Minimising the Risk of Cross-Country Faults in Systems using Arc Suppression Coils

R. Burgess
University of Southern Queensland
West St
Toowoomba
Queensland 4350
Australia
robert.burgess@usq.edu.au

A. Ahfock
University of Southern Queensland
West St
Toowoomba
Queensland 4350
Australia
tony.ahfock@usq.edu.au

Abstract

Arc suppression coil systems are able to improve the high voltage system reliability and safety. One of the reasons why these systems are not more widely used is the occurrence of simultaneous faults caused by the neutral voltage displacement combined with the transient voltages at the time of the initial earth fault. These transient over-voltages are analysed in detail and the capability of system components to withstand the over-voltages is assessed. Simple methods to estimate the transient voltages on overhead power systems are developed. Testing of power system components ability to withstand transient over-voltages and a new method of minimising the transient over-voltages are proposed.

1. INTRODUCTION

Arc suppression coil systems are based on the Petersen coil principle[1]. The Petersen coil performs the arc suppression by compensating the post-fault steady state current. The high voltage system supply point neutrals are earthed through inductors which are tuned to the total line to earth capacitance of the system. When an earth fault occurs there is very little voltage on the faulted phase line and the voltages on the other phases and the neutral are displaced accordingly. This results in the normal line to line voltage being applied between the two healthy phase lines and earth for the duration of the fault. If the inductor is properly tuned the capacitive current resulting from the voltage displacement is equal and opposite to the current in the earthing inductor. The residual fault current will be very small and will not be sufficient to maintain an arc. There is therefore no arc damage at the point of the fault and many faults self extinguish. This can result in a significant increase in system performance [2].

The fault event can be associated with a step-voltage injection triggered by the fault occurrence that excites the various propagation modes of the multi-conductor lines comprising the network and results in a complex high-frequency electromagnetic transient. The wave shape of the transient depends on the input impedances of components connected to the line terminations. Depending on the timing of the fault, the addition of the transient voltages to the displaced voltages of the healthy phase lines can cause over-voltages that will in some cases cause insulation failure on the otherwise healthy phase lines[3-6]. There are then two phase to earth faults often on remote parts of the system. The arc suppression system cannot compensate for either of these faults. These cross-country faults can cause disconnection of two separate lines. The phenomenon of these transient voltages adding to the displaced voltage and thus increasing the strain on the insulation of the healthy phases has long been recognized[6]. Experience has shown that there is likely to be an increased

incidence of simultaneous faults when arc suppression coil systems are used [3-5]. One of the authors has personal experience of an arc suppression coil system in a 66 kV sub-transmission system in Queensland, Australia being permanently taken out of service because of the incidence of cross-country faults. This history has contributed to reluctance by electricity supply authorities to install arc suppression coil systems in Australia.

Existing systems that have been operated with effectively earthed neutrals for many years will have components which, while they can safely withstand the normal line to earth voltage, will not withstand the over-voltages at the time of a line to earth fault when the system is not effectively earthed. In many countries transmission and distribution systems are effectively earthed. There is renewed interest in arc suppression coil systems due to increasing public pressure to improve the safety and continuity of supply and because of recent developments in the arc extinguishing properties of modern systems. If proper account is not taken of the transient over-voltages, either trial installations will be a failure and all work will stop, or trial installations will not proceed because of the uncertainties surrounding the incidence of cross-country faults.

The likely magnitudes of these over-voltages are analysed in detail and the implications for existing power systems discussed. Simple methods for estimating the approximate magnitudes, frequency and durations of the transient voltages are given.

 A method of replicating the transient over-voltages in a high voltage test facility is suggested and a new method of controlling these over-voltages is proposed. Testing of power system components and control of transient over-voltages are discussed as complementary strategies for minimising cross-country faults.

2. LITERATURE REVIEW

The availability of digital control, high voltage thyristors and other power electronic devices has led to the development of automatic tuning systems [7-10]. A method of automatically determining the system parameters has been proposed [11]. Over-voltages caused by fault currents flowing through line inductances in unearthed systems that are not fully compensated have been analysed [12]. There have also been significant developments in methods to locate a permanent fault [13-19]. A method of minimising the effect transient DC offset currents have on the extinction of the arc has also been proposed [20].

As illustrated above, there is currently significant research activity aiming at improving the performance of arc suppression coils.

3. A RADIAL LINE WITHOUT ANY BRANCHES

Whilst this is not a general analysis it is still valuable as it allows a physical understanding of the phenomena involved. The maximum voltage, the frequency of oscillation and the decay time can be estimated.

3.1 The worst case scenario for the peak voltages

Consider the simple system shown in Figure 1. A single length of line is supplied by the star winding of a transformer. The transformer neutral is earthed through an inductor tuned to the

total system line to ground capacitance. As an aid to the understanding of the transient phenomena the line is simplified to show the distributed line to earth capacitances as combined into lumped capacitances at each end of the line. The practical distributed capacitance case is analysed later. Consider an earth fault near the transformer with a fault resistance of R_f.
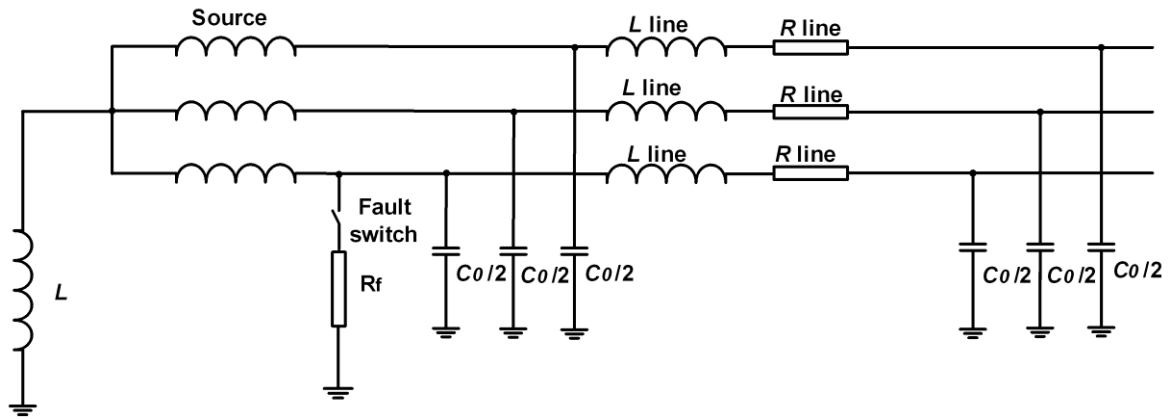

