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Planning for the future in uncertain times

Recovery voltage analysis of the Matimba – Phokoje 400 kV transmission line during a single phase-to-earth fault

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SUMMARY

The paper aims to demonstrate the potential impact of network expansion and the subsequent creation of resonant poles close to power frequency. The importance of the combination of transmission line transposition and a neutral earthing reactor on long shunt compensated lines is once again demonstrated. It also emphasise the importance of performing sound insulation coordination studies as part of the initiation of new projects where network expansion might cause a change in the compensation factor. It demonstrates the risk associated with introducing high compensation factors. Two separate transmission line geometries are evaluated in ATP to demonstrate the risk of high induced over-voltages during open phase conditions. The tower geometries represent two common designs utilised within the Eskom transmission grid. It is observed that when the line reactors are retained, the substation location is extremely sensitive to induced over-voltages due to the exponential slope of the induced voltage function. Careful consideration should be taken in future applications. Additionally, there is currently no information available that confidently acknowledge premature/accelerated insulation ageing may or may not be caused by temporary over-voltages below the withstand level. It leaves it to the utilities to interpret and evaluate the severity of stresses on equipment. It has been confirmed that equipment with magnetic cores are considered to be vulnerable when exposed to these temporary over-voltages. Although the equipment buyer/user gains confidence in the withstand capability after successful factory acceptance tests, there is no certainty as to how the insulation integrity changes over time and what the impact is of multiple temporary over-voltages over the operating life. Complete elimination of over-voltage where possible should be encouraged.

KEYWORDS

Insulation co-ordination, temporary over-voltage, single phase auto reclose, secondary arc current, recovery voltage, insulation withstand level.

1 BACKGROUND

Long transmission lines consist of a large distributed capacitance which is the primary cause of Ferranti voltage rise at the open end of the line. The current criteria [1] in Eskom for an un-acceptable over-voltage caused by Ferranti is when the voltage at the receiving end exceeds 1.1 p.u. The criteria also include controlling the sending end voltage to the pre-switching voltage of 1.025 U_n (for U_n = 400 kV). This value is the targeted voltage as described by the System Operator which presents a realistic scenario for a Ferranti analysis. When the study indicates an unacceptable Ferranti rise, shunt compensation is introduced to compensate the positive sequence line capacitance. The compensation factor can be described by the relationship of the positive sequence susceptance of the compensated line [2].

$$k[\%]=\frac{B_L}{B_C}=\frac{1/(\omega_{S.}L_+)}{(\omega_{S.}C_+)}=\frac{1}{\omega_{S.}{}^2L_+C_+} \qquad (1.1)$$

Where

B_L is the inductive susceptance of the shunt reactor,

B_C is the capacitive susceptance of the transmission line,

$\omega_{S.}$ is the system angular frequency at 50 Hz,

L_+ is the positive sequence inductance of the reactor, and

C_+ is the positive sequence capacitance of the transmission line.

Shunt compensation on busbars and transmission lines is separated in their functional purpose. The application of these functions is clearly separated in theory, but in practice it is not always executed correctly. Bus reactors are usually installed to be switchable to allow for on demand utilisation. Line reactors are preferred not to be switchable (without a separate circuit breaker) and forms part of the transmission line during all conditions. In the past, Eskom has standardised on 100 MVar reactors to be used in the 400 kV transmission network. The combination of the large 100 MVar reactors and the Ferranti criteria of the past (remote open end not allowed to exceed 1.05 p.u) created scenarios where compensation factors were already exceeding 75 %. When the compensated line is looped in and out of a new substation, the compensation factor is changed. The compensation factor can be increased from an acceptable value of 75 % to 95 % and is determined by the new line length. Additionally, the transpositions on the line could be isolated during these scenarios and has a significant impact on the induced voltages during open phase conditions. High compensation factors shifts the resonant pole closer to the power frequency and could create scenarios of resonance during single phase auto reclose (SPAR), resulting in very high temporary over-voltages (TOV's).

1.1 Single phase auto reclose and open phase conditions

Experience has proven that the majority of over-head transmission single-phase-to-ground faults are caused by transients. Lightning often causes flash-overs and provides a perfect opportunity for primary fault current to flow. Fault clearing is optimised by removing only the faulted phase temporarily and reconnecting it after a short duration. This method is referred to as SPAR schemes.

The most important advantages of SPAR schemes are [3]:

- Transient stability improvement,
- Reduction of shaft torsional stresses,
- Radial transmission lines, and
- Reduction in switching over-voltages.

During a SPAR sequence, the circuit breaker remains open for a selected duration (dead time) to ensure the de-ionisation of the fault current channel. Many factors such as system voltage, fault current magnitude, fault clearing time, wind speed and electromagnetic coupling from healthy phases determines the dead time to selected.

The Eskom cycle for single phase auto reclose (ARC) is as follows [4]:

1ph fault – 1ph trip – 1 second dead time – 1 ph reclose – 3 ph trip and lockout if fault remained after 1 second dead time.

1.2 Secondary arc currents and recovery voltage

During an open phase condition, after the primary fault current is interrupted, strong capacitive and inductive coupling from the healthy phases enables the arc to be sustained for a period. This arc is referred to as the secondary arc and if the secondary arc current is large enough, the arc could be sustained for prolonged durations (exceeding the dead time), leading to unsuccessful reclosure. After the extinction of the secondary arc, the recovery voltage is initiated on the open phase. The magnitude of the secondary arc and the recovery voltage has a great influence on the success rate of the SPAR scheme. The electromagnetic coupling form the healthy phases exists as the electromagnetic force behind the secondary arc during the dead time. When the electromagnetic coupling is strong, the secondary arc extinction is hampered. The voltage caused by the capacitive coupling (recovery voltage) is a function of the phase-to-phase and phase-to-earth capacitances of the transmission line, as well as the voltage on the healthy phases. The capacitances are directly related to the length of the line and the line geometry. The inductive coupling should not be neglected and is primarily a function of the load current in the healthy phases.

