



# Lightning protection for equipment on MV feeders

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*This article presents the influence of lightning on MV feeders supplying small power users (400/230 V) with focus on insulation failures leading to poor power quality. In order to minimise power interruptions, lightning-related trips are reduced mainly by minimising MV equipment failure. Examples of arc quenching are included.*

In order to minimise distribution (11 and 22 kV) feeder breaker operations during lightning storms, the feeder was designed at an insulation level (BIL) of 300 kV. The line insulator has a BIL of 150 kV. A section of the wood pole was used to add another 150 kV, totalling 300 kV BIL. It was also possible that the wood path could assist with arc quench up to 20 A [1]. Although the wood path is an advantage for indirect strokes, it resulted in severe wood splitting due to direct strokes. In some cases conductors fall to lower levels and become dangerous to humans and animals. Unfortunately, the higher the BIL, the higher the amplitude of the injected travelling waves on the feeders. Numerous fuse failures as well as transformer failures occurred during lightning storms. This was taken care of by developing lightning-proof fuses, drop-out line surge arresters and Combi units as shown in Figure 1.



Figure 1: Combi unit (A), lightning-proof fuse (B) and drop-out line surge arrester (C).



## Enhancing feeder performance

A feeder's lightning performance is measured against the number of trips due to lightning. This research was done by monitoring the Theunissen – Brandfort pumps (TBP) 11 kV feeder's performance. (This is located in the middle of the Free State province, South Africa). The 300 kV BIL design resulted in substantial damage due to wood splitting. Investigation [2] undertaken shows that impulses due to lightning strikes with magnitudes of higher than 7 kA can cause splitting of the wood (see Figure 2).



Figure 2: Wood damage due to lightning

Replacing damaged wood poles results in customer outages. Sometimes the damaged pole is also in very difficult or inaccessible terrain. It is therefore necessary to prevent wood splitting as far as possible. The detailed study was based on actual measurement of lightning (direct and indirect flashes) to investigate whether the BIL cannot be lowered by doing away with the bare wood gap.

In the TPB feeder, the BIL varies from 95 kV to fully insulated wood poles (no bonding or any earth wires). About 10% of the poles are fitted with 150 kV BIL insulators in series with a 150 kV BIL wood insulation to earth (totalling 300 kV BIL). The rest of the poles are fitted with 95 kV BIL porcelain insulators. About 30% of these wood poles are fully insulated (no bonding earth wire) – the rest (60%) are either fully bonded (BIL around 95 kV) or have a very small wood gap. Figure 3 shows the typical feeder poles.



Figure 3: 300 kV BIL and 95kV BIL structures.

## Measurement equipment and set-up

### Power frequency loggers

Power frequency loggers (Impedograph and ELSPEC 4430, effective sampling rates of 12 kHz and 400 kHz respectively) have been used

BIL – Basic Insulation Level  
 CT – Current Transformer  
 GPS – Global Positioning System  
 LTS – Lightning Tracing System  
 NEC – Neutral Earthing Compensator  
 NETFA – Testing facility within the Electrotechnical Cluster of SABS Commercial  
 RMS – root mean square  
 SCADA – Supervisory, Control and Data Acquisition

**Abbreviations**

to monitor current and voltage on the feeder. The loggers are synchronised with GPS timing resulting in the lightning surges on the power frequency being accurately time stamped. The recorder has two three phase inputs – one for the resistor voltage divider and one for the breaker CTs. A resistor voltage divider was installed to capture voltage recordings and the current is recorded by using the relevant protection CT (600/1 CT ratio) of the feeder breaker. The basic setup of equipment is shown in *Figures 4 and 5*.

