8TH SOUTHERN AFRICA
REGIONAL CONFERENCE

14 - 17 NOVEMBER 2017

" Electricity Supply to Africa and Developing Economies …. Challenges and opportunities."

Technology solutions and innovations for developing economies

Magnetic induced currents and voltages on earthed lines due to faults on adjacent lines

W.J Dirkse van Schalkwyk
Eskom Holdings SoC Ltd
South Africa

C.J van der Mescht
Eskom Holdings SoC Ltd
South Africa

SUMMARY

High voltages and currents on earthed equipment can pose danger to the public and the risk of an incident increases in densely populated areas. Voltages and currents can be induced on power lines that are out of service. Lightning, faults on adjacent lines and inadvertent restoration of supply can induce currents in the kA, and voltages in the kV range onto an earthed line. Currents in the mA range can also be induced by capacitive coupling and atmospheric conditions.

Proper earthing needs to be done before work can commence on MV lines. The general understanding is that when more earths are used, it will result in better protection against electrical shock. This is however not true, and significant current and voltage surges can be experienced in such cases during fault conditions on adjacent MV lines.

It was concluded not to rely on an earth spike alone, but to make use of an equipotential zone as well. Secondly, it is strongly advised not to make use of an earth at the substation. Earthing should only be done on the site where work is being done.

KEY WORDS:

Magnetic coupling, earth faults, earth configuration, induced currents.

1. INTRODUCTION

1.1 Background

When working on power lines earthing practices are followed in order to protect personnel against:

- Inadvertent restoration of supply
- Static charges
- Lightning surges
- Induced voltages and currents

There is a common understanding that by driving an earth spike into the ground is a sufficient way to earth an overhead line. Tests were performed to test this point whereby an earth-fault was created on a 22 kV overhead line onto an earth spike. The photos shown in Figure 1-1 indicate that the electrical contact between the earth spike and ground was so poor that the electrical arc jumped to ground.

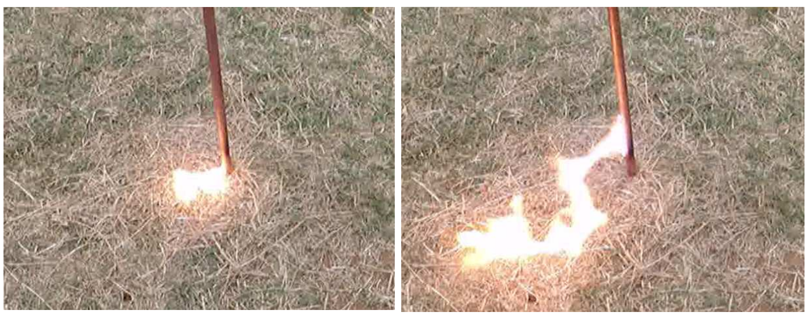

Figure 1-1 Electrical arc originating from earth spike due to poor electrical connection to earth

1.2 Inadvertent restoration of supply

Inadvertent restoration of supply onto an earthed section of line will result in high fault currents causing high step and touch potentials around the earth spike. This can also cause the grass to catch fire as shown in Figure 1-2.

Figure 1-2 Veld fire caused by fault current flowing to earth via an earth spike

1.3 Lightning surges

Figure 1-3 shows a recording of a -18 kA direct strike 14 km away from the recorder to a de-energized line. This is quite significant with regards to the safety of the public in close vicinity and personnel who perform work on overhead lines under dead conditions.

