CAPACITIVE COUPLING ON OVERHEAD POWER LINES

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Abstract

This paper contains research performed on the effects of capacitive coupling on overhead power lines under loss of phase conditions in an earthed system. The research was triggered by a contact incident which occurred on a 11kV overhead line during unplanned maintenance performed under live conditions.

Keywords: Earthing, Medium voltage, Capacitive coupling, Live work

1. INTRODUCTION

Currently there is a drive in Eskom to utilise live work teams to perform maintenance and project related work under live conditions in order to ensure that the supply to customers is not interrupted. During live work operations overhead jumpers are broken on a regular basis in order to perform the desired scope of work. Up until now not much attention has been given in the case where jumpers are broken on the backbone of a MV overhead line which supplies a T-off that does not exceed 5 km in length.

A contact incident occurred in April 2015 where a live work employee was repairing a broken jumper supplying a 1.1km T-off on a 11kV T-structure. The new jumper that was already connected to the T-off was a bit too long. The operator stood in a bended position and held the jumper between his knees to cut it to size. After he cut the jumper, he stood straight up with the jumper still between his knees. Unfortunately his shoulder then touched the red phase of the backbone part of the feeder. The insulations of his pants and jacket was not enough to withstand the induced voltage on the T-off.

The person experienced an electrical shock when attempting to join the red phase jumper. According to live work standards currently implemented, live work teams are permitted to make and break jumpers on 11kV to 44kV networks under live conditions provided that the length of the section of network is less than 5km in length and no load on the T-Off.

2. LITERATURE REVIEW

During normal operating condition of an overhead line the effects of phase to phase and phase to earth capacitive coupling will be negligible due to the to the resultant voltage of a balanced network being zero. However under loss of phase conditions the capacitive coupling of the two healthy phases will induce a capacitive voltage on the dead phase.

Under a phase to earth fault condition in an earthed system there will also be a capacitive current present with the magnitude being dependent on the length of the network. It has been recorded that capacitive currents could reach up to 60A in the case of a 22kV overhead network with a length of 600 kilometres which includes the length of the backbone and all T-off's.

2.1 Electrical shock

Quite a number of studies have been performed with regards to the effects of electrical shock on the human cardiovascular system. It has been recorded that in the case of a 50Hz system a fault current as little as 100mA could result in fibrillation of the heart as shown in Table 1. Fibrillation can be defined when the muscles of the heart starts to move in a disorganised manner (independently from each other) and not in a coordinated manner. This will cause the heart to not pump blood as effectively as under normal conditions which might result in brain damage and cardiac arrest.

Table 1: Physiological effect of shock [1]

Electric Current (1sec. Contact)	**Physiological Effect**	**Voltage required to produce the current with assumed body resistance:**	
		100,000 ohms	1,000 ohms
1 mA	Threshold of feeling, tingling sensation.	100 V	1 V
5 mA	Accepted as maximum harmless current.	500 V	5 V
10-20 mA	Beginning of sustained muscular contraction ("Can't let go" current).	1 kV	10 V
100-300 mA	Ventricular fibrillation, fatal if continued. Respiratory function continues.	10 kV	100 V
6 A	Sustained ventricular contraction followed by normal heart rhythm (defibrillation). Temporary respiratory paralysis and possibly burns.	600 kV	6000 V

Studies conducted by Nave & Nave [1] have shown that after the skin of a human is punctured the resistance of the human body reduces quite substantially as shown in Table 2.