Figure 1. Simple System Schematic Diagram

The symmetrical component representation of the system is as shown in Figure 2.
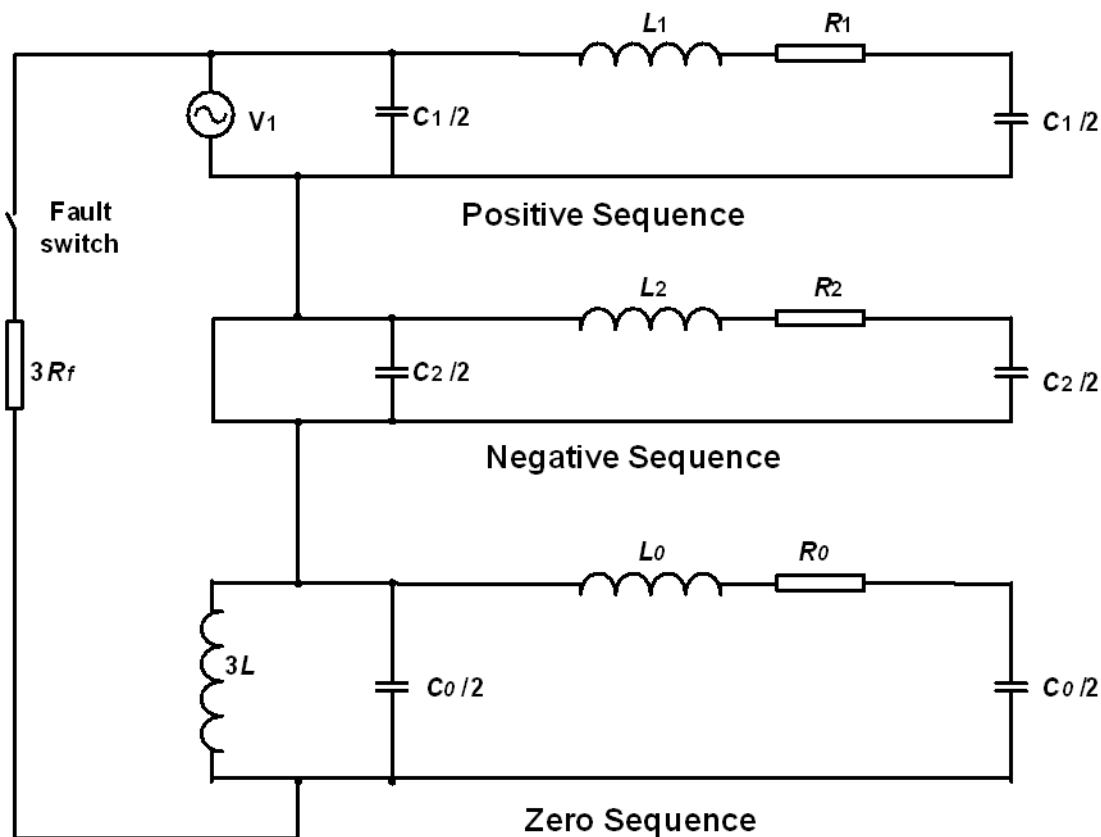

Figure 2 Symmetrical Network Representation of the Simple System

If the source impedances are ignored and the fault is at the source, the transient voltages and currents will be predominantly of the common mode type affecting each of the phase conductors in an identical manner. The zero sequence network can then be used to analyse the transient voltages and currents.

At the instant the fault is applied, provided the voltage of the faulted line is not zero, a step voltage will be applied across the zero sequence network at the fault point. The resultant current will flow to charge the line to earth capacitance of the far section of the line and oscillation in voltage and current will follow until it decays because of the effect of the resistances.

There are then three voltages being applied to the far end of the lines.

1. The positive sequence fundamental frequency voltage,
2. The zero sequence fundamental frequency voltage, and
3. A transient voltage alternating at the natural frequency of the line zero sequence inductance and capacitance and decaying to zero.

Depending on the time of the fault in the fundamental frequency cycle, these voltage transients may cause serious over-voltages on the healthy lines.

The positive and negative sequence source impedances can be ignored in this analysis because we are analysing a worst case scenario. Any source impedance will have the effect of reducing the magnitude of the step voltage change across the zero sequence network. Analysis using ElectroMagnetic Transients Program (EMTP) software has confirmed that if realistic supply transformer impedances are used and the impedances are adjusted to typical values as seen by the transient currents there will be a slight decrease in the maximum value of the peak transient voltage.

Although the zero sequence diagram shows the line capacitances lumped at the ends of the line, the analysis presented in this section is also applicable to a distributed model.

In the case of distributed capacitances and a perfect system without any resistance either in the line or in the ground plane, a step transient current/voltage wave will travel to the end of all three lines and be reflected back to the fault point. It will travel back and forth setting up a square wave oscillation. In a practical system with some resistance the magnitude will decay. Because the resistances as seen by the higher frequency components of the square wave are much higher than the resistances as seen by the major frequency of the square wave, the wave shape of the oscillation will closely approximate a sine waveform within a few cycles. The main frequency, magnitude and decay time will be close to but not quite equal to that given by the simplifying assumption of capacitances lumped at the ends of the line.

