Analysis of a 405 km transmission line with series compensation

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This paper presents an investigative case study and energy efficiency analysis of the 405 km, 420 kV transmission line between Insukamini substation in Bulawayo in Zimbabwe and the Matimba thermal power station in South Africa. Three scenarios were evaluated: 1) where a line to ground fault occurred on the secondary bus, 2) where an impedance fault occurred on the two transmission lines and 3) where the combination of the above two faults occurred. An analysis was made on the energy efficiency of the load with respect to the three scenarios by means of a simulation model.

The development of the simulation model for this specific case study is explained in detail. The simulation model was slightly adapted in order to simulated 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. Part of this paper provides an overview of transmission line theory and series compensation theory.

This paper focus on an investigative case study and efficiency analysis of the 405 km, 420 kV transmission line between Insukamini substation in Bulawayo in Zimbabwe and the Matimba thermal power station in South Africa (which is routed through Botswana). 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. The Norconsult and Zimbabwe report provides more detail on this specific transmission network [8, 11]. In the Eskom revenue application documentation submitted to NERSA, Eskom considers the transmission network losses to amount to approximately 4% [7].

It was therefore decided to develop a simulation model for this specific case study and perform an efficiency analysis on the load for 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: 1) where a line to ground fault occurred on the secondary bus, 2) where an impedance fault occurred on the two transmission lines and 3) where a combination of the two faults occurred.

An efficiency analysis was then performed

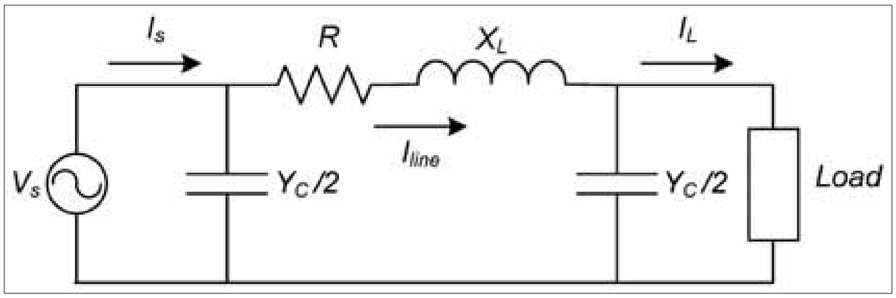

Fig. 1: Equivalent circuit of a transmission line.

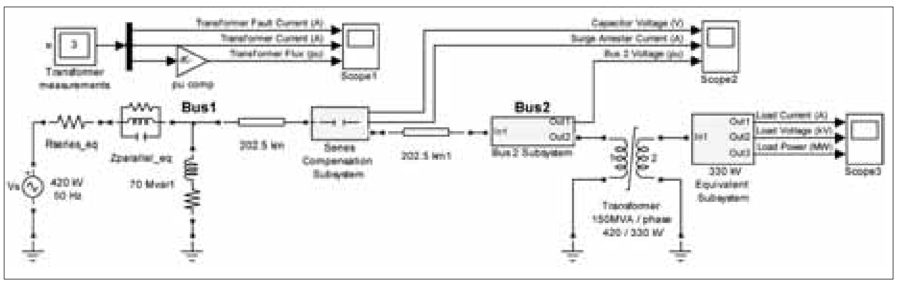

Fig. 2: Overview of the transmission line with series compensation.

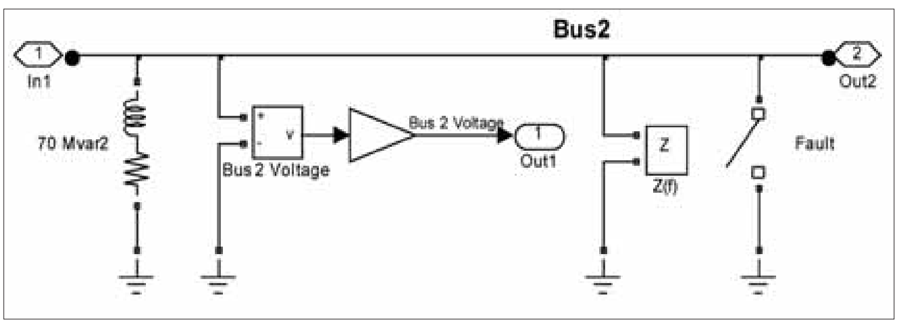

Fig. 3: Bus 2 subsystem.

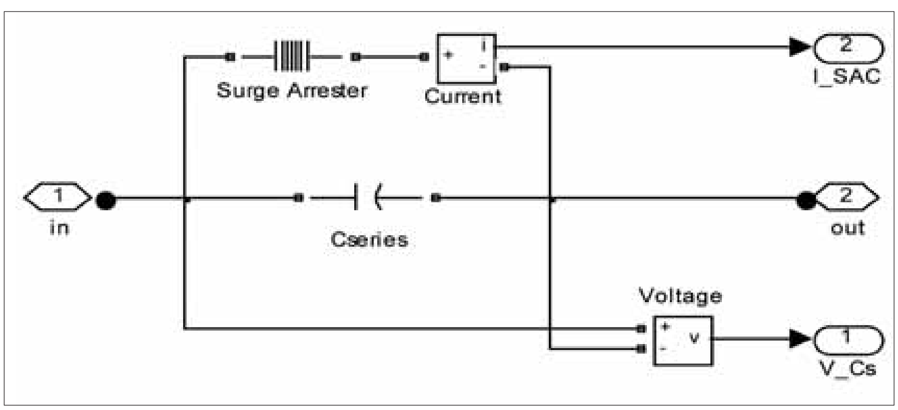

Fig. 4: Series compensation subsystem.