Table 2: Typical human body resistance to electrical current

Body Area	Resistance (ohms)
Wet Skin	1,000
Internal body (hand to foot)	400 to 600
Ear to Ear	~100

2.2 Capacitive coupling

Capacitive coupling currents are dependent on the following system parameters in an electrical network:

- Conductor size
- Distance between the overhead conductors and earth
- Distance between the overhead conductor phases
- System operating voltage

For a three phase system the phase to phase capacitance (for equal spacing of conductors) can be calculated by using the formula:

$$C = \frac{\pi \varepsilon_0}{In\left(\frac{d-r}{r}\right)} \text{ F/m}$$

where

ε_0 = 8.85x10-12 F/m, permittivity
d = distance between centres of conductors
r = radius of conductors

The formula for reactance is [6]:

$$X_c = \frac{1}{2\pi f C l}$$

It is evident that the spacing between conductors, the conductor size and the operating voltage will have a notable effect of the amount of capacitive coupling current that will be present in a system.

3. RESEARCH METHODOLOGY

3.1 Simulations

The electrical modelling software packaged, ATP draw [4], was used to model the contact incident in order to determine the induced voltage on the "dead" phase and the potential difference across the operator when contact was made between the red phase of the backbone and the red phase of the disconnected t-off.

The simulations included all the specifics of the contact incident like the system voltage, conductor size, and length and the structure type. Figure 1 shows the t-off where the red phase conductor broke, disconnecting the t-off from the main line.

Figure 1: Photo of the pole where the contact incident took place

Figure 2: location where operator experience electrical shock

3.2 Structure and Conductor Types

Additional scenarios were modelled with ATP where different structure types were used which ranged from the standard T-frame, staggered vertical and vertical configurations as shown in Figure 3.

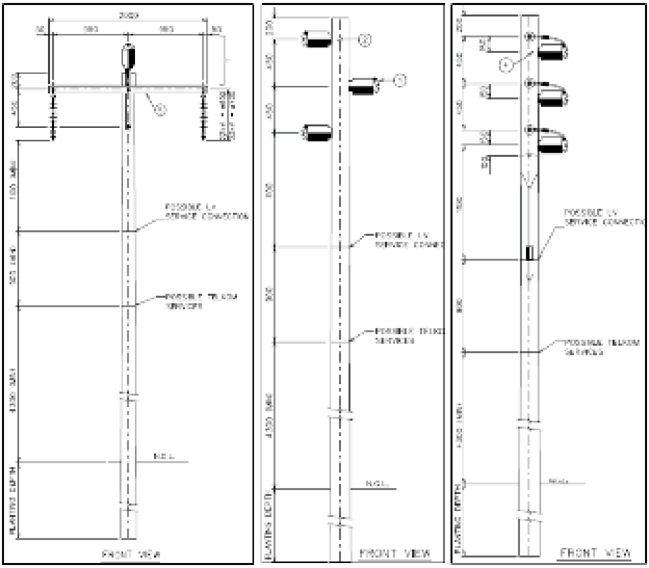

Figure 3: Dimensions of T-frame, staggered vertical and vertical structures respectively

Hare and Fox conductor types were used in the simulation models to the fact that Eskom MV networks are mainly standardised and built using these two conductor types. Specification with regards to the two conductor types are given in Table 3.

Table 3: Conductor specifications

Conductor type	**Diameter (mm)**	**Total area (mm^2)**	**R_{DC} at 20 °C operating temperature (Ω/km)**	**R_{AC} at 20 °C operating temperature (Ω/km)**	**Capacitance @ 1ft spacing (μF/km)**
Fox	8.37	42.79	0.85	0.7822	0.01305
Hare	14.16	122.48	0.30	0.2733	0.01487

The operating voltages that were used to conduct all simulation models were 11kV and 22kV since most Eskom MV network are operated at these voltages.

4. SIMULATION RESULTS AND DISCUSSION

Under normal operating conditions the phase-to-phase voltage is approximately 11kV and the phase-to-earth voltage 6.35kV. As soon as the red phase jumper broke, the disconnected portion of line was no longer at the substation reference voltage and the two healthy phases (white and blue) running in parallel induced voltage onto the disconnected red phase portion.