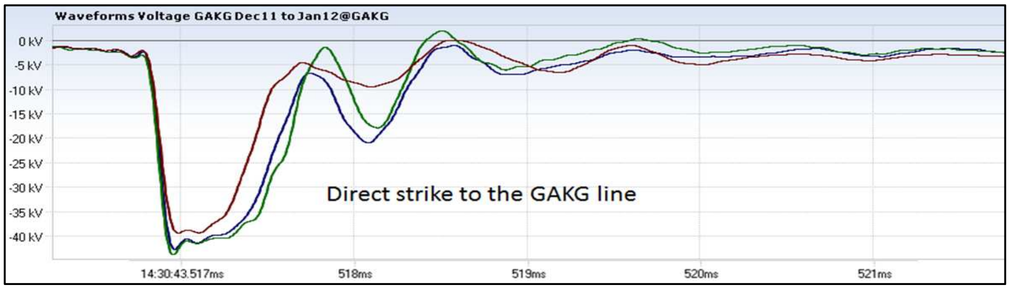

Figure 1-3 Lightning surge on overhead line

1.4 Ground potential rise

A practical test was performed in order to measure the step potential around an earth spike. Three 1.5 meter earth spikes were inserted into earth approximately 0.5 meters apart. One of the three earth spikes as shown in Figure 1-4 was connected to the overhead line in order to measure what the ground potential rise will be if the overhead line had to be inadvertently closed.

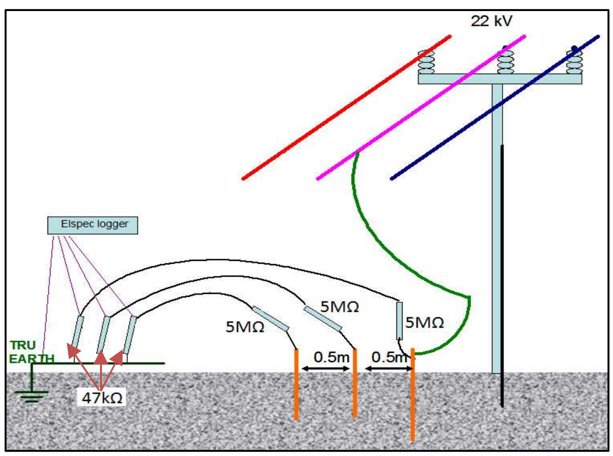

Figure 1-4 Ground potential rise test

After the line was energised onto the earth spike the voltage was recorded by making use of a resistor divider circuit. The results shown in Figure 1-5 indicates that approximately 20% of the line phase-to-earth voltage was measured 0.5 m from the energised earth spike. Approximately 2% of the line phase-to-earth voltage was measured 1 m from the energised earth spike.

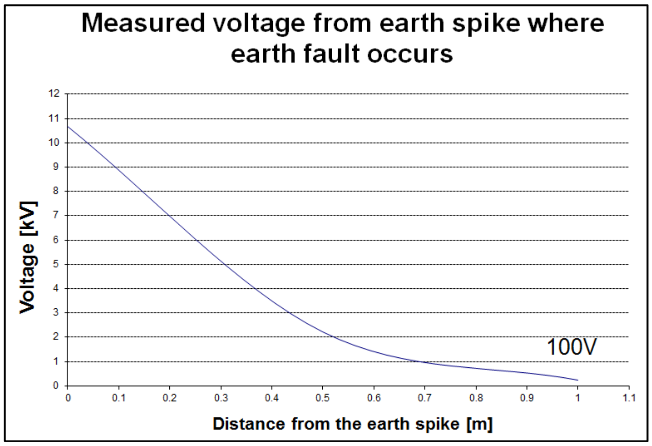

Figure 1-5 Step potential

2. MAGNETIC INDUCED CURRENTS

2.1 Background

According to Faraday's law a current in a circuit will electromagnetically induce a current on another circuit that is running in parallel. When considering a steady-state three-phase overhead line the magnetic induced current in another parallel overhead three-phase line will be very small. This is due to resulting current phasor being very close to zero as three-phase currents are usually balanced [1] [2].

However, a single phase fault will result in an induced current on any nearby parallel circuit whereby the magnetic flux contours crosses such a circuit. The resultant current phasor will also no longer be close to zero due to the imbalance caused by the fault current [1] [2].