To theoretically evaluate the over-voltages initiated by SPAR on over-compensated transmission lines, open phase conditions can be considered. Open phase conditions are created where one or two phases are energised, and the remaining phase(s) remains open. When the transmission line is shunt compensated these scenarios can become problematic.

The following assumptions are relevant for the evaluation:

- The transmission line is fully transposed and lossless,
- Circuit elements are linear,
- The shunt reactors inter-phase magnetic coupling is neglected,
- Series impedance is neglected, and
- The neutral point of the reactor is solidly earthed.

Figure 12 represents the circuit configuration when the line is compensated with a reactor.

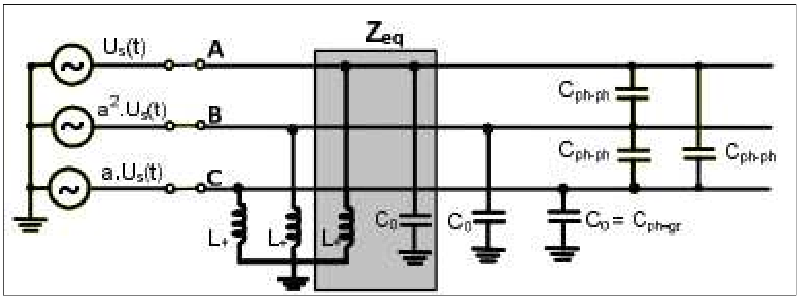

Figure 1: Application of shunt line reactor [2]

The combined impedance for the isolated open phase is then given by [2]:

$$Z_{eq}=X_C//X_L=\frac{1}{j(\omega_s C_0)}//j(\omega_{s.}L_+)=\frac{j(\omega_{s.}L_+)}{1-\frac{\left(\frac{C_0}{C_+}\right)}{\left(\frac{k}{100}\right)}} \tag{1.2}$$

$$C_0=C_{ph\text{-}gr} \tag{1.3}$$

$$C_+=C_{ph\text{-}gr}+3C_{ph\text{-}ph} \tag{1.4}$$

Where C_0 is the zero sequence capacitance which is equal to the phase-to-ground capacitance $C_{ph\text{-}gr}$ and the equivalent impedance is a function of the compensation factor.

Perfect resonance will occur during the following condition:

$$\frac{k}{100}=\frac{C_0}{C_+}\rightarrow Z_{eq}\approx\infty \tag{1.5}$$

The application of shunt reactors compensate for positive sequence line capacitance. The uneven compensation of positive and zero sequence capacitance leads to high risk of resonant conditions at high compensation levels. The induced voltage for the open phase conditions as a function of transmission line length are given by:

$$U(Length) = 1/\left[\left[\frac{3\left(1-\frac{1}{\omega_{s.}{}^2L_+C_+Length}\right)}{\left(1-\frac{C_0}{C_+}\right)}\right]-n\right] \tag{1.6}$$

Where n = 1 for one open phase condition and n = 2 for two open phases condition. And to calculate the induced voltage on the open phases the equation yields:

The compensation factor that results in perfect resonance can be calculated by the following equation:

$$k_{resonance}=\frac{1+\frac{2}{3}\left(\frac{C_+}{C_0}-1\right)}{\left(\frac{C_+}{C_0}\right)} \tag{1.7}$$

1.3 Neutral Earthing Reactor

To reduce the auto reclose dead time or to improve the SPAR success rate, artificial methods are applied to reduce the secondary arc current. These methods include:

- Fixed four reactor scheme (also known as a NER),
- Switchied four reactor scheme,
- High speed earhthing switch scheme.

It has been demonstrated that the use of a fixed four reactor scheme (4^{th} reactor referred to as the neutral earthing reactor (NER)) assists with detuning the series resonant circuit. The un-equal compensation of positive and zero-sequence line capacitance leads to open-phase resonant conditions. In order to de-tune the resonant circuit the use of an additional zero-sequence impedance is included. The equivalent impedance includes an additional inductance in series with the shunt reactor inductance in the zero-sequence circuit. Transpositions are applied to ensure an even and balanced capacitive coupling between the phases. The mutual coupling is assumed to be equal between all phases. This provides a fixed ratio between the zero and positive sequence capacitance along the line. During an open phase condition of phase A, Figure 23 demonstrates the combination of inductance and capacitance that forms the equivalent impedance. The healthy phases B and C are coupled via their respective equal phase-to-phase capacitances.

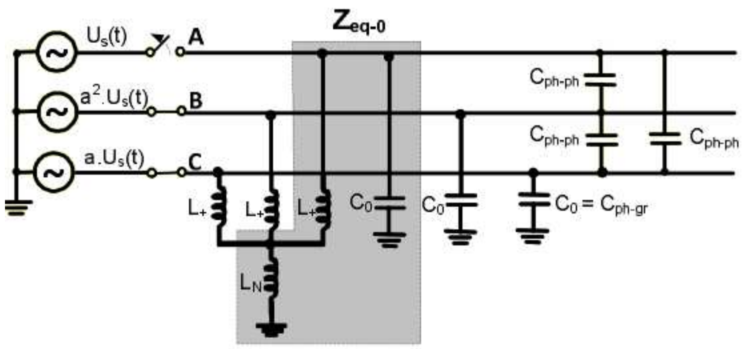

Figure 2: Neutral Earthing Reactor

The equivalent impedance is then given by:

$$Z_{eq}=X_C//X_{Leq}=\frac{1}{j(\omega_s C_0)}//j(\omega_{s.}(L_+ + L_N)=\frac{j\omega_{s.}(L_+ + 3L_N)}{1-\omega_{s.}^2(L_+ + 3L_N)C_0} \quad (1.8)$$

The neutral reactor is then applied to either ensure an even compensation between the positive and zero-sequence capacitances or can be applied to compensate the inter-phase capacitive coupling to minimise the secondary arc current.