Consider a low impedance fault to earth on the 'A' phase at a time 't' such that;

$$\theta = \omega t \tag{1}$$

Let the phase voltages at the source just before the occurrence of the fault be;

$$E_a = E \sin \omega t^- \tag{2}$$

$$E_b = E \sin(\omega t^- - 120^0) \tag{3}$$

$$E_c = E \sin(\omega t^- + 120^0) \tag{4}$$

Ignoring voltage drops due to load, the steady state voltages at the fault point with the fault in place will be:

$$E_1 = E \sin \omega t \tag{5}$$

$$E_2 = 0 \tag{6}$$

$$E_0 = -E \sin \omega t \tag{7}$$

The line voltages at the fault point will then be;

$$E_{fa} = E_1 + E_2 + E_0$$

$$= E \sin \omega t - E \sin \omega t = 0 \tag{8}$$

$$E_{fb} = a^2 E_1 + a E_2 + E_0$$

$$= E \sin(\omega t - 120^0) - E \sin \omega t \tag{9}$$

$$E_{fc} = a E_1 + a^2 E_2 + E_0$$

$$= E \sin(\omega t + 120^0) - E \sin \omega t \tag{10}$$

Let δt be the time taken for a current/voltage wave to travel from the fault point to the end of the line.

Neglecting the small changes in voltage as a result of the load currents and the line capacitive currents, these steady state voltages will appear at both ends of the line. At the instant of the fault all of the line voltages at the source will change by $-E \sin \theta$. A current/voltage wave will travel to the end of the line. When it reaches the end, the voltages on each phase line at the far end will change by $-2E \sin \theta$. The voltages at the end of each phase line when the transient pulse arrives will be;

$$E_{ea}(t + \delta t) = E \sin(\theta + \omega \delta t) - 2E \sin \theta \tag{11}$$

$$E_{eb}(t + \delta t) = E \sin(\theta + \omega \delta t - 120^0) - 2E \sin \theta$$
$$= E[-0.5 \sin \theta \cos \omega \delta t - 0.5 \cos \theta \sin \omega \delta t - 0.866 \cos \theta \cos \omega \delta t + 0.866 \sin \theta \sin \omega \delta t - 2 \sin \theta]$$

$$E_{ec}(t+\delta t) = E\sin(\theta + \omega\delta t + 120^0) - 2E\sin\theta$$
$$= E\left[-0.5\sin\theta\cos\omega\delta t - 0.5\cos\theta\sin\omega\delta t + 0.866\cos\theta\cos\omega\delta t - 0.866\sin\theta\sin\omega\delta t - 2\sin\theta\right]$$

(13)

However, for short transmission lines, as $\omega\delta t$ is very small, $\cos\omega\delta t$ will be very close to unity and $\sin\omega\delta t$ will be very close to zero.

Therefore $E_{eb}(t+\delta t) \approx E\left[-0.5\sin\theta - 0.866\cos\theta - 2\sin\theta\right]$

$$\approx -E\left[2.645\sin(\theta + 19.11^0)\right] \tag{14}$$

$$E_{ec}(t+\delta t) \approx E\left[-0.5\sin\theta + 0.866\cos\theta - 2\sin\theta\right]$$

$$\approx -E\left[2.645\sin(\theta - 19.11^0)\right] \tag{15}$$

The four worst case scenarios are for a fault at a time such that

$$\theta = \pm 90^0 \pm 19.11^0 \tag{16}$$

In these cases the peak voltage will be 2.645 p.u.

Allowing for the time taken for the wave to reach the far end of the line the maximum value will be slightly higher. The value depends on the length of the line and the relative phase angles of the voltages at each end of the line. The absolute maximum is such that the fault occurs at the time of maximum voltage on the faulted phase and reaches the open end of the line at the time of maximum voltage on one of the healthy phases. In this case, by examination of equations (11) to (13), the maximum transient voltage will be 3 p.u.. If the line length between the fault location and the end of the line is such that $\omega\delta t = 60^0$, then substituting into equation (13) gives:

$$E_{ec}(t+\delta t) = -3E\sin\theta \tag{17}$$

For this to occur, in the case of a purely air insulated overhead line and allowing for the partial conductivity of the ground plane, the length would be approximately 850 km. For lines of this length it is usual that there will be a significant difference in the phase of the voltages at either end. There will also be significant attenuation of the wave because of the time taken. Therefore, for long lines, the likely transient voltages can only be analysed on an individual case by case basis for particular loading conditions.

3.2 Estimation of frequency and decay time for a typical 11 kV overhead line type.

A single line system consisting of 20 km of 11 kV three phase 7/3.75 AAC overhead line with flat construction and supplied by the star winding of a transformer was modelled. The transformer neutral was earthed through a tuned arc suppression coil with negligible resistance.

The line inductance and resistance parameters are affected by the higher frequency of the transient currents.

The zero sequence line to earth capacitance is given by the well known formula:

$$C_0 = \frac{2\pi k}{3Ln\left(\dfrac{4H}{GMD}\right)} \quad F/m \tag{18}$$

where:

$H =$ The conductor height

$GMD =$ The Geometric Mean Diameter of the conductor configuration as a bundle for zero sequence representation.

$k = 8.85 \times 10^{-12} \ F/m$

For the 20 km length of line where $GMD = 469mm$ and $H = 9m$:

$C_0 = 0.0854 \ \mu F$

As a first approximation of the transient frequency of oscillations, the time taken for the current/voltage wave to travel to the end of the line and return was taken as half a cycle. The method proposed by Gatous and Pissolato [21] to allow for the skin effect, and the well known complex depth of return method as reiterated by Wang and Liu [22] were used to calculate R_0 and L_0, for this frequency. Using these values the frequency of oscillation for the simple model with lumped capacitances was revised using the formula:

$$\text{Frequency in radians per second} = \frac{\sqrt{8L_0 C_0 - R_0^2 C_0^2}}{2L_0 C_0} \tag{19}$$

New values for R_0 and L_0 were then found.

By successive iterations it was found that;

$R_0 = 161.1 \ \Omega$

$L_0 = 77.98 \ mH$

Frequency $= 2803$ Hz

The time constant for the decay of the oscillations was calculated using equation (20).

Time constant in seconds $= \dfrac{2L_0}{R_0}$ (20)

$$= 0.968 \; ms$$

The EMTP software was used to check these calculations.

