# Investigation and efficiency analysis

## 405 km transmission line with series compensation

*By R Gouws, North-West University*

*This article presents an investigative case study and efficiency analysis of the 405 km, 420 kV transmission line between Insukamini substation in Bulawayo, Zimbabwe and the Matimba thermal power station in South Africa (which is routed through Botswana).*

An analysis was done on the energy efficiency of the load with respect to three scenarios by means of a simulation model. The simulation model was slightly adapted in order to simulate series compensation on the network. From the results obtained from the simulation model it can be seen that the energy efficiency decreases for all three scenarios.

The three scenarios evaluated:

- Line to ground fault occurred on the secondary bus.
- Impedance fault occurred on the two transmission lines.
- Combination of the above two faults occurred.

The transmission line is equipped with three Bison conductors per phase and two overhead earth wires. At Insukamini substation a 750 MVA, 420 kV/330 kV interbus transformer (three single-phase units each rated at 250 MVA) links up the 420 kV and 330 kV systems. The transmission line is further equipped with a directly connected 100 MVAr, 420 kV reactor. A + 200/- 100 MVAr Static VAr Compensator (SVC) is connected to the 330 kV busbar system [8, 11].

In the Eskom revenue application documentation submitted to NERSA, Eskom considers the transmission network losses to amount to approximately 4% [7] – which was the reason for developing a simulation model and performing an efficiency analysis on the load for the different fault scenarios. For the simulation model the load is connected to the transmission line by means of a 420 kV/330 kV interbus transformer and the 405 km transmission line is divided into two equal parts with a series compensation network at the centre.

The following three fault scenarios were investigated:

***First scenario:*** Where a line to ground fault occurred on the secondary bus.

***Second scenario:*** Where an impedance fault occurred on the two transmission lines.

***Third scenario:*** Where a combination of the two faults occurred.

### Overview – transmission lines

One of the major components of an electric power system is the power transmission line. The major function of the transmission line is to transport electrical energy from the power source to the load with minimal power loss. The transmission line depends on the following four electrical parameters [6]:

- Series resistance
- Series inductance
- Shunt capacitance
- Shunt conductance

A transmission line is considered a medium-length line when the length is between 80 km and 240 km. The single-phase equivalent circuit of the transmission line can be represented by means of an equivalent π circuit with approximated lumped-parameters. The shunt capacitance of the line is usually divided into two equal parts, one at the sending end and one at the receiving end of the line. *Figure 1* shows the equivalent circuit of a transmission line [6].

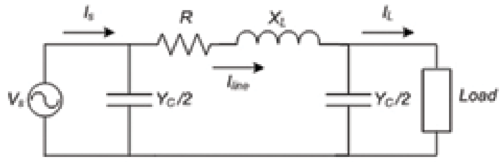

*Figure 1: The equivalent circuit of a transmission line.*

The lowering of the reacting impedance and reducing of the voltage drop of the transmission line over long distances are two of the main advantages of series compensation. By including series capacitance to the transmission line the reactive impedance can be lowered, which in turn will lower the voltage drop across the transmission line. The more compensation is included, the more the voltage drop is reduced. This will allow more power to be received by the load [3,4].

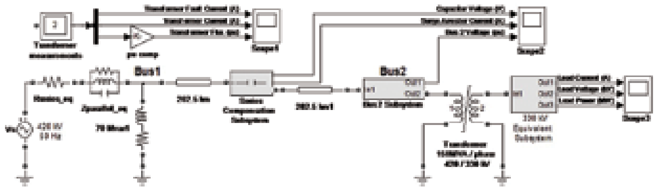

*Figure 2: Overview of the transmission line with series compensation.*

## Simulation case study

The simulation model (see *Figure 2*) was adapted in order to simulate series compensation on the network for this specific case study [10]. Only one phase of the system was simulated to simplify the simulation model.

A 420 kV, 405 km transmission line was used to transmit power from Bus 1 (the equivalent 420 kV system) to Bus 2 (the equivalent 330 kV system). Bus 2 is represented by means of the Bus 2 subsystem block.