1.4 Evaluation of induced voltages when line was shortened due to new substation

Eskom has several 400 kV transmission tower designs and are used with different bundle configurations. Transmission line geometry primarily determines the line parameters and when compensated, results in different resonant poles. In Eskom, the standardised size of 100 MVar reactors were applied to almost all lines where shunt compensation were required, usually yielding high compensation degrees. The following section aims to reveal the risk of introducing resonant poles close to power frequency when compensated lines are shortened due to network expansion. While it is a fairly simple procedure to determine whether shunt compensation is required after such a change in line length, the recommendation of removing the line reactor is sometimes not executed due to various reasons.

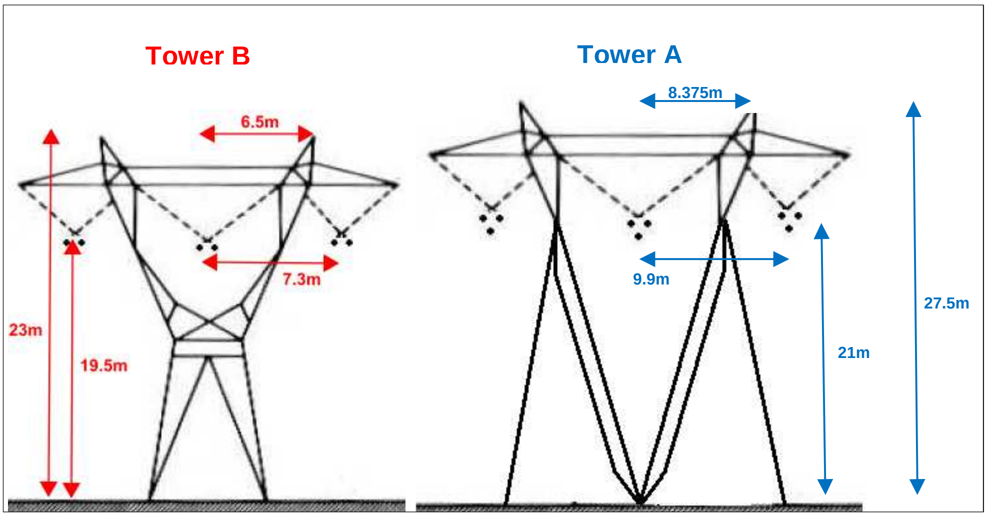

Figure 3: 400 kV Transmission line geometries

Table 1: Transmission line parameters for Tower A and B

Transmission line parameters	Tower A	Tower B
Inductance (zero sequence) mH/km	**1.53**	**3.5**
Inductance (positive sequence) mH/km	**0.59**	**1.012**
Capacitance (zero sequence) nF/km	**9.2**	**8.5**
Capacitance (positive sequence) nF/km	**13**	**11.7**

It is clear that the transmission line geometry dramatically impacts the resonant pole conditions for the two lines evaluated. The resonant pole conditions are calculated as per equation (1.6) and the induced recovery voltages on the open phases are simulated in ATP.

Table 2: Open phase resonant conditions for Transmission line A and B

Configuration	Parameter	Substation 1 150 km	Substation 2 200 km	Substation 3 250 km
Transmission Line A Shunt compensated 100 MVar	**Compensation factor k**	**101.8 %**	**76.4 %**	**61 %**
	Natural frequency 1 open phase	**53.1 Hz**	**48.6 Hz**	**41.2 Hz**
	Induced open phase voltage (peak)	**580 kV**	**666 kV**	**199 kV**
Transmission Line B Shunt compensated 100 MVar	**Compensation factor**	**113.2 %**	**85 %**	**68 %**
	Natural frequency 1 open phase	**55.8 Hz**	**51 Hz**	**43.2 Hz**
	Induced open phase voltage (peak)	**240 kV**	**973 kV**	**227 kV**

From the calculation the resonant poles are located at 169 km for Line A and 187 km for Line B. To determine the compensation factor that results in perfect resonance, equation

(1.7) is applied. The result is that both line configurations will result in perfect resonance when the compensation factor is 90 %.