To check the calculation of the line capacitance a simulated 1 Hz zero sequence voltage was applied to both ends of a half kilometre of the above 11 kV line type. By measuring the capacitive current, the zero sequence capacitance was found for a 20 km length of line:

$C_0 = 0.0857 \mu F$

To check the calculation of the line inductance and resistance a three phase to earth zero impedance fault at one end of a half kilometre of the above 11 kV line type was simulated and a 2803 Hz zero sequence sine wave source was applied to the other. By measuring the current magnitude and phase angle the line parameters were found to be;

$R_0 = 153.5 \; \Omega$

$L_0 = 76.88 \; mH$

Allowing for the approximations inherent in the methods used to find the parameters for the EMTP line representation, these values confirm the calculations.

The 20 km single line model was analysed using the EMTP software. A phase to earth fault was applied to phase C near the source and the voltages appearing at the end of the line as calculated by EMTP are shown in Figure 3.
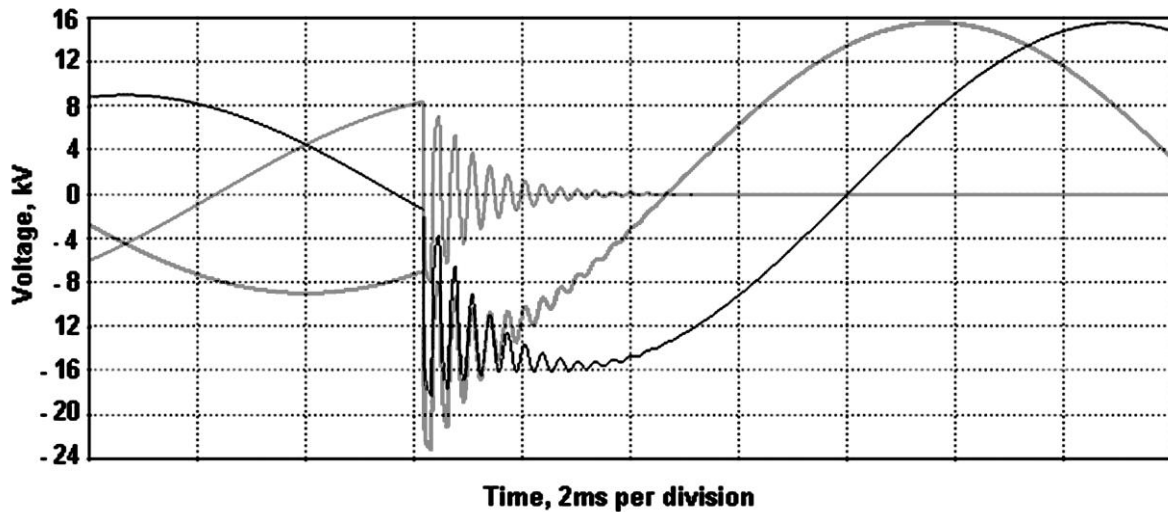
Figure 3 Transient voltages for the single line model as shown by EMTP

It can be seen that the peak voltage on a healthy phase line is 23.2 kV which is 2.58 p.u.

Frequency = 3082 *Hz*

Time constant of decay = approximately 1 *ms*

These values from the distributed capacitance line model are within 10% of those calculated using lumped capacitances.

The single line model was replicated by a physical model with resistors and reactors chosen to accurately represent the zero sequence line impedances as seen by the high frequency oscillating currents but with a safe voltage applied. The major difference was that, whereas the EMTP model used distributed line capacitance, the physical model used capacitances lumped at the ends of the lines. As shown in Figure 4 the transient voltages were similar to those shown by the EMTP model.
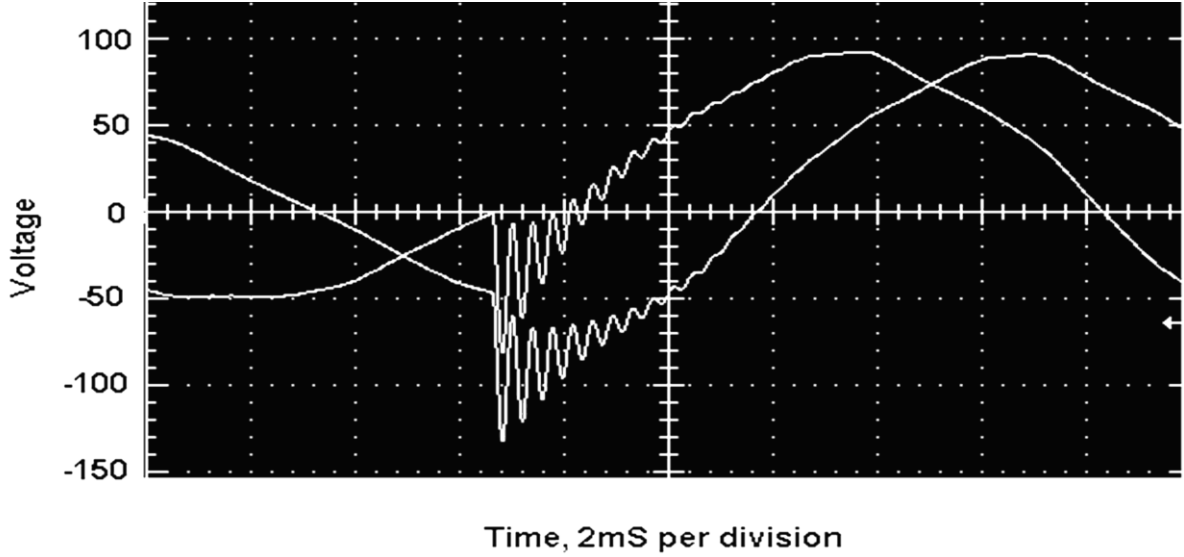
Figure 4 Transient voltages on the un-faulted phase lines of the physical model

Both the EMTP simulation and the physical model used a full three phase system and not symmetrical components. The close agreement validates the assumption that the voltage and current transients under consideration are predominantly of the common mode or zero sequence type. A close study of Figure 4 shows the frequency of oscillation to be very close to 2803 Hz with a time constant of decay close to 1 ms as calculated using the zero sequence network. In both cases the line to earth capacitance is lumped at the ends of the line. The slightly higher frequency given by the EMTP model is as a result of correctly representing the line to earth capacitances as distributed along the line.