The induced voltages may be calculated by using the following matrix which was developed by Carson and later modified by Clarke [3]:

$$\begin{bmatrix} V_1 \\ V_2 \\ . \\ . \\ . \\ V_m \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & \dots & Z_{1n} \\ Z_{21} & Z_{22} & \dots & Z_{2n} \\ . & . & \dots & . \\ . & . & \dots & . \\ . & . & \dots & . \\ Z_{m1} & Z_{m2} & \dots & Z_{mn} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ . \\ . \\ . \\ I_m \end{bmatrix} \text{V/m} \quad \textbf{(1)}$$

Adding the line length, Equation 1 can be expressed as:

$$\boldsymbol{V} = \boldsymbol{Z} \times \boldsymbol{I} \times L_{length\ of\ parallel\ path} \quad \textbf{(2)}$$

It can be observed that the level of the induced voltage is directly proportional to the parallel interaction path length and is dependent of the magnitude of the current. The approximate electromagnetic equations with regards to the impedances are [3]:

$$Z_{mm} = Z'_{mm} + Z_g - 2Z_{mg} \quad \textbf{(3)}$$

for m = n and

$$Z_{mn} = Z'_{mn} + Z_g - Z_{mg} - Z_{ng} \quad \textbf{(4)}$$

for m ≠ n.

The self-impedance of the conductor $\mathrm{Z'_{mm}}$, mutual-impedance between conductors $\mathrm{Z'_{mn}}$, and mutual impedance between conductor and ground ($\mathrm{Z_{mg}}$, $\mathrm{Z_{ng}}$) can be mathematically expressed as [3]:

$$Z'_{mm} = r_m + 4\pi f 10^{-7} ln\left(\frac{1}{GMR_m}\right) i \ \Omega/\mathrm{m}$$

$$Z'_{mn} = 4\pi f 10^{-7} ln\left(\frac{1}{D_{mn}}\right) i \ \Omega/\mathrm{m}$$

$$Z_g = 9.865 \times 10^{-7} f \ \ \Omega/\mathrm{m}$$

$$Z_{mg} \ or \ Z_{ng} = 2\pi f 10^{-7} ln\left(\frac{1}{660 \times \sqrt{\frac{\rho}{f}}}\right) i \ \Omega/\mathrm{m}$$

where r_m is the resistance of the conductor (Ω/m), D_{mn} is the distance between the conductors (m), ρ is the resistivity of the earth (Ω.m), GMR_m is the geometric mean radius for conductor m (m) and f is the power system frequency (Hz).

For the case where the magnetic field induction is calculated between a live three-phase overhead line and a de-energised three-phase overhead line, V_4, V_5 and V_6 can be calculated by setting I_4, I_5 and I_6 to zero. If the earth-fault current is such that it is much bigger in magnitude as compared to the load current the impedance can be approximated by [1]:

$$Z = \frac{\omega\mu_0}{8} + \frac{\omega\mu_0}{2\pi} ln\left(\frac{660\times\sqrt{\frac{\rho}{f}}}{D} i\right) \Omega/\mathrm{m} \quad \textbf{(5)}$$

where μ_0 is the permeability of free space ($4\pi \times 10^{-7}$ H/m), ω is the radian frequency ($2\pi f$) D is the distance between the conductors (m), ρ is the resistivity of the earth (Ω.m) and f is the power system frequency (Hz).

2.2 Magnetic induced voltage case study

Table 1 shows the parameters that were used for calculations and simulations to determine the induced voltage on a de-energised overhead line running in parallel to an overhead power line which encounters an earth-fault.

Table 1 System variables

System variable	Value
System phase-to-phase voltage	22 kV
Earth fault current	340 A
Conductor type	ASCR Hare
Length of parallelism	12 km
Soil resistivity	500 Ω.m
Power frequency	50 Hz
Distance from faulty phase to closest de-energised conductor	10 m
Height of conductors above ground	10 m

Formulas 3 and 4 (as per the EPRI AC Transmission line reference book) [3], and 5 (as per the Eskom Power Series book) [1], were then used to calculate the induced voltages on the de-energized line. Table 2 summarizes the results.

Table 2 Calculated induced voltages on de-energised circuit

Formula used	Induced voltage
Formulas (3 and 4) - EPRI	1378 V
Formula (5) - ESKOM	1401 V

The formulas yield similar results. In order to verify these calculations a simulation was performed with ATPDraw using the same system variables. Figure 2-1 shows the ATP model and Figure 2-2 the resultant induced voltage.