The simulation yielded a 8.2kV potential difference when measuring between the "dead" red phase conductor of the T-off (Vjumper) and the "live" red phase conductor of the main line on the T-off and the "live" red phase conductor (Vline). Figure 4 below shows the schematic diagram of the simulation where the red phase jumper was broken. The voltage waveforms show that the induced voltage was approximately 180° out of phase with the red phase reference voltage of the substation.

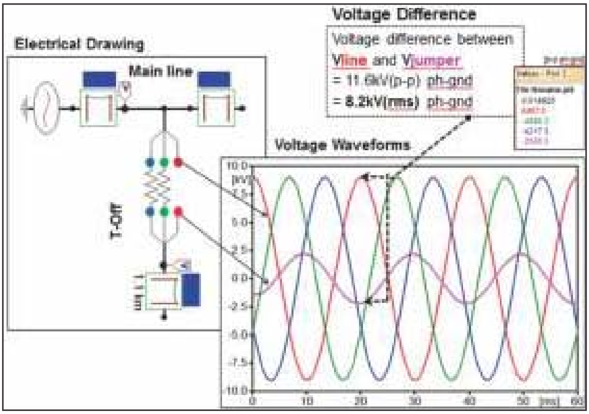

Figure 4: Simulated results indicating 8.2kV voltage difference between V_{line} and V_{jumper}

The phasor diagram of the waveforms in Figure 4 can be found in Figure 5. Phasor diagram 1 shows normal system voltage, phasor diagram 2 shows the induced voltage from the parallel healthy phases on the t-off and phasor diagram 3 shows the resultant potential difference.

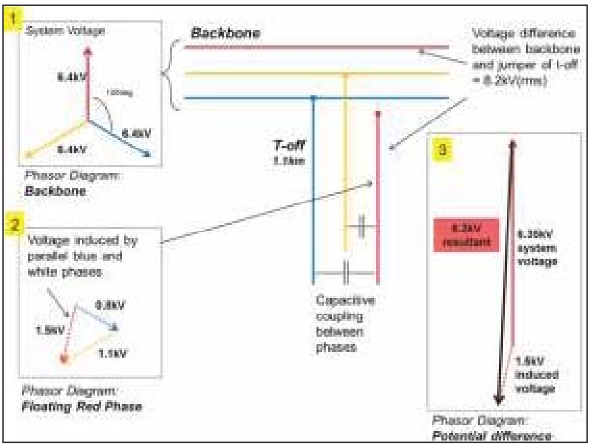

Figure 5: Phasor diagram depicting the potential difference between V_{line} and V_{jumper}

The current that was induced by the capacitive coupling on the 1.1 kilometre section of line was 20mA as shown in Figure 6. This further substantiates the reason why the person experienced an electrical shock when attempting to join the red phase jumper.

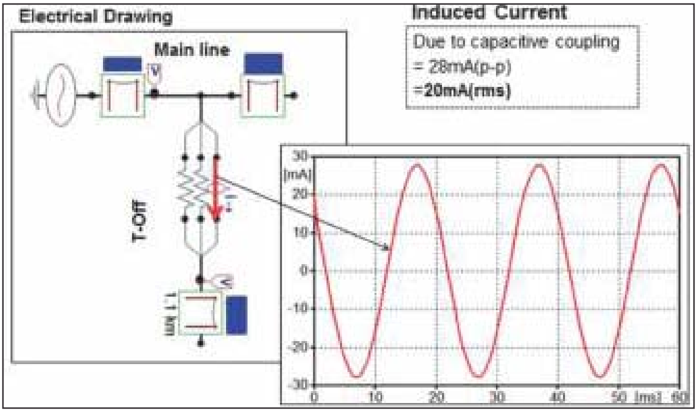

Figure 6: induced current due to capacitive coupling

Further simulations were done to show the effect that the line length and the amount of connected phases have on the induced current flow when energizing a t-off. Table 4 below shows the capacitive coupling current on a 11kV Hare line built on a T-frame structure with 10m poles. As the line length increases from1km to 5km the capacitive coupling current also increases. When all 3 phases of the t-off is being connected to the backbone, the capacitive coupling current will be the largest when the last phase is connected to the backbone and the reason for this is that the other two phases already energized to system voltage induces voltage on the last phase to be connected.