3.3 Approximate methods for transient voltage estimation

The maximum transient voltage in a non-effectively earthed system will be 3 p.u.

The time taken for a current\voltage wave to travel from the fault point to the end of an overhead line and return can be determined approximately. Ignoring the effects of insulators and the proximity to the conductive ground plane, the current/time wave will travel at the speed of light that is approximately $3x10^8$ metres per second. However the EMTP analysis in this paper shows that for a practical 11 kV overhead system, with a partially conductive ground plane, the speed will be reduced by a factor of 0.82. The calculations in [23] for a 345 kV line give a factor of 0.87. For a first approximation a factor of 0.85 would give sufficient accuracy. For more detailed analysis a full simulation using EMTP or other software would be appropriate. This time will correspond to half a cycle of the transient oscillation.

Therefore;

$$\text{Frequency} = \frac{2.55x10^8}{4D} Hz \qquad (21)$$

where D is the total line distance in metres.

The time constant for the decay of these oscillations is given by equation (20).

10

The values of L_0 and R_0 are frequency dependent. As the frequency increases L_0 decreases and R_0 increases. As we are interested in the worst case scenario we need only estimate the time constant for the minimum oscillating frequency that relates to the longest length of line.

The time constants for the decay of the transient oscillations for a range of all aluminium conductors and a typical 11 kV overhead line construction are shown in Figure 5.
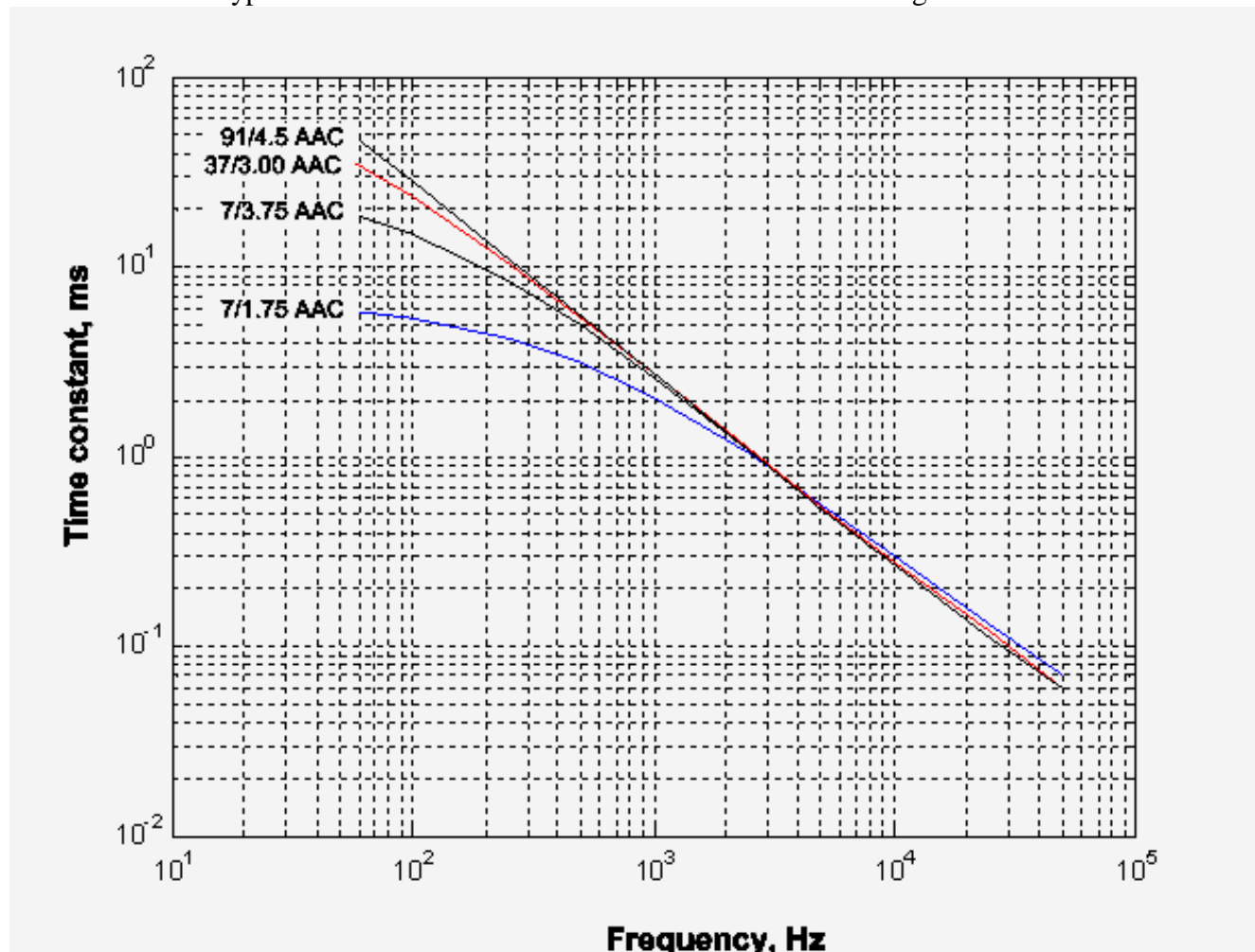

Figure 5 Time constants for the decay in transient oscillations for typical 11 kV overhead line construction

4. TYPICAL ZONE SUBSTATION DISTRIBUTION SYSTEM

The above analysis is based on a single radial line without any branches. In cases where there are branch lines the interaction of the transient steps becomes more complex. At each branch the transient voltage will reduce according to the relative surge impedances of the outgoing conducting paths. Despite this reduction, there are circumstances where two or more of these transient voltages can coincide and reinforce each other. In some situations they can add together to give a peak voltage slightly higher than the maximum values for a single line. For example in the case of a 40 km typical 7/3.75 AAC 11 kV overhead line with a 10 km spur line mid way along there can be a peak transient voltage of up to 2.713 p.u. Without the spur line the corresponding peak transient voltage is 2.630 p.u.