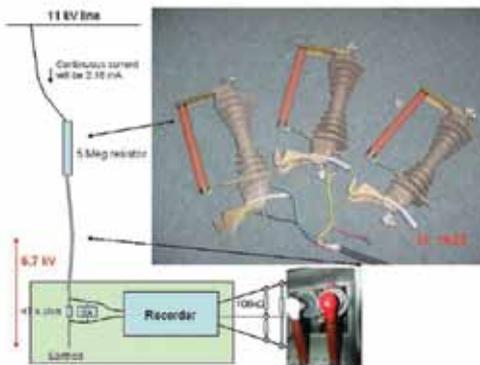


Figure 4: Measurement equipment setup (A).



Figure 5: Measurement equipment setup (B).

**Lightning tracking system (LTS)**

In order to relate captured impulses to lightning events, LTS data was used. Accurate time-stamping as well as information about the magnitude, polarity and exact geographical position of each lightning stroke is stored in the LTS database. The LTS consists of 19 sensors monitoring lightning activity in South Africa. This information is sent to a central master station where some calculations regarding the position, intensity and time are done. The LTS system has a flash detection efficiency of 90% and a stroke location accuracy of 500 m.

**Analysis of measurements**

Impulses recorded by the power loggers are compared with the breaker operation alarms from SCADA and information from the protection relays. The recorded impulses and breaker operations are then related to lightning using LTS to establish the size and polarity of the lightning stroke that caused the fault. A detailed feeder inspection in that area is then done to find the exact position (pole) where lightning terminated. The time and polarity of the stroke together with voltage and current data from power loggers are used in determining whether the stroke terminated directly on or next to the feeder.

Should the recorded transient (leading edge of the first deviation of the waveform) be positive while the LTS recorded the stroke as negative, it means that the stroke did not terminate on the feeder – an indirect stroke. Conversely, should the recorded transient be negative (leading edge) with the corresponding LTS recording also negative it means that it was a direct stroke.

**Measured results and arc quenching**

A finding on the feeder is that no trips or fault current could be attributed to an indirect lightning stroke or flash. The lightning ground flash density along the feeders is shown in *Figure 6*. Most of the faults due to direct flashes are quenched before breaker operation. The time taken for the fault current to quench, varied between 10 ms and 2,7 s. The fault current that became quenched also varied from as little as 110 A to in excess of 1 000 A. Most of the quenched fault currents were between phases.

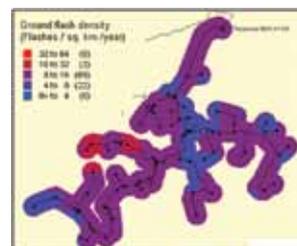


Figure 6: Lightning ground flash density / km<sup>2</sup> / year for the TBP 11 kV feeder.

**Measured results on feeder performance**

Each lightning event that was captured by the logger at the substation was matched with the Lightning Tracking System as described in the measurement setup section. One flash is seen as one event and can consist of up to 20 strokes. The figures in *Table 1* show the end state of the breaker operation after the complete flash event.

TBP 11 kV 4 Feb 2008 to 3 Feb 2009					
Direct strokes (52) : Faults			Indirect strokes (2078): Faults		
ph-ph	1 ph - earth	No trip	ph-ph	1 ph - earth	No trip
15	6	31	0	0	2078

Table 1: Measured results on TBP 11kV feeder.

Analysis of Table 1 shows that there were in total 52 direct strokes that caused a power frequency current. Of these events, 15 resulted in either phase to phase or 3 phase power frequency faults that sustained until the breaker cleared the fault. A total of six single phase to earth faults caused breaker operations. The remaining 31 events were either 3 phase, or phase to phase faults that quenched before the breaker could operate. A total amount of 2 078 indirect strokes were recorded by the LTS within 1 km from the feeder and none of them caused any power frequency fault current to flow.

### Example of worst case indirect stroke

The worst case indirect lightning stroke was found to be a -120 kA stroke 20 m from on section of the feeder that did not cause a flashover. At that point the feeder's BIL was 190 kV (150 kV line insulator plus 40 kV stay insulator). Figure 7 - Figure 10 show the measured waveform, the LTS result and a photo of the site.