Table 4: Capacitive coupling current for different line lengths and amount of phases connected (Hare conductor on a T-structure)

length of t-off (km)	Phase being energized	capacitive coupling (induced) current (mA) RMS
	connecting first phase:	20.5
1km	connecting second phase:	32.0
	connecting third phase:	34.8
	connecting first phase:	62.7
3km	connecting second phase:	97.3
	connecting third phase:	106.0
	connecting first phase:	105.1
5km	connecting second phase:	165.1
	connecting third phase:	178.6

Six additional simulations were done in which the configuration were changed in order to see to what extent each variable affected the amount of induced current on a 1 kilometre section of line. The results are listed in Table 5.

Table 5: Effect of variable change with regards to induced current.

#	kV	Conductor type	Structure type	Pole length	Induced Current (mA rms) (1km t-off)*	Induced Current (mA rms) (5km t-off)*
study 1	11	Fox	T-structure	9m	**28**	**151**
study 2	11	Hare	T-structure	9m	**35**	**178**
study 3	11	Hare	T-structure	10m	**35**	**179**
study 4	11	Fox	Staggered Vertical	10m	**44**	**252**
study 5	11	Fox	Vertical	10m	**44**	**262**
study 6	11	Hare	Vertical	10m	**61**	**314**
study 7	22	Hare	Vertical	10m	**121**	**627**

* the simulation results shows the induced current when connecting the 3rd phase of the t-off.

Comparing study #1 and #2, the conductor type was changed from Fox to Hare which resulted in a 25% increase in the induced current. Comparing study #2 and #3, the distance between the overhead conductors to earth was increased from 9m to 10m which resulted in a negligible increase in the induced current. Comparing study #3 and #4 the conductor type was changed from Hare to Fox and the structure type was also altered which decreased the distance between phase conductors which resulted in a 26% increase in induced current. Comparing study #5 and #6, the increase in the conductor size resulted in a 39% increase in the induced current. Comparing study #6 and #7, the induced current increases by the same factor with which the voltage increases.

5. CONCLUSION AND FURTHER RESEARCH

The Eskom standard for High Voltage Live Working in Distribution and Transmission [2] specifies the maximum line length as 5km when energizing or de- energizing 11kV to 44kV line. According to the simulation results a capacitive coupling current of 627mA will flow then energizing a 5km 22kV line. This amount can be considered a life threatening. No earth fault protection or sensitive earth fault protection will operate for inducted current (capacitive coupling current) due to the small range. It is proposed that the use of by-pass leads be considered when energizing a t-off of any length using live work, to ensure that the induced current will flow through the by-pass lead and not accidently through the operator's body.

The design of the network greatly determines the amount of induced current that will flow when energizing a portion of the network to the main line. The system voltage, the conductor size and the distance between phases plays the significant role in the amount of induced current.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

ATPDraw Software, http://www.atpdraw.net/

IEC 60479 Parts 2 and 3, Effects of current passing through the human body, general (1984) and special aspects (1987) respectively.

Nave & Nave. Physics for the Health Sciences. 3rd ed. : W. B. Saunders, 1985.

Overhead Power Lines: Planning, Design, Construction, Kiessling F., Nefzger P., Nolasco J.F. and Kaintzyk U., 1st editon, Springer Verlag Berlin Heidelberg, 2003

Pillay T. and Bisnath S. (eds), The planning, design and construction of overhead power lines, 1st edition, Johannesburg, Crown Publications, Feb 2005

Power Systems Analysis and Design, Glover J.D., Sarma M.S. and Overbye T.J., fourth edition, Thomson, 2008

Standard for High-Voltage Live Working, 34-1148 Part 13 – Live Work, Rev 2 Aug 2012.