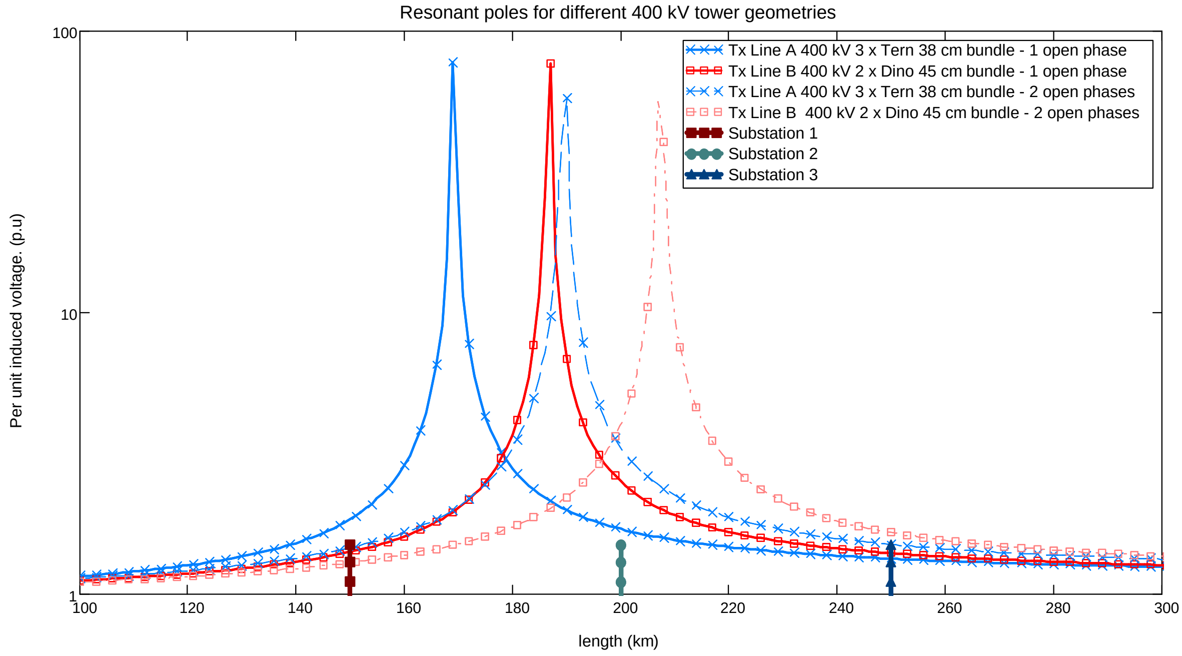

Figure 4: Resonant Pole plot for Line A and B as a function of line length

Only three positions were evaluated at 150 km, 200 km and 250 km. It should be noted that exponentially higher induced voltages could occur when the line reactor is not removed and new substations are integrated into the network.

1.5 Withstand capability of equipment connected to open-phase

It is clear that when network expansion causes transmission line compensation factors to be changed, resonant poles are shifted. During SPAR, open phase conditions may result in large recovery voltages. The recovery voltages may be classified as temporary over-voltages when the RMS value exceeds U_m for two cycles. During these events, connected equipment to the open phase includes current transformers, line reactors, capacitive voltage transformers, surge arresters. These TOV's effects power quality and can potentially lead to dielectric or thermal failure of equipment. Cigre WG 33.10 originally covered this subject in a series of publications between 1990 and 2000 [5]–[8] .

A review of the equipment characteristics results in the confirmation that one of the important factors to consider is the presence of a magnetic core. The equipment group with a magnetic core includes the line reactor and current transformer for example. The withstand characteristic as a function of time is determined by the magnitude of the over-voltage and the duration the equipment is subjected to the over-voltage. Over-excitation of the magnetic core may result in increased temperatures. There is no clear indication of how the insulation of this equipment is degraded when subjected to temporary over-voltages. The conclusion of the Cigre working group 33.10 [9] was that very little representatives (representing utilities and equipment manufacturers) was in a position to present a temporary over-voltage withstand characteristic for magnetic core equipment. It was noted that the required withstand capability for the particular equipment is a matter between the purchaser and supplier.

Eskom has specified a withstand characteristic as follows:

Table 3: Eskom withstand requirement for transformers and reactors [1]

Voltage	**Withstand requirement**
$\mathbf{U}_{\mathbf{max}}$ = 1.05 $\mathbf{U}_{\mathbf{n}}$	Continuously for 400 kV and above
1.05 $\mathbf{U}_{\mathbf{max}}$	Withstand for 10 minutes
1.25 $\mathbf{U}_{\mathbf{max}}$	Withstand for 1 minutes
1.5 $\mathbf{U}_{\mathbf{max}}$	Withstand for 5 seconds
1.75 $\mathbf{U}_{\mathbf{max}}$	Withstand for 1 second

Various tests are performed by manufacturers, with the primary purpose to confirm the dielectric integrity and over-voltage withstand capability. Induced or long duration voltage tests are performed to establish insulation integrity at the fundamental power frequency. However, the shorter duration tests are carried out at higher frequencies (180 Hz – 200 Hz) to prevent core saturation. Various manufacturers provided information (although very limited) to allow Cigre to summarise the captured data to produce a guideline for TOV withstand characteristic [9]. It should be noted that it is almost impossible to accurately quantify temporary over-voltage effects. Careful consideration should be taken when conclusions are drawn to classify a TOV event as non-detrimental or indeed detrimental on equipment insulation. It is important to understand that there is no information available to quantify the degree of insulation degradation caused by these over-voltage events. If the design life of the equipment is 30 years, it is certain that the withstand characteristic will change. It is unclear how over-voltages may or may not contribute accelerated ageing or excessive gassing that may lead to partial or eventually complete insulation failure. It is then a healthy engineering approach to aim for complete elimination of over-voltages where possible and to further minimise the frequency of occurrence where elimination is not possible.

2 CASE STUDY

The original 400 kV Matimba – Insukumini transmission line was commissioned as a fully transposed 400 km transmission line. A few years after it was commissioned, the line was turned into Phokoje 400 kV substation almost exactly at the 200 km mid-point. The original transmission line was operated as a fully transposed 400 km transmission line since the original transpositions was located at 133 km and 267 km. However, in the case where the new substation is introduced at the 200 km midpoint, the line is segmented into two 200 km sections, each with only one transposition. The network configuration is given in Figure 56. Transpositions on the line is important to equalise the mutual capacitive coupling and performs well in combination with a Neutral Earthing Reactor (NER) to limit secondary arc currents and recovery voltages during the dead time prior to single-phase auto reclose.

Additional problems were introduced when the Neutral Earthing Reactor (NER) at Matimba was not replaced after catastrophic failure of both the main line reactor and the NER. The neutral of the new 100 MVar line reactor of the Phokoje line was solidly earthed and operated in this arrangement (present situation). After a single-phase-to-ground fault, high temporary over-voltages were measured at the 400 kV line reactor terminals. A temporary over-voltage of 1.6 p.u was measured during the dead time prior to a successful auto reclose (ARC).