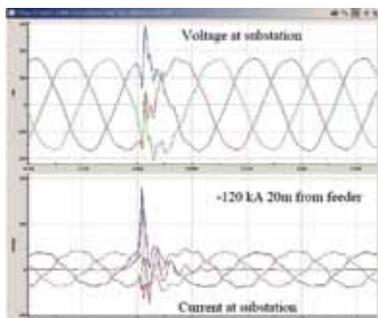


Figure 7: Voltage and current waveforms measured at the substation.

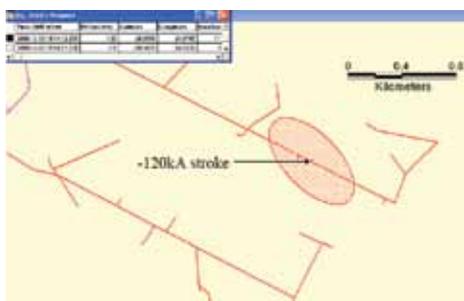


Figure 8: Lightning tracking system result.



Figure 9: The scene.



Figure 10: Pole closest to the tree where a -120 kA stroke terminated.

### Comparison of the theoretical and practical results

Theoretical predictions indicate that 103 trips should have occurred on the TBP feeder due to lightning. The difference between the amount of calculated and measured trips is most probably due to arc quenching, the feeder being screened by trees and other high objects in the environment. Table 2 summarises the comparison between theory and practical measurements. Lightning related trips means faults that are initiated by lightning and can be either temporary or permanent. The average number of direct flashes per year to a line (Ns) is given by Eriksson as [3]:

$$N_s = N_g (28H^{0.6} + w) \times L \times 10^{-3} \text{ per year}$$

Year	Total trips	Lightning related trips
4 Feb 2008 to 3 Feb 2009	87	21
Theoretical predicted figures for number of direct flashes		103

Table 2: Number of breaker trips on the TBP feeder.

### Examples of arc quenching

Arc quenching is caused by one of the following: Wind that blows the arc away; hot air around the arc rises, causing the fault path resistance to increase until the arc self-extinguishes or a magnetic force that blows the arc away.

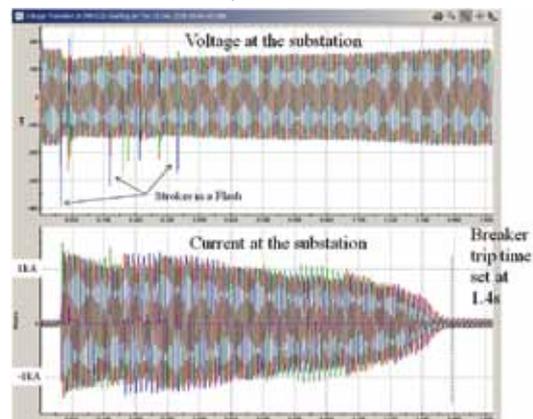


Figure 11: Example of a three phase fault that quench after 1 360 ms, just before the over-current protection operated.

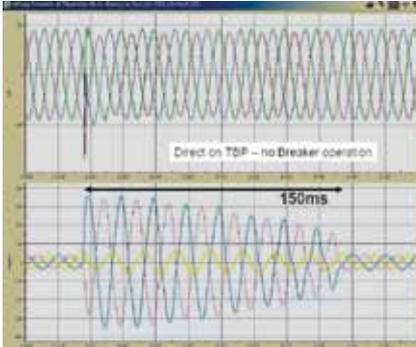


Figure 12: Phase to phase fault that quenched.

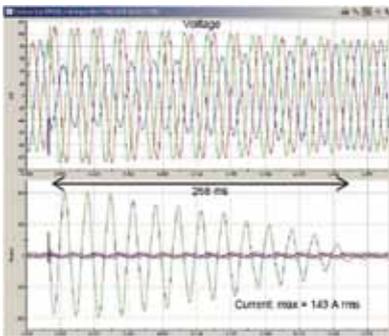


Figure 13: Single phase fault that quenched.