To evaluate transient overvoltage effects on power distribution systems a realistic urban zone substation distribution system model as shown in Figure 6 was analysed using EMTP software.

Figure 6 Urban Zone Substation distribution system.

Using EMTP software and with a tuned arc suppression coil, a phase to earth fault at a point 7 km from the bus bar was simulated. The transient voltages recorded at the far ends of the four longest feeders were as shown in Figure 7. The highest transient voltage peak was 2.69 p.u.

Figure 7 Transient Voltages on a Healthy Phase of the Urban Distribution System.

The tuning of the arc suppression coil has little effect on these transient voltages. Provided the transformer neutral is not effectively earthed, transient voltages will occur. It should be noted that while arc suppression can also be arranged by the use of shunt circuit breakers combined with ungrounded networks there will still be transient voltages at the time of the fault and therefore there is still the potential for simultaneous faults.

5. IMPLICATIONS FOR EXISTING SYSTEMS

Where all of the equipment in service complies with the standard insulation levels set out in Table 2 or Table 3 of AS 1824.1 [24], which is based on IEC 71-1 (1993), these transient over-voltages will not cause a cross-country fault. In practice there are many high voltage distribution systems with components that have not been manufactured to meet current standards and that have not been tested to the current standards. There are also likely to be many components that have deteriorated to the extent that, while they can still withstand 1.0 p.u. voltage with a safety margin, they will not withstand these transient over-voltages. It may not be feasibly to upgrade all components in the system.

Similarly metal oxide surge arrestors suitably rated at 1.732 p.u. and in specified working order will not reach a thermal run away condition with short duration 3 p.u. voltages. However, in many high voltage systems there are likely to be surge arrestors that have deteriorated to the extent that they will allow arcing and power follow currents to flow resulting in cross-country faults.

The implications for existing high voltage distribution systems can be determined by removing samples of the insulators and surge arrestors for withstand voltage tests using waveforms similar to these transient voltage waveforms. An economic way of carrying out this type of analysis initially may be to test all apparently healthy components removed from service for other reasons. The percentage failure of the components that are tested will provide a good indication off the likelihood of cross-country faults.

6. TESTING OF SYSTEM COMPONENTS

The system shown in Figure 8 was set up in a high voltage testing facility to illustrate one simple method of testing the ability of power system components to withstand the transient over-voltages.
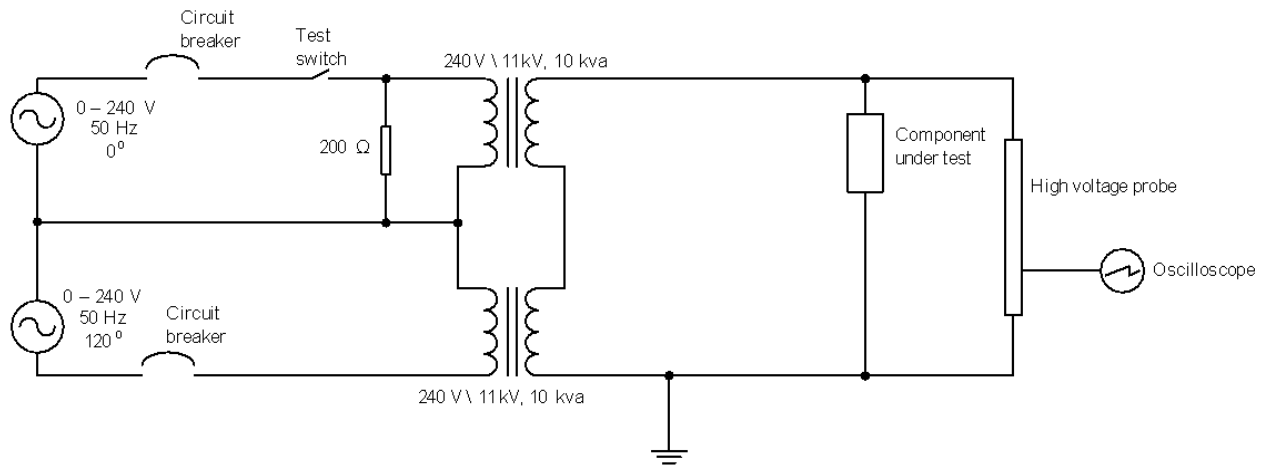
Figure 8 Arrangement for Testing Network System Components