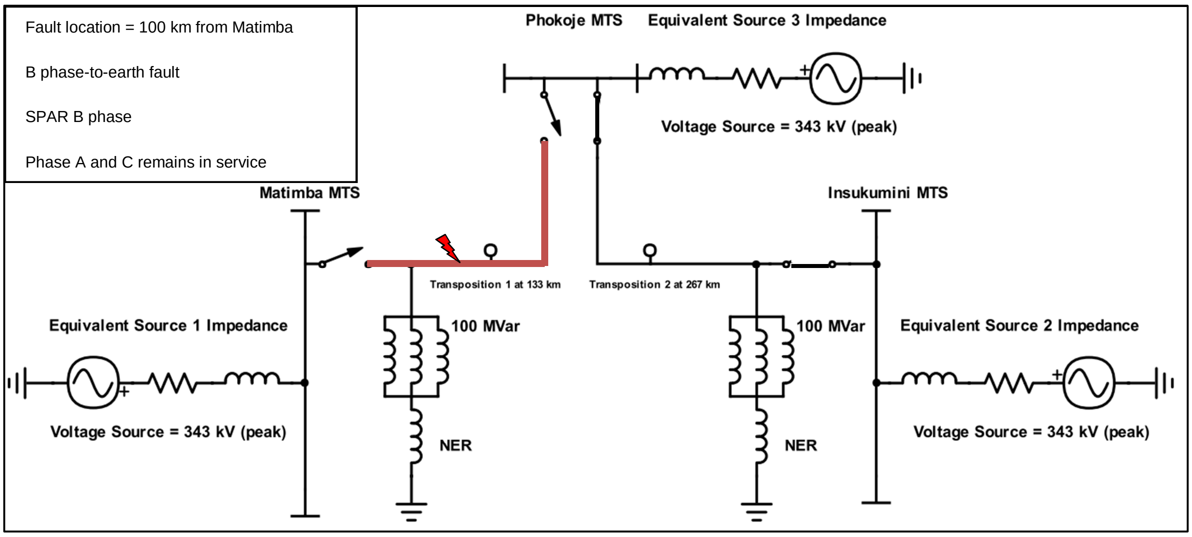

Figure 5: Matimba - Phokoje - Insukumini network configuration

It is anticipated that with a high compensation factor, the natural frequency of this circuit is very close to the power frequency of 50 Hz. The combination of the semi-transposed line and solidly earthed reactor creates a scenario where line connected equipment during open phase conditions are subjected to high TOV's.

2.1 Fault recordings

Two instances of single phase-to-ground faults are observed. The faults were recorded on 18 November 2015 and 4 April 2016. The voltage is measured at the line bay voltage transformer. In Figure 67, the primary fault occurs at 0.26 s and reaches a maximum of 10.6 kA RMS. The primary fault current is interrupted within 100 ms. The secondary arc remains until 0.84 s and then extinguishes. The recovery voltage is initiated and reaches a maximum voltage of 361 kV RMS. The phase is returned to service by the SPAR scheme at 1.4 s and the load nominal load current is re-established.

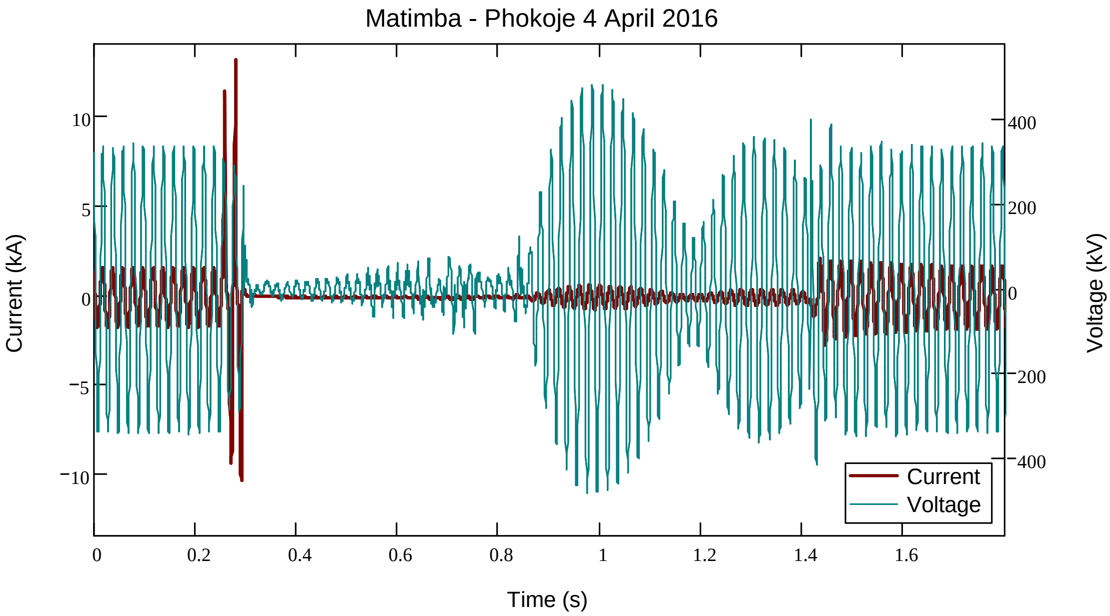

Figure 6: Matimba - Phokoje fault recording (Without NER) 4 April 2016

Another instance was captured on 18 November 2015 and is shown in Figure 78. The fault is initiated at 0.66 s and reaches a maximum of 17.7 kA RMS. The fault is cleared after 100 ms and the secondary arc remains for a short duration and extinguishes at 0.8 s. Similar recovery voltages are measured and reaches a maximum of 360 kV RMS.