### Remarks on feeder BIL

The design of power lines require careful consideration of all factors such as optimal performance, complying with environmental legislation, ensuring the predetermined lifespan of the equipment and preventing danger to human life, to which no value can be attached, etc. Many thousands of flashes along the test feeder were studied for the past year and even much more for the past five years. No incident where an indirect stroke caused a power frequency fault was detected. An early finding is that the general MV construction is quite immune against indirect strokes even on sections of the feeder built at a BIL of 150 kV. The problematic wood gap on the pole can then be closed should this be true.

Most of the power frequency faults caused by direct lightning flashes quenched before the relevant breaker tripped. No relation could be found in these cases between the feeder construction, the amplitude of the fault current (fault level) and the time for a fault to quench. Arc quenching needs further investigation and modelling. In the near future arc quenching will be investigated by installing a breaker on the neutral of the NEC to reduce the earth fault current to only capacitive current, and thereby encouraging arc quenching.

### Minimising equipment failure

Equipment failures can be minimised by the installation of line surge arresters; a drop-out type surge arrester was developed for this purpose. Fuse failures can be reduced by installing a lightning-proof fuse and a Combi unit can be installed at transformer installations to protect both the transformer and the fuse.

### Line surge arrester

Line surge arresters refer to additional arresters strategically placed along a feeder at points of high lightning density. Line surge arresters are currently installed in South Africa on 11 kV, 22 kV, 33 kV, 66 kV, 88 kV, 132 kV and 275 kV lines. The use of line surge arresters on HV lines is to prevent the feeder breaker from tripping due to lightning. The purpose of line surge arresters on MV feeders is mainly to minimize equipment failure.

### Drop-out line surge arrester

A drop-out type surge arrester was developed for MV feeders, where the arrester will fall open once it becomes faulty.

### Advantages

A faulty arrester is noticeable from ground level and quick and easy to replace. The line arrester can be changed while the line is energised which saves operating time, customer outages and cost. It can be temporarily disconnected from the feeder during fault finding. The line arrester can be replaced from ground level with a link or operating stick and therefore eliminating the risk of falling from heights or electrical contact.



Figure 14: Drop-out line surge arrester.

### Operation and installation

The drop-out function of the surge arrester is mainly for maintenance purposes. A faulty arrester can be changed from ground level quickly and effortlessly.



Figure 15: The operation of the surge arrester once it becomes faulty.



Figure 16: The installation of drop-out line surge arresters.

### Lightning-proof fuse

Annually many thousands (12 789) of rural fuses in the North Western Region are lost particularly during bad weather (lightning) conditions. If the overtime costs to replace the fuse, material costs and wear and

tear on vehicles are taken into account, it is not difficult to see that this inconvenience has large financial implications as well as customer dissatisfaction. An alternative fuse technology is presented to avoid nuisance fuse failures on rural feeders due to lightning impulses while also making proper 50 Hz protection grading possible.

### Fuse operations at lightning frequencies

It is relatively easy to grade fuses for correct 50 Hz current operation, but fuses are also sensitive for high currents such as these found in lightning. Normally lightning consists of a first stroke followed by several subsequent strokes as it can be seen in the illustration shown in Figure 17.

The illustration shows that lightning consists of three major components namely an amplitude component, the rate at which the current rises and an energy component that exists due to the dc current found within a lightning flash.

The total surface area underneath the wave form represents the energy that needs to be dissipated by the fuse and surge arresters on the line.

The combination of all of the above given factors contributes to the reason why rural feeder over current protection fuses blow for lightning impulses. In practice this means that since lightning flashes are of very short duration and consists of high peak values with a dc component, the maximum RMS current handling capability of the fuse is reached almost instantaneously, resulting in a blown fuse (this is mainly due to the energy dissipation in the fuse). However, this problem can be avoided by introducing a few passive components into the circuit.