The input voltages were adjusted to provide the steady state voltages of the power system. The test transformers were found to have adequate leakage inductance, shunt capacitance and resistance. The resultant test voltage waveform was typical of that to be found in practice. Point of wave switching can be arranged so that the worst case scenario is replicated for each test. A sample of the voltage applied to the component under test is shown in Figure 9.
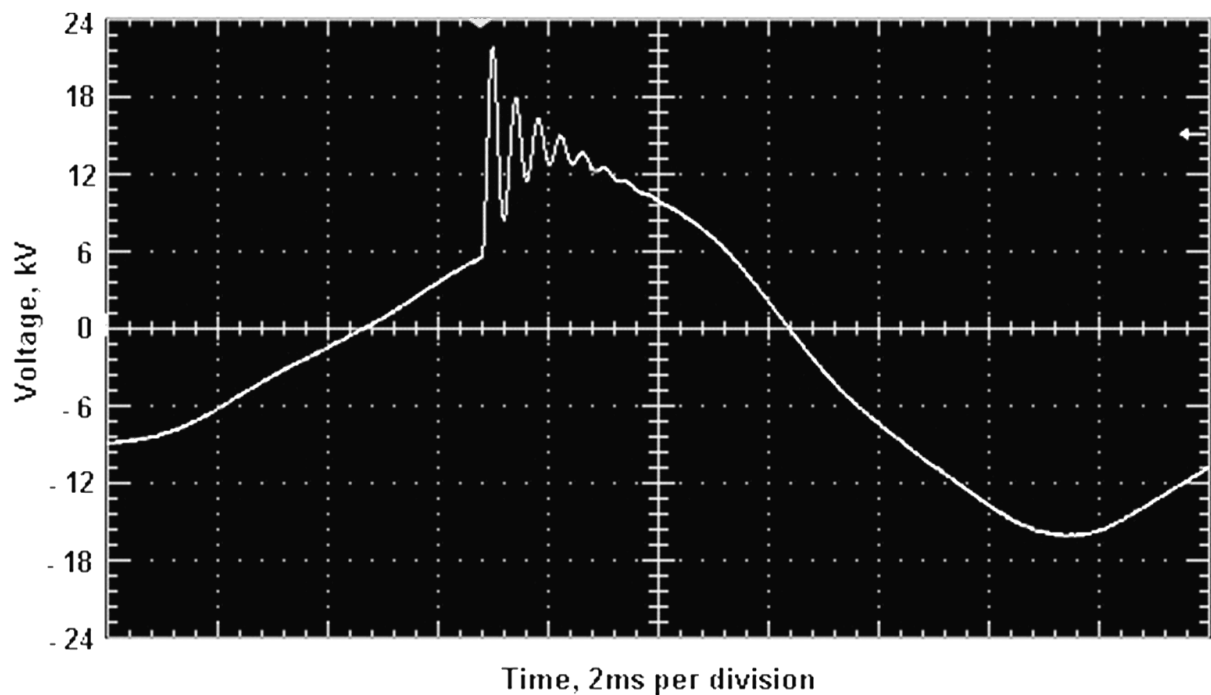

Figure 9 Test Voltage Applied to Power System Components

7 A METHOD OF CONTROLLING TRANSIENT OVER-VOLTAGES

A new method has been developed for controlling the transient over-voltages. A bipolar thyristor bank is connected in parallel with the arc suppression coil to effectively earth the neutral of the supply transformer from the time of the fault to the first current zero.

When a single line to ground fault occurs in a non-effectively earthed system, the rate of change of the neutral voltage is very rapid. The derivative of the neutral voltage can then trigger the thyristors very close to the instant of the fault and before the transient oscillations have been established. By then interrupting the current at a current zero the resultant oscillations are much smaller. A resistor is connected in series with the thyristor bank to limit the maximum current and to reduce the oscillations at the time of the current interruption. The minimum rate of rise of the neutral voltage used to trigger the thyristor banks is selected such that triggering will occur for a single line to ground fault at any location in the distribution system but such that triggering will not occur at the maximum rate of rise of the transient oscillating voltages.

The resulting transient voltages for the previously analysed fault conditions on the urban distribution system are shown in Figure 10.
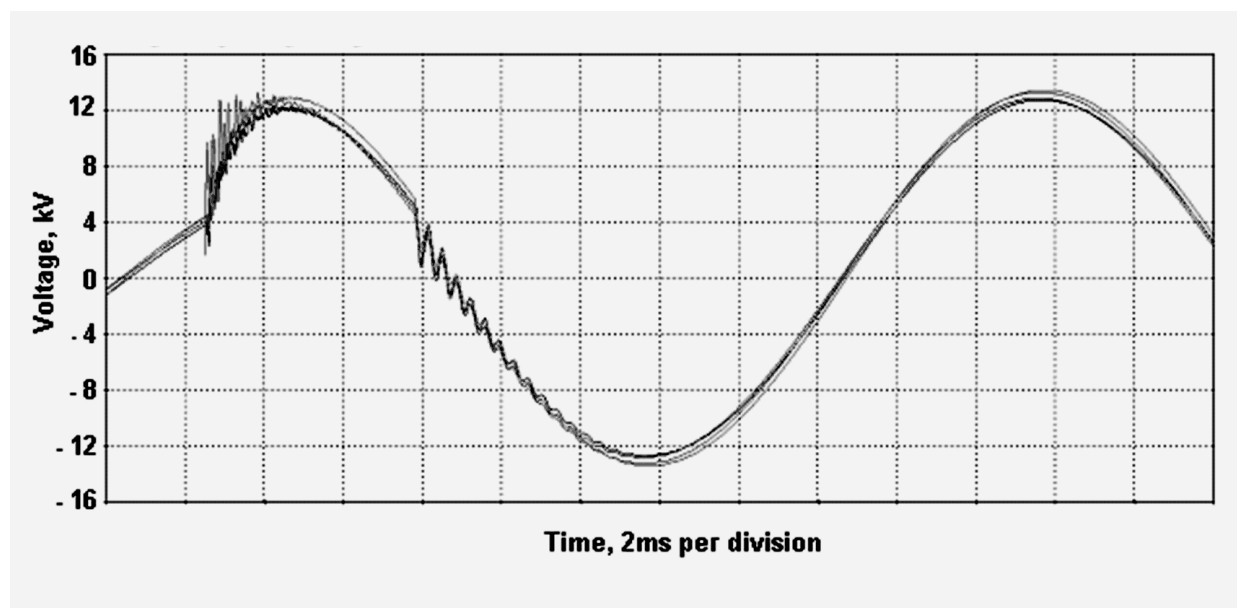

Figure 10 Transient Voltages on a Healthy Phase of the Urban Distribution System with Thyristor Control.

8. CONCLUSION

The evaluation methods used confirm that there will be significant over-voltages as a result of transients at the time of the fault in distribution systems using arc suppression coils. Although these transient voltages would not cause cross-country faults in a power distribution system that is properly designed and using equipment that is in good condition and which complies with modern standards, there are many distribution systems that have been built many years ago with equipment that has never been tested to the current standards. The equipment may also have deteriorated. A second fault means that there are then two faults that cannot be protected by the arc suppression coil system with possible resultant arcing damage and an increase in the number of permanent faults. A new method to eliminate the over-voltages caused by the transient oscillations has been proposed.

It is recommended that network companies considering the installation of arc suppression coil systems in long established solidly earthed systems begin a program of testing existing

components to find the capability of the system to withstand these transient over-voltages. In the first instance this can be carried out at low cost by returning for test all otherwise apparently healthy insulating components removed from service for other reasons.

Testing of system components and controlling the magnitude of the transient over-voltages should both be considered as part of the strategy for implementing arc suppression coil systems in power networks that were previously effectively earthed.

9. REFERENCES

[1]   E. M. Hunter, "Some Engineering Features of Petersen Coils and Their Application," *Transactions of theAmerican Institute of Electrical Engineers,* vol. 57, pp. 11-18, 1938.

[2]   A. Newbould and K. Chapman, "Improving UK power quality with arc suppression coils," in *Developments in Power System Protection, 2001, Seventh International Conference on (IEE)*, 2001, pp. 487-490.

[3]   J. H. Naylor, *Power System Protection Volume 1: Principles and components: Chapter 3 Fault calculation* vol. 1: The Institution of Electrical Engineers, 1995.

[4]   J. L. Blackburn, *Protective relaying: principles and applications*. New York: M. Dekker, 1987.

[5]   W. E. Corporation., *Electrical transmission and distribution reference book*. Array East Pittsburgh, Pennsylvania, 1964.

[6]   T. W. Ross and H. G. Bell, "Recent developments in the protection of three-phase transmission lines and feeders," *Electrical Engineers, Journal of the Institution of,* vol. 68, pp. 801-823, 1930.

[7]   L. Cheng, Q. Chen, Y. Zhang, and C. Zhang, "The Principle of a Novel Arc-suppression Coil and its Implementation," in *Power Electronics and Motion Control Conference, 2006. IPEMC 2006. CES/IEEE 5th International*, 2006, pp. 1-5.

[8]   L. Cheng, Q. Chen, and Y. Zhang, "Design principle of a novel automatic tuning arc suppression coil system," in *Electrical Machines and Systems, 2008. ICEMS 2008. International Conference on*, 2008, pp. 4483-4488.

[9]   Y. Xu, Z. Wang, and H. Zhang, "The Automatic Following Control of Arc Suppression Coil with Thyristor Switched Capacitors," in *Industrial Electronics and Applications, 2006 1ST IEEE Conference on*, 2006, pp. 1-5.

[10]   Caixu, "A new arc-suppression coil with magnetic bias and its characteristics analysis," in *Electrical Machines and Systems, 2003. ICEMS 2003. Sixth International Conference on*, 2003, pp. 903-906 vol.2.

[11]   G. Druml, A. Kugi, and O. Seifert, "New method to control Petersen coils by injection of two frequencies," in *Electricity Distribution, 2005. CIRED 2005. 18th International Conference and Exhibition on*, 2005, pp. 1-5.

[12]   A. Cerretti, F. M. Gatta, A. Geri, S. Lauria, M. Maccioni, and G. Valtorta, "Temporary overvoltages due to ground faults in MV networks," in *PowerTech, 2009 IEEE Bucharest*, 2009, pp. 1-8.

[13]   O. Chilard, G. Donnart, and D. Renon, "EDF patented protection "PDTR" against resistive phase-to-ground faults in compensated MV distribution," in *Electricity Distribution, 2005. CIRED 2005. 18th International Conference and Exhibition on*, 2005, pp. 1-6.

[14]   F. Ortolani and A. Leikermoser, "Neutral compensation and network monitoring - Test field experience in determining resonant point and homopolar parameters with active and passive pulse injection," in *Electricity Distribution, 2009 20th International Conference and Exhibition on*, 2009, pp. 1-4.

[15]   M. Lukac, "Determination of earth faulted line with transient method," in *Electricity Distribution, 2009 20th International Conference and Exhibition on*, 2009, pp. 1-4.

[16]   W. Y. Huang, R. Kaczmarek, and P. Bastard, "An efficient treatment of transient residual currents in distribution networks grounded with Petersen coil," in *Developments in Power System Protection, 2004. Eighth IEE International Conference on*, 2004, pp. 685-688 Vol.2.

[17]   P. Bertrand, R. Kaczmarek, X. Le Pivert, and P. Bastard, "Earth-fault detection in a compensated earthed network, without any voltage measurement: a new protection principle," in *Electricity Distribution, 2001. Part 1: Contributions. CIRED. 16th International Conference and Exhibition on (IEE Conf. Publ No. 482)*, 2001, p. 4 pp 482-485. vol.3.

[18]   H.-c. Shu, S.-x. Peng, and X.-b. Zhao, "Integration of multi-algorithm for single-phase fault detection in distribution system with arc suppression coil grounding using extenics," in *Electric Utility Deregulation and Restructuring and Power Technologies, 2008. DRPT 2008. Third International Conference on*, 2008, pp. 2111-2115.

[19]   Q. Yilong, T. Weipu, and Y. Yihan, "H-Infinity Control Theory Apply to New Type Arc-suppression Coil System," in *Power Electronics and Drive Systems, 2007. PEDS '07. 7th International Conference on*, 2007, pp. 1753-1757.

[20]   H. Zhang, Y. Xu, and Z. Wang, "Research on a New Extinction Coil Operation Mode for Resonant Earthed Neutral System," in *International Conference on Power System Technology, 2006.*, 2006, pp. 1-5.

[21]   J. O. M. O. Gatous, J. Pissolato, "Frequency-dependent skin-effect formulations for resistance and internal inductance of a solid cylindrical conductor," in *IEE Proc-Microw. antennas propag.*, pp.212-216 vol. 151, No 3, 2003.

[22]   S.-J. L. Yaw-Juen Wang, "A review of Methods for Calculation of Frequency-dependent Impedance of Overhead Power Transmission Lines," in *Natl. Sci. Counc.* vol. 25, No 6, 2001, pp. 329 - 338.

[23]   D. K. Tran and D. Phi, "Laplace analysis and computer simulation of transient current in power transmission lines Pt, 2-Polyphase systems with lossy earth return," *Electrical Engineers, Proceedings of the Institution of,* vol. 124, pp. 137-140, 1977.

[24]   S. Australia, "AS 1824.1 - 1995 Insulation co-ordination Part 1: Definitions, principlesa nd rules," 1995.