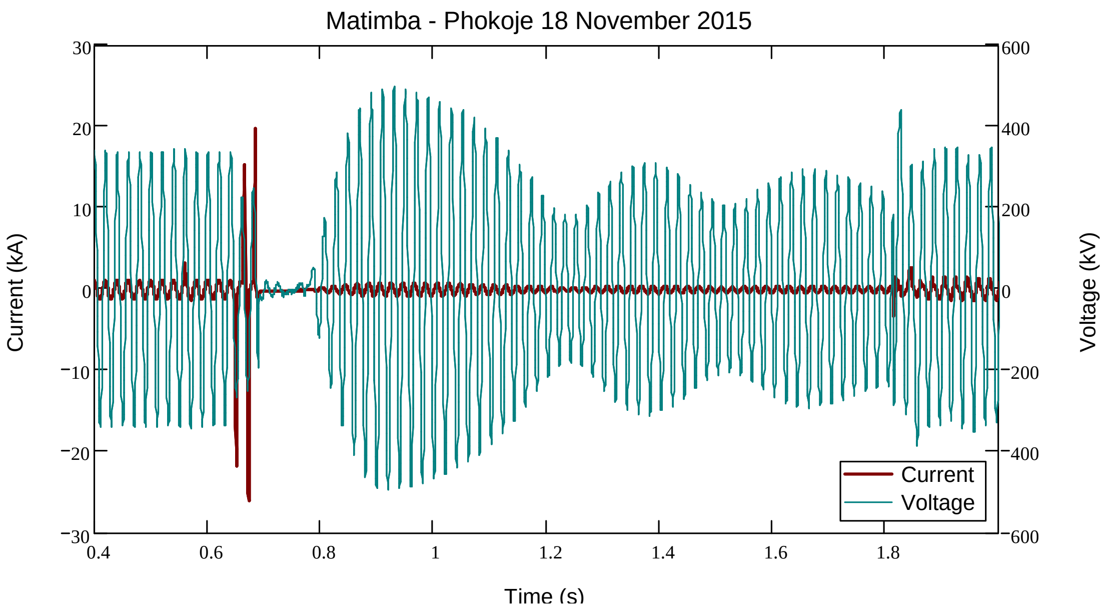

Figure 7: Matimba - Phokoje fault recording (Without NER) 18 November 2015

2.2 Simulation

The source is represented by a Thevenin equivalent of Matimba power station. The equivalent impedance is R = 0.3 Ω and L = 14.7 mH. This is equal to an X/R ratio of 14. The load is modelled with a resistive element to represent a balanced 130 MW load. The fault occurs between phase A and ground, 100 km away from Matimba. The primary fault is initiated at 0.27 s, the circuit breaker are fully open at 0.37 s. Fault clearing time is 100 ms. The secondary arc remains for a further 570 ms. After the secondary arc extinguishes at 0.9 s, the recovery voltage is established. The SPAR scheme ensures that the circuit breakers are fully closed at 1.57 s.

The simulation includes the evaluation of 3 configurations as shown in Figure 89:

1. Semi- transposed (transposition at 133 km) without NER (similar to recordings)
2. Semi- transposed (transposition at 133 km) with NER
3. Fully- transposed (transposition at 67 km and 133 km) with NER

It is assumed that the line reactor installed is also utilised for the generator stability at the power station. There are no busbar reactors installed at Matimba substation, which prohibits the removal of line reactors without providing a replacement on the busbar. This may be a very costly exercise although this is preferred. The idea then is to find the most cost effective solution to eliminate the over-voltage. The purpose of the simulation is to evaluate the remedial actions to minimise both the recovery voltage and secondary arc currents.

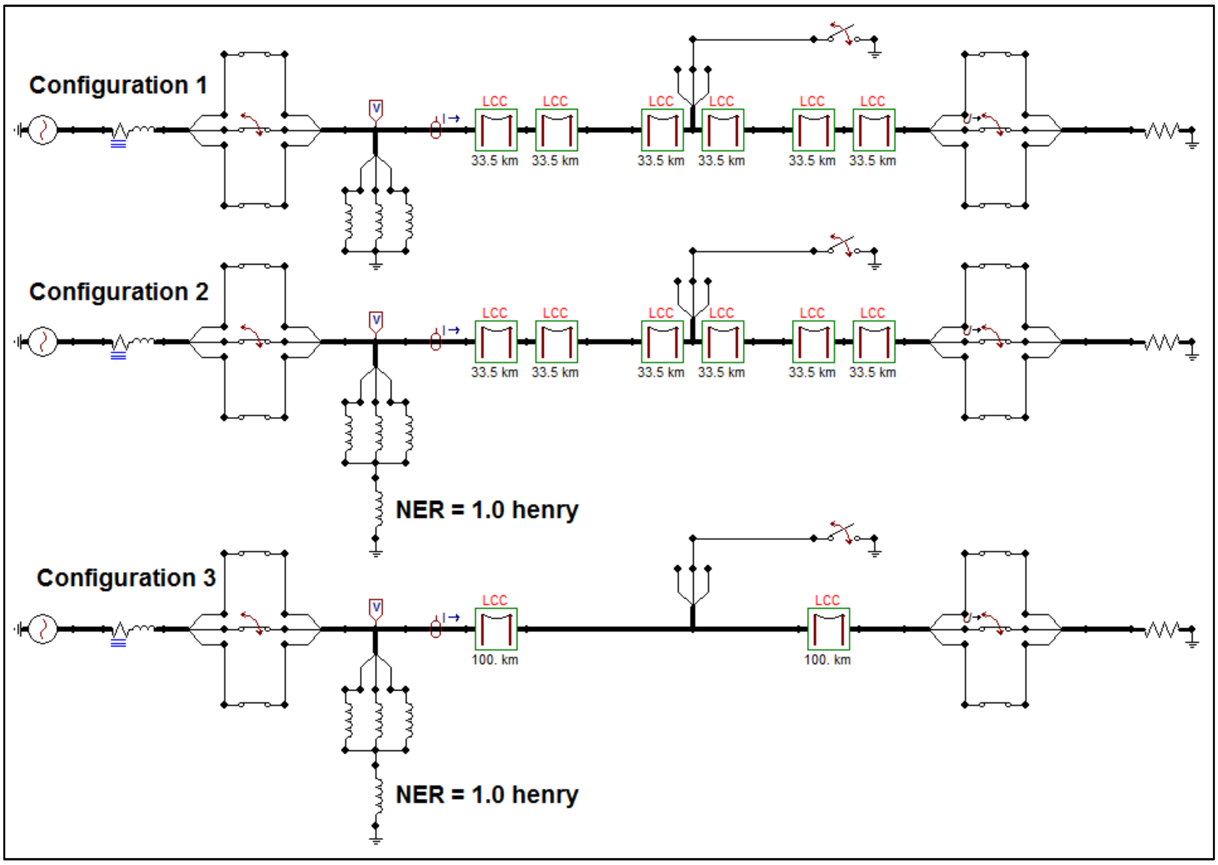

Figure 8: ATP simulation model

Extending the life of the equipment and ensuring improved SPAR performance forms part of the objective. The three scenarios result in the recovery voltages as indicated in Figure 910.