The model for the Bus 2 sub-system can be seen in *Figure 3*. The Bus 2 voltage is calculated by the Bus 2 sub-system. The breaker resistance ($R_{on}$) in this sub-system was chosen at 0,01 , the breaker snubber resistance ($R_s$) was chosen infinite and the breaker snubber capacitance ($C_s$) was given a zero value. The 70 Mvar2 components have an active power (P) of 233,3 kW, inductive reactive power (QL) of 70 MVAr and capacitive reactive power ($Q_c$) of zero.

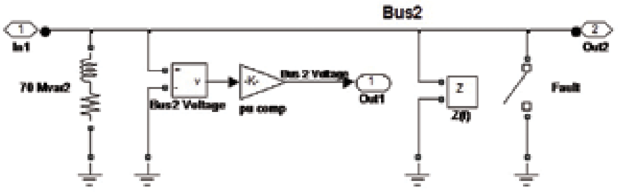

*Figure 3: Bus 2 sub-system.*

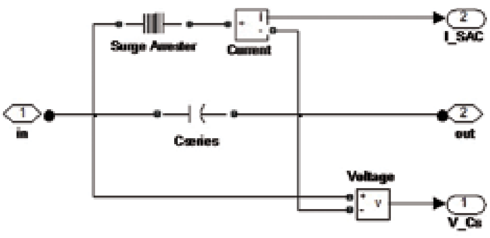

*Figure 4: Series compensation sub-system.*

The transmission capacity is increased by adding a series compensation sub-system at the centre of the transmission lines. The model for the series compensation sub-system can be seen in *Figure 4.* The transmission line is shunt compensated at both ends by means of a 210 MVar shunt reactance (70 MVar/phase).

The series compensation sub-system (see *Figure 4*) consists of a series capacitor and a metal oxide varistor (simulated by means of a 30 column surge arrester block). The series compensation sub-system calculates the capacitor voltage and surge arrester current. The surge arrester block implements a highly non-linear resistor and is used to protect power equipment against overvoltage. The series capacitor represents 40% of the line reactance and the metal oxide varistor is included to protect the series capacitor [2, 9].

A single-phase, 150 MVA, 420 kV/ 330 kV saturable transformer was used to simulate the 450 MVA three-phase transformer [1, 5].

*Figure 5* provides the 330 kV equivalent sub-system. The 220 kV equivalent sub-system calculates the load current, load voltage and load power. The load in this sub-system has an active power of 200 MW. The efficiency loss of the network due the induced faults is calculated from the available load power.

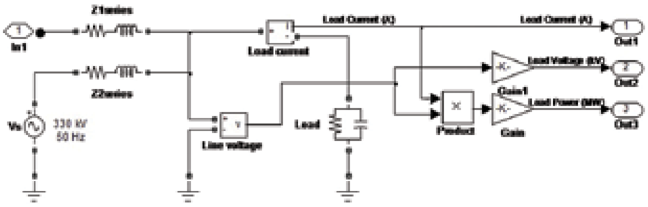

*Figure 5: 330 kV equivalent sub-system.*

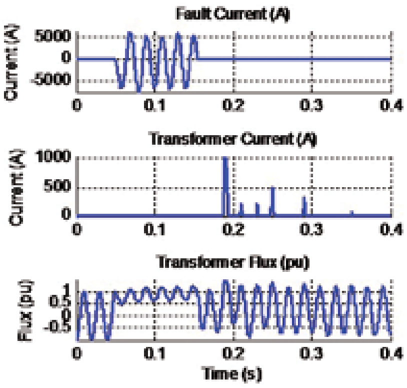

*Figure 6: Fault current, transformer current and transformer flux.*

## Results

### *Ground to line fault on the secondary bus*

For the ground to line fault on the secondary bus the simulation time was chosen 0,4 s and a 6-cycle line to ground fault was induced at Bus 2 (see *Figure 3)*. The fault was induced after three cycles and cleared after nine cycles.

*Figure 6* shows the fault current, transformer magnetizing current and transformer flux for this scenario. When the line to ground fault is induced the fault current, transformer current and transformer flux peaks around 5 kA, 1 kA and 1 pu, respectively. The transformer current peaks around 0,19 s and the transformer flux saturates around an average of 1 pu during fault inducement. The transformer flux returns to its original state the moment the fault is cleared.