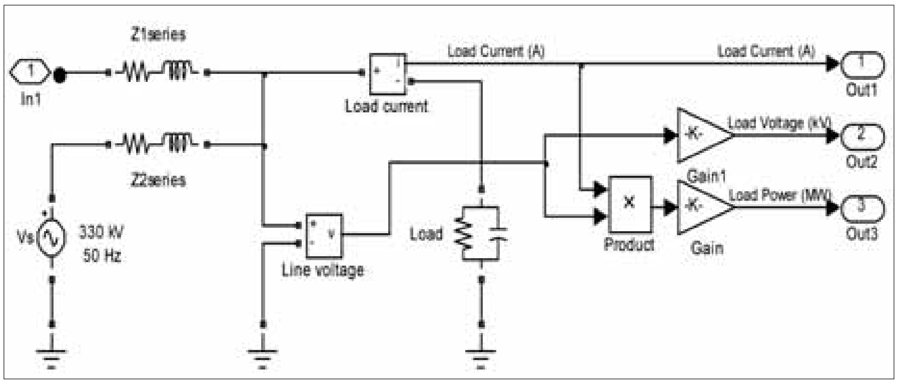

Fig. 5: 330 kV equivalent subsystem.

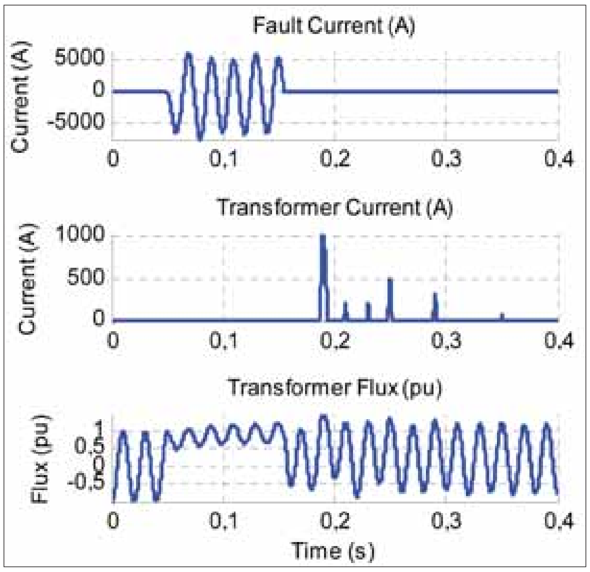

Fig. 6: Fault current, transformer current and transformer flux.

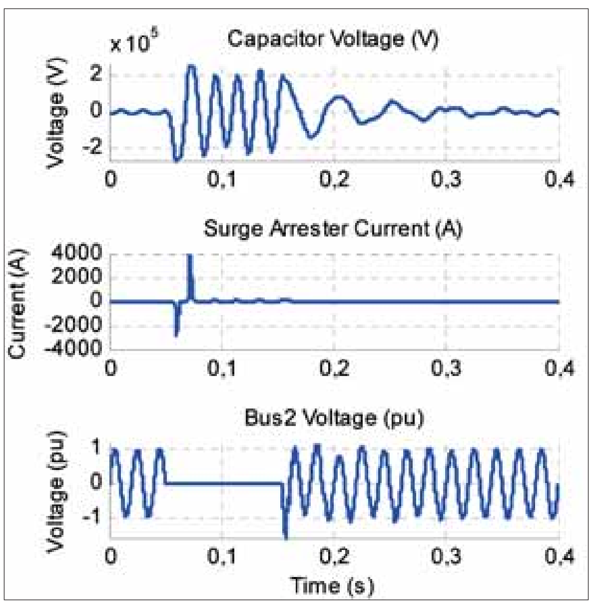

Fig. 7: Capacitor voltage, surge arrester current and Bus 2 voltage.

on the available load power in order to determine the efficiency loss of the network, due to the faults.

Overview on 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: 1) series resistance, 2) series inductance, 3) shunt capacitance and 4) shunt conductance [6].

A transmission line is considered a medium-length line when the length is between 80 km and 240 km. The singlephase 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. Fig. 1 shows the equivalent circuit of a transmission line [6].

The lowering of the reactive 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 can be is reduced. This will allow more power to be received by the load. Gustavsen et al. And Karamakković et al., provides more detail on equivalent circuit models for transmission lines and series compensation networks [3, 4].

Simulation case study

This section provides the development of the simulation model for the 405 km, 420 kV transmission line between Insukamini substation in Bulawayo in Zimbabwe and the Matimba thermal power station in South Africa (which is routed through Botswana).

The simulation model (shown in Fig. 2) for the abovementioned case study was developed in order to obtain sufficient simulation results for the three different fault scenarios. The simulation model of Sybille et al. 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.

From this Fig. it can be seen that 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 subsystem is presented in Fig. 3. The Bus 2 voltage is calculated by the Bus 2 subsystem. The breaker resistance (Ron) in this subsystem was chosen at 0,01 Ω, the breaker snubber resistance (R_s) was chosen infinite and the breaker snubber capacitance (C_s) was given a zero value. The 70 Mvar components have an active power (P) of 233,3 kW, inductive reactive power (Q_L) of 70 Mvar and capacitive reactive power (Q_c) of zero.

The transmission capacity is increased by