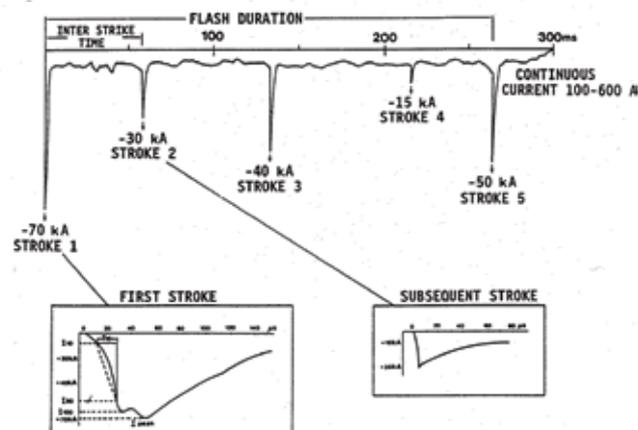


Figure 17: Three basic components found in a lightning flash [4]

### Circuit configuration and parameters

By introducing a spark gap in parallel with a fuse, which is in series with an inductor into the circuit, with the latter acting as a low impedance path at 50 Hz and as a high impedance device at lightning frequencies it was found that the arising problems due to lightning frequencies can be avoided with great success.

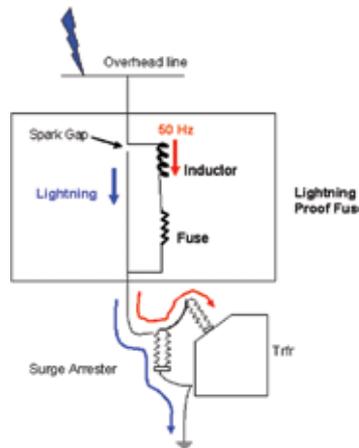


Figure 18: Circuit configuration including a lightning-proof fuse.

During normal 50 Hz operation the inductor must act as a low impedance path with low over all energy dissipation. The impedance of the inductor at power frequency is given by:

$$\text{Equation 1: } X_L = 2 \cdot \pi \cdot f \cdot L_c$$

Where:

$X_L$  = Power frequency impedance.

$f$  = Power frequency.

$L_c$  = Inductance.



Figure 19: Lightning-proof fuse operation.

This will ensure that the fuse will work correctly for normal over current situations. However, from Equation 1 it can be deduced that the impedance of the circuit will be high for lightning frequencies resulting in the current attempting to find an alternative conducting path. The maximum volt drop across the inductor is 75 kV at lightning frequencies and 0,15 V at 50 Hz. The power frequency will pass through the inductor and fuse while the lightning impulses will flash over the spark gap, bypassing the fuse element.

### Impulse test results

All current impulse tests have been performed at NETFA close to Pretoria using 8/20  $\mu$ s current impulses. The 8/20  $\mu$ s current impulse test was done to determine the breakdown currents of the 3 A and 5 A fuses. The 3 A fuse lasted for five tests in succession (without blowing on the last test) with current varying from 20 kA to 70 kA.

### Advantages and disadvantages

The advantage of the lightning proof fuse is that it eliminates nuisance fusing on MV feeders caused by lightning and still allows sufficient protection grading. The fuse fits in a standard fuse bracket.

The disadvantage of the fuse is that it does not protect the pole mounted transformer from lightning. Secondly, whenever the fuse blows for a 50 Hz fault at the transformer, a standing back flash-over across the spark gap while the fuse is falling open will occur, which will be cleared by the upstream breaker. The breaker will auto-reclose in about 3 s and the faulty transformer is isolated from the network.

### Combi unit

The Combi unit consists of a post insulator in the middle with a drop out type surge arrester on the one side and a drop out fuse on the other side. Should the fuse blow, only the fuse will fall open while the arrester stays closed. In the case where the surge arrester GLD (ground lead disconnect) operates, both the fuse (fuse element still healthy) and the surge arrester fall open.