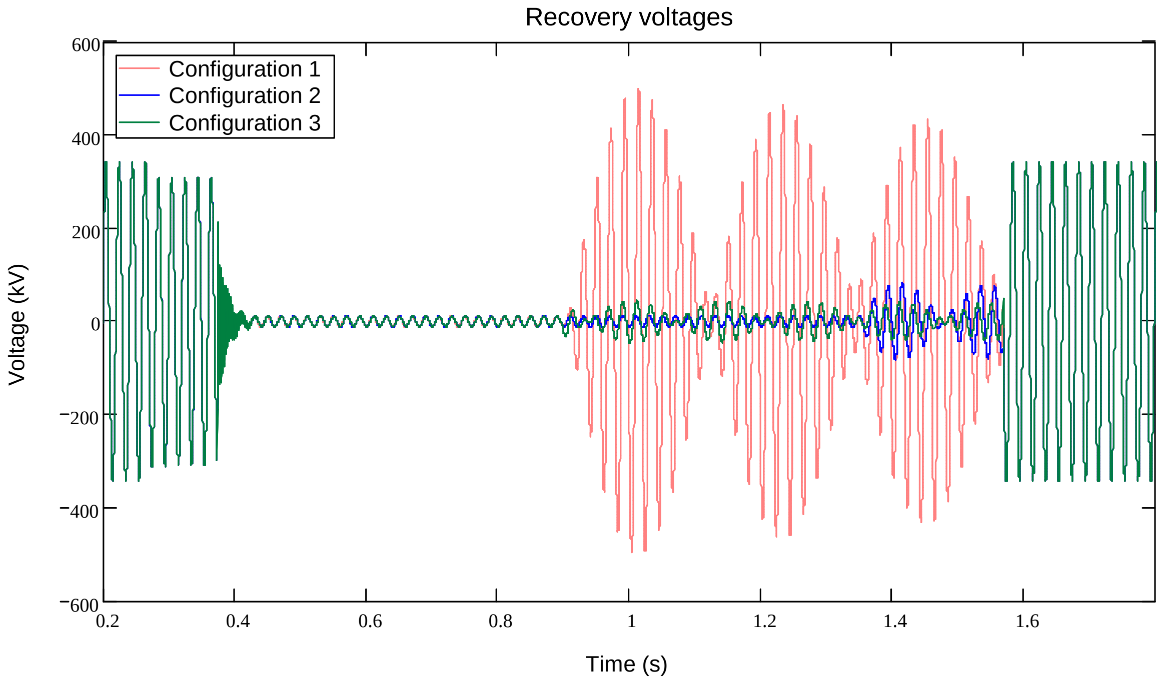

Figure 9: Simulated recovery voltages for different configurations

For illustrative purposes the recovery voltages are plotted in Figure 1011 as true RMS signals to demonstrate the magnitude and duration of the TOV.

