Utility Engineers and the New Energy Alliance in Boston, Massachusetts, conducting transmission substation design for National Grid in the North Eastern United States. His particular areas of interest include Substation Engineering and Network Planning.

David completed his undergraduate studies at the University of Sydney in 2007 on a cadetship program with EnergyAustralia. Throughout his studies and following graduation, he has gained a broad range of experience within Ausgrid (formerly EnergyAustralia) in Distribution Network Planning, Distribution Protection and Voltage Regulation, Substation Design, Smart Grid Technology Evaluation and Field Construction. David maintains regular contact with colleagues at Ausgrid and abroad