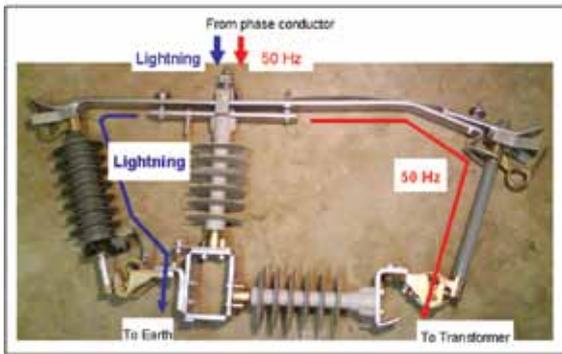


Figure 20: Illustration of the operation of the Combi unit.

### Development of the Combi unit

The Combi Unit was initially developed to minimise the MV fuse and transformer failures during lightning activities. The MV fuses were exposed to lightning due to the pole mount transformer configuration as it was installed line side of the surge arrester. The surge arrester was only protecting the MV transformer. Should the arrester be placed line side of the fuse to protect both the fuse and transformer, the arrester could only be changed after the feeder was isolated.

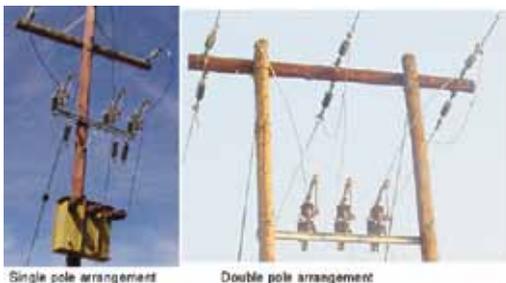


Figure 21: Combi unit installations.

### Advantages of using Combi unit

- Change fuse and surge arrester from ground level:

- o No slip and fall from step ladder
- o No risk of electric contact
- Transformer and fuse protected against lightning
- No nuisance fusing due to lightning
- Protection grading possible
- Transformer is always protected against lightning
- A faulty fuse or arrester is noticeable
- Can be used as an isolation point
- Use standard Eskom fuse/holder and bracket
- Surge arrester has the same dimension as a dropout line arrester
- No outage necessary for replacement of fuse or arrester
- Shorter replacement time

### Performance of Combi unit

A total of 1 064 pole mount installations has been fitted with Combi units over the past five years. At all these installations at least one transformer failure occurred annually. After the installation of Combi units only 11 transformers failed over the last three years instead of an expected 1 500 transformer failures. Reasons for the failures:

- Two installations had neither neutral arresters nor any connection between the 400 V neutral and earth. This seems to be the reason for failure of the transformers.
- One installation was hit by a lightning flash consisting of 18 strokes. The arresters failed but in the process the transformer was damaged.
- One transformer failed shortly after installation with no lightning around – maybe the transformer was already damaged.
- Seven installations still need to be visited.

To minimise the risk of falling objects, a tool was developed to replace drop-out surge arresters and fuses from ground level using a link stick. Figure 22 shows the insertion tool.



Figure 22: The insertion tool to replace fuses and drop out surge arresters.

### Conclusion

- No indirect stroke recorded on the 11kV TBP line ever caused a line fault, even with more than 50% of the line insulated at only 95 kV.
- 150 kV BIL (line with only insulators and no wood gap) seems to be more than enough to prevent an indirect lightning stroke from causing a fault.
- The phenomenon of arc quenching needs to be further investigated.
- Maintenance and operating on lines are much easier when using

drop-out-type surge arresters that can be changed from ground level under live conditions.

- Lightning-proof fuses make proper protection grading for power frequency possible and eliminates nuisance fusing caused by lightning.
- The Combi unit reduces equipment failure (fuses and transformers) significantly.

### References

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