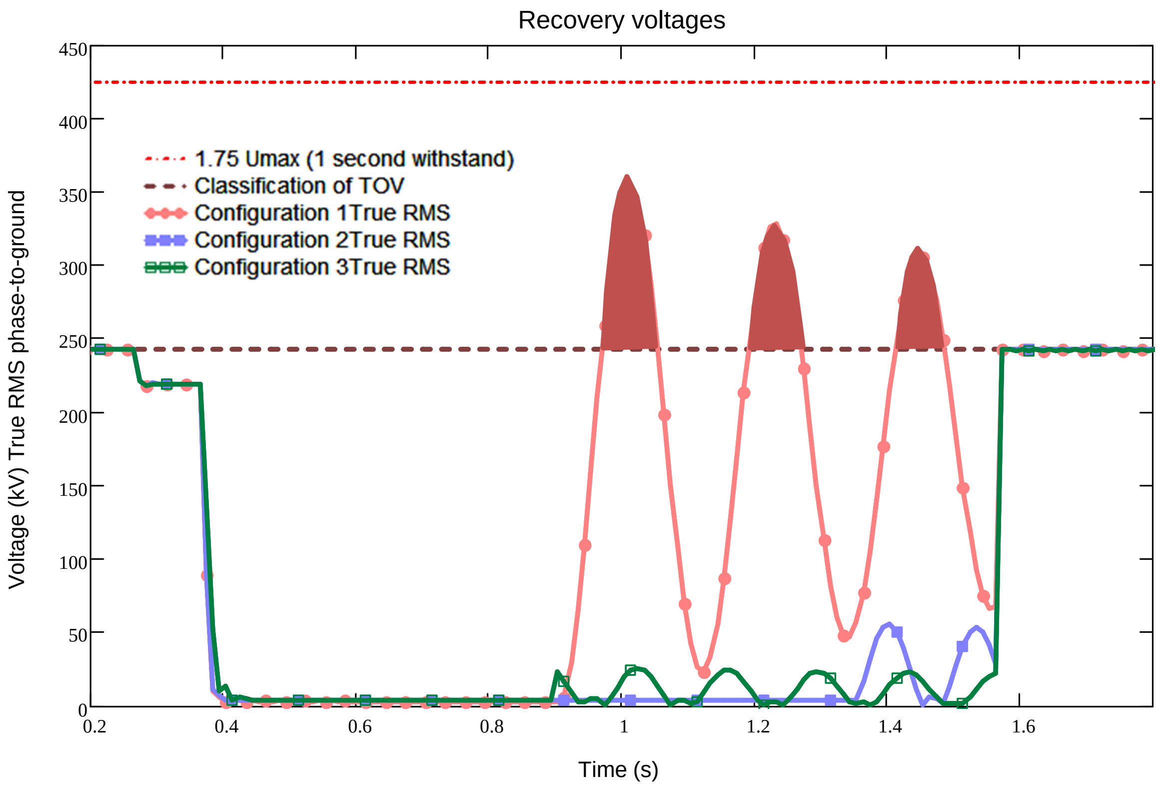

Figure 10: True RMS of recovery voltages

The secondary arc currents are evaluated for the 3 configurations and are plotted in Figure 1112. All the secondary arc currents contained a 19 A DC offset. The currents in the figure is normalised around the zero crossing.

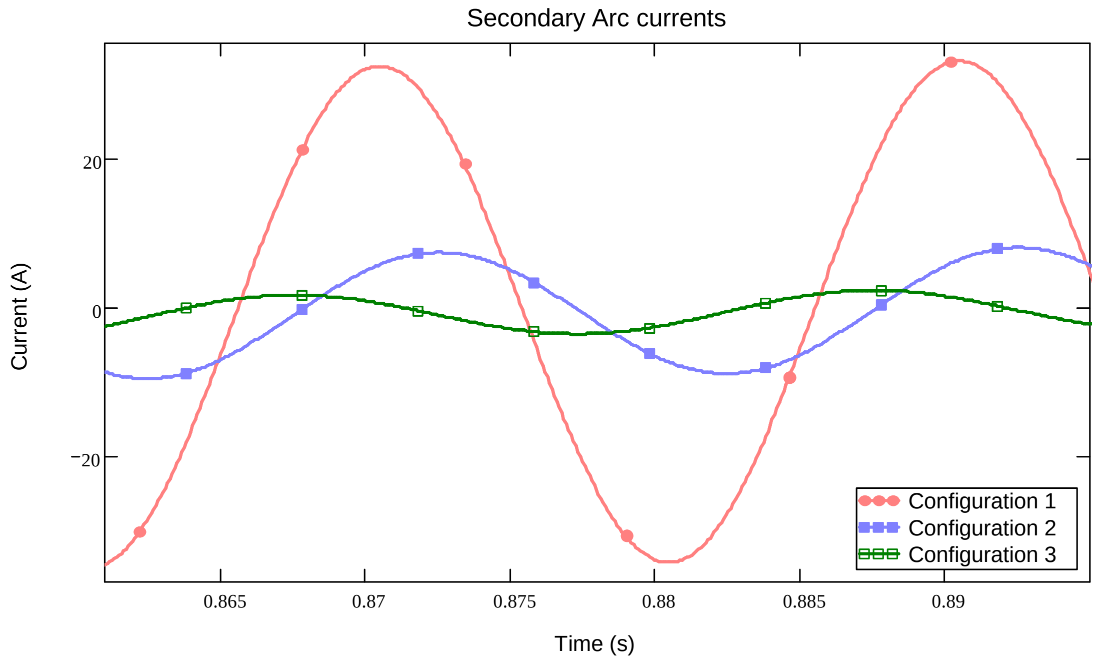

Figure 11: Secondary arc currents for the different configurations

It is noted in literature that the duration of the secondary arc should be minimised to allow for reliable SPAR schemes. Knudsen listed the following decisive factors [10]:

- The magnitude of the recovery voltage.
- The rate of rise of the recovery voltage.
- The magnitude of the secondary arc current.

It is also mentioned that the secondary arc resistance will modify the current to be interrupted and the voltage appearing just after the interruption. This will contribute to the destabilisation of the arc. A summary of the simulated results are tabulated as follows:

Table 4: Recovery voltage and secondary arc currents summary

Scenario	**Recovery voltage RMS line-to-ground (kV)**	**Secondary arc current RMS (A)**
Configuration 1	353	23.3
Configuration 2	55	6
Configuration 3	25	2.3

From the summary table it is clear that the complete transposition with a NER results in the smallest recovery voltage and secondary arc current. A more practical solution is to install a NER as per configuration 2. The recovery voltage is reduced to 16 % of maximum expected voltage in configuration 1. The secondary arc current is reduced to 26 % of the maximum expected value in configuration 1.

3 CONCLUSION

The paper aims to demonstrate the potential impact of network expansion and the subsequent creation of resonant poles close to power frequency. The importance of the combination of transmission line transposition and a neutral earthing reactor on long shunt compensated lines is once again demonstrated. It also emphasise the importance of performing sound insulation coordination studies as part of the initiation of new projects where network expansion might cause a change in the compensation factor. It demonstrates the risk associated with introducing high compensation factors. Two separate transmission line geometries are evaluated in ATP to demonstrate the risk of high induced over-voltages during open phase conditions. The tower geometries represent two common designs utilised within the Eskom transmission grid. It is observed that when the line reactors are retained, the substation location is extremely sensitive to induced over-voltages due to the exponential slope of the induced voltage function. Careful consideration should be taken in future applications. Additionally, there is currently no information available that confidently acknowledge premature/accelerated insulation ageing may or may not be caused by temporary over-voltages below the withstand level. It leaves it to the utilities to interpret and evaluate the severity of stresses on equipment. It has been confirmed that equipment with magnetic cores are considered to be vulnerable when exposed to these temporary over-voltages. Although the equipment buyer/user gains confidence in the withstand capability after successful factory acceptance tests, there is no certainty as to how the insulation integrity changes over time and what the impact is of multiple temporary over-voltages over the operating life. Complete elimination of over-voltage where possible should be encouraged.

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