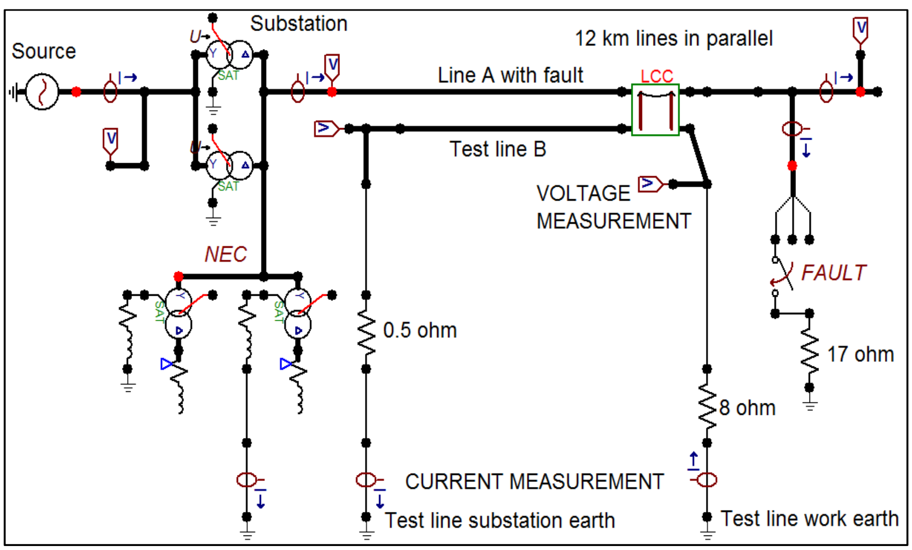

Figure 2-1 ATPDraw model

The induced voltage of 1390 V that was simulated in ATP correlates well with the calculated results of 1378 V and 1401 V.

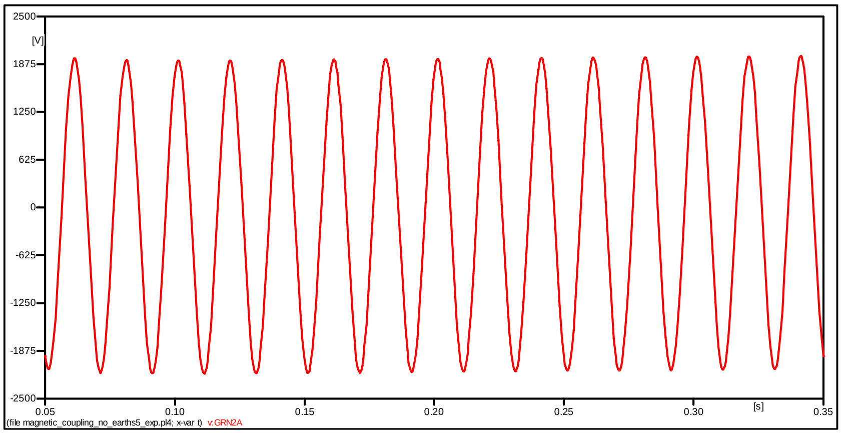

Figure 2-2 Simulated induced voltage (1390V rms)

This ATP model was then used to simulate the magnitude of the induced voltage for the following earthing arrangements:

- *No earths applied* on the overhead line when conducting work
- Control earth applied *at the substation* and working earths applied at the place where work is being conducted (12 km from the substation)
- Control earth *and* working earth applied only at the place where work is being conducted

The effect which the different earthing arrangements have on the magnitude of the induced voltage is summarised in Table 3.

Table 3 Induced voltage simulation results

Scenario	**Magnitude of induced voltage**
No earths applied	1390 V
Control earth applied at *substation and working earths 12 km away* (overhead line earth at two points)	883V
Both Control and working earths applied at the *work location* (overhead line earthed at one location)	2 V

The results in Table 3 suggests that it would be a safer practice to earth an overhead line at only one location when conducting dead work as compared to earthing an overhead line at two locations. The danger to personnel which are to perform work on the earthed MV line can be minimized by conducting such work in an equipotential zone. However, general workers and members of the public can be exposed to high voltages.