*Figure 7* provides the capacitor voltage, surge arrester current and bus 2 voltage. The capacitor voltage, surge arrester current and bus 2 voltage peaks around 200 kV, 4 kA and 1 pu, respectively.

The surge arrester voltage reaches minima and maxima around 0,06 s and 0,07 s, respectively.

The low frequency component (caused by the parallel resonance of the series capacitor and the two shunt reactance's) is clearly visible in the capacitor voltage and Bus 2 voltage.

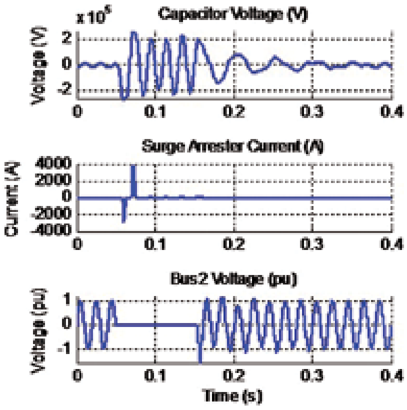

*Figure 7: Capacitor voltage, surge arrester current and Bus 2 voltage.*

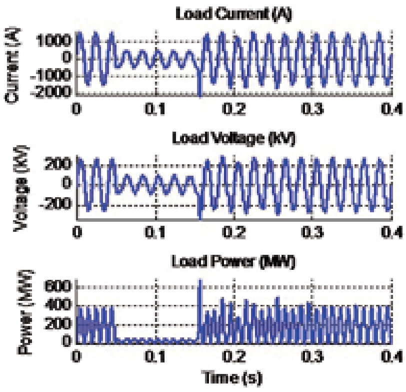

*Figure 8: Load current, load voltage and load power.*

The load current, load voltage and load power peaks at around 1 kA, 200 kV and 600 MW, respectively. With the line to ground fault induced the available load power drops to almost zero. When the fault is restored the available load power increased to its original value. The load current and load voltage follow the same trend. With the ground to line fault induced, the surge arrester conducts at every half cycle and the current increases in the series capacitor and produces an overvoltage that is limited by the surge arrester. The resulting overvoltage makes the surge arrester conduct. With the fault cleared the low frequency component and flux offset cause the transformer to saturate and produce magnetising currents.

| Impedance Increase (%) | Resistance (Ω/km) | Resistance Increase (Ω/km) | Inductance (H/km) | Inductance Increase (H/km) | Power Consumption (MW/ time) | Efficiency Decrease [loss] (%) |
|---|---|---|---|---|---|---|
| Initial Value | 1,1 x $10^{-2}$ | | 8,67 x $10^{-4}$ | | 212,229 | |
| 3 | 1,13 x $10^{-2}$ | 3,3 x $10^{-4}$ | 8,94 x $10^{-4}$ | 2,66 x $10^{-5}$ | 311,716 | 0,242 |
| 10 | 1,21 x $10^{-2}$ | 1,1 x $10^{-3}$ | 9,55 x $10^{-4}$ | 8,76 x $10^{-5}$ | 209,996 | 1,052 |
| 20 | 1,32 x $10^{-2}$ | 2,2 x $10^{-3}$ | 1,04 x $10^{-3}$ | 1,73 x $10^{-4}$ | 208,694 | 1,665 |
| 40 | 1,54 x $10^{-2}$ | 4,4 x $10^{-3}$ | 1,21 x $10^{-3}$ | 3,46 x $10^{-4}$ | 205,817 | 3,021 |
| 60 | 1,76 x $10^{-2}$ | 6,6 x $10^{-3}$ | 1,39 x $10^{-3}$ | 5,19 x $10^{-4}$ | 204,024 | 3,866 |
| 80 | 1,98 x $10^{-2}$ | 8,8 x $10^{-3}$ | 1,56 x $10^{-3}$ | 6.92 x $10^{-4}$ | 203,321 | 4,197 |
| 100 | 2,20 x $10^{-2}$ | 1,1 x $10^{-2}$ | 1,73 x $10^{-3}$ | 8,67 x $10^{-4}$ | 202,765 | 4,459 |

*Table 1: Energy efficiency and transmission line impedance.*

## Impedance fault on the two transmission lines

For the impedance fault on the two transmission lines, the simulation time chosen was 0,4 s and no line to ground fault was induced. *Table 1* provides the result obtained from the simulation model for this scenario. The initial values that were chosen for the transmission line resistance and inductance were 0,011 /km and 8,6 7 x $10^{-4}$ /km, respectively. The power consumption of the load at this initial condition was 212 229 MW/time, where the time was chosen 0,4 s. When the impedance was increased by 3%, the resistance increased by 0,00033 /km and inductance increased by 2,66 x $10^{-5}$ /km. The power consumption on the load decreased to 211,716 MW/time, which resulted in a total efficiency of 99,798% (or 0,242% decrease in efficiency). When the resistance and inductance were doubled (impedance increase of 100%), the power consumption of the load decreased to 202,765 MW/time, which resulted in a total efficiency of 95,541% (or 4,459% decrease in efficiency).

*Figure 9* provides a graph of energy efficiency against transmission line impedance for the data of *Table 1.* A second order polynomial of y = 0,0949*x* was fitting through the data. The corresponding $R^2$ component is calculated at 0,9978. From this figure it can be seen that the efficiency decreased with an increase in transmission line impedance.

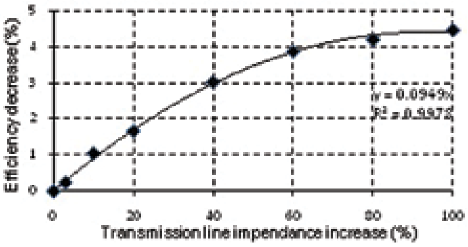

*Figure 9: Efficiency against transmission line impedance.*

For this scenario the combined line to ground fault and impedance fault were induced on the network. A line to ground fault with a breaker resistance (Ron) of 0,01 was chosen and an impedance fault with an impedance increase of 100% was chosen.

*Figure 10* shows the initial value results (with no fault induced) and combined scenario results (with the line to ground fault and impedance fault combined). In order to successfully demonstrate this result the simulation time was chosen 0,16 s and a 2-cycle line to ground fault was induced. The line to ground fault was induced after one cycle and restored after three cycles.

From *Figure 10* it can be seen that the load current, load voltage and load power peaks at around 1 kA, 200 kV and 500 MW. On average over the provided time period it can be seen that the load power for the combined scenario is lower than the load power for the initial values condition.

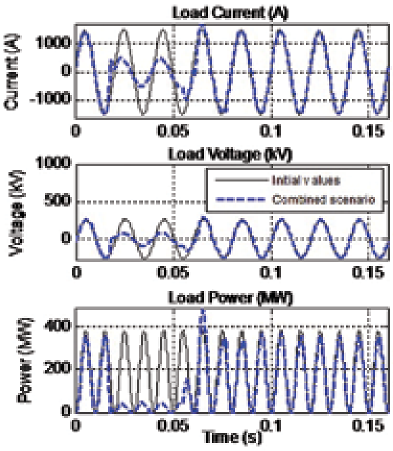

*Figure 10: Initial value and scenario results.*

## Conclusion

***First scenario:*** The available power on the load drastically decreased the moment the fault was induced. The available power restored to its initial value the moment the fault cleared. During this fault almost no power was transferred to the load, as shown in *Figure 8*. It was therefore decided not to calculate the efficiency loss for this scenario and the scenario was only used for investigative purposes.

***Second scenario:*** The energy efficiency of the load followed a curve with respect to the impedance of the transmission line. The load efficiency decreased when the transmission line impedance increased. A more than 1% efficiency loss on the load was calculated for an impedance increase of only 10% (resistance increase of 1,1 m /km and inductance increase of 87,6 µH/km). *Table 1* and *Figure 9* provide a summary of the efficiency loss with impedance increase.

***Third scenario:*** The available load current, load voltage and load power decreased, the moment the two faults were induced. It is again visible from *Figure 10* that almost no power is transferred to the load the moment the line to ground fault (fault from scenario 1) is induced.

## Acknowledgement

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