3. MAGNETIC COUPLING SITE TEST

3.1 Overview of test site

A test was done to determine the safety contribution of a substation earth. Two 22 kV overhead lines that run in parallel for a distance of 12 km were used to conduct the test. One of the lines was earthed at the substation and at the end of the line where the measurements were taken. The other line was kept alive and an earth fault was created on it as shown in Figure 3-1. The earth resistance was measured to be in the range of 400 Ω.m to 500 Ω.m.

Figure 3-1 Test site of two 22 kV parallel feeders. An earth fault was created on the line on the left and measurements done on the line on the right

3.2 Measurement circuit

An ELSPEC logger was used to measure the MV voltages and currents at the substation and at the end of the overhead lines where the test was conducted. Regowski coils were used to measure the current through the NEC and the MV lines. A voltage divider circuit was used in order to measure what the induced voltage will be on the earthed MV line due to the magnetic coupling of the earth-fault current.

3.3 Practical measurements

The earth fault current of 340 A on the live line induced a current of 106 A on the test line that was earthed on both sides. An induced voltage of 857 kV was recorded at the point where the working earth (resistance of 8 Ω measured to earth) was applied. The high voltages measured on the earthed line were primarily due to the magnetic induced current on the line that was earthed at two locations. The results of the measured induced current and voltage are shown in Figure 3-2.

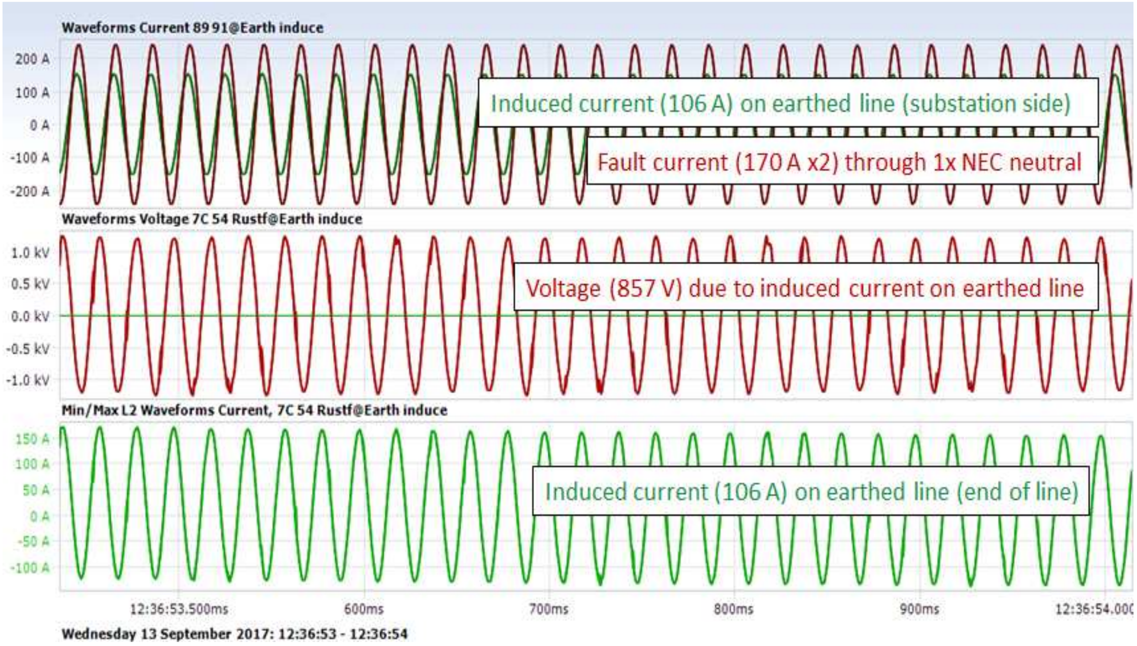

Figure 3-2 Induced voltage and current on parallel line which was earthed at two locations

3.4 Effect of earthing resistance on induced voltage

Further simulations were performed in ATPdraw in order to determine what the effect would be on the magnitude of the induced voltage if the resistance of the working earths is varied whilst also applying control earths at the substation. The earthing resistance of the working earths was varied from 4 Ω to 300 Ω while the control earth resistance at the source was kept constant (0.5 Ω). The earth fault current 343 A in the parallel feeder of was used in the simulation. The results in Figure 3-3 shows that a higher induced voltage can be expected to be present at a higher earthing resistance. Control earths and working earths should be in close vicinity in the presence of parallel circuits.

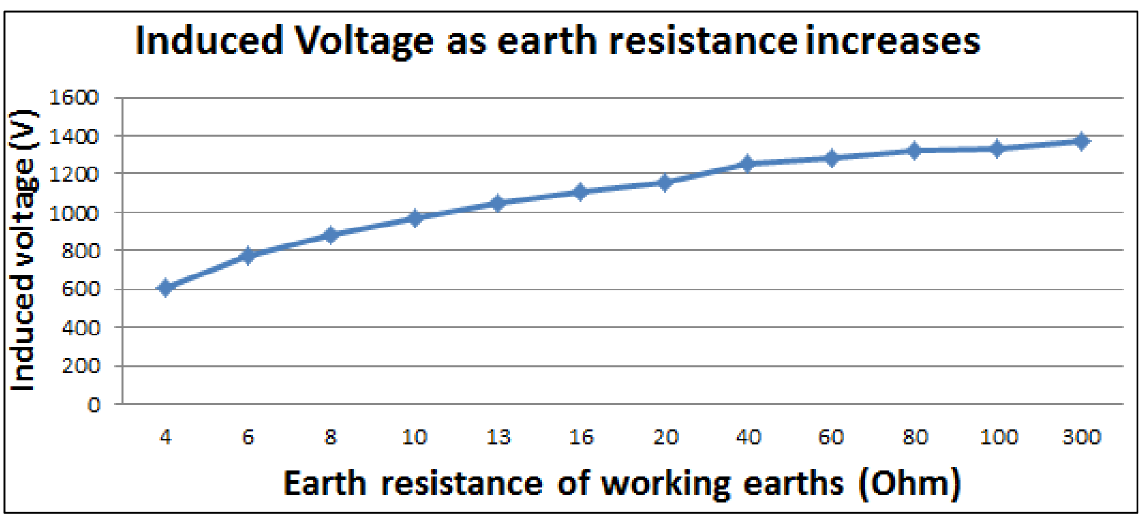

Figure 3-3 Simulated induced voltage at different working earth resistances

4. CONCLUSION AND CLOSURE

Faults on adjacent (parallel) lines can prove to be fatal for any utility personnel performing work on overhead lines. In order to minimize the induced current and associated voltage rise at the work site, it is strongly recommend to earth only at the place of work and not at any other point.

Lightning, faults on adjacent lines and inadvertent closing onto an earthed line can induce significant currents at the place where work is done. It is important to bond earthed sections, wires, metal, vehicle, bucket and ladder that are not bonded to the main working earths (true earth) through some metal connection together.

The earth potential rise test performed in this paper found that in the specific case a voltage drop of approximately 80 % of the full phase-to-earth voltage was present across two earth spikes which were spaced 0.5 m from each other. It is therefore recommended that all utility personnel and members of the public keep away from all earthing points at the work site.

References

[1] A. Britten, M. Korber and R. Ramnarain, "Coupling," in *Eskom Power Series - The planning, design and construction of overhead power lines*, Sandton, Crown Publications cc, Eskom Holdings Ltd, February 2005, p. 311.

[2] M. Costea, I. Baran and T. Leonida, "Factors influencing the magnetic coupling between parallel circuits," in *6th International conference on Energey and Environment - CIEM*, Bucharest, Romania, November 2013.

[3] D. A. Douglass, J. R. Stewart and B. Clairmont, "Electrical Characteristics of Conductor Configurations and Circuits," in *EPRI AC Transmission Line Reference Book - 200kV and Above, Third Edition*, California, EPRI, December 2005, pp. 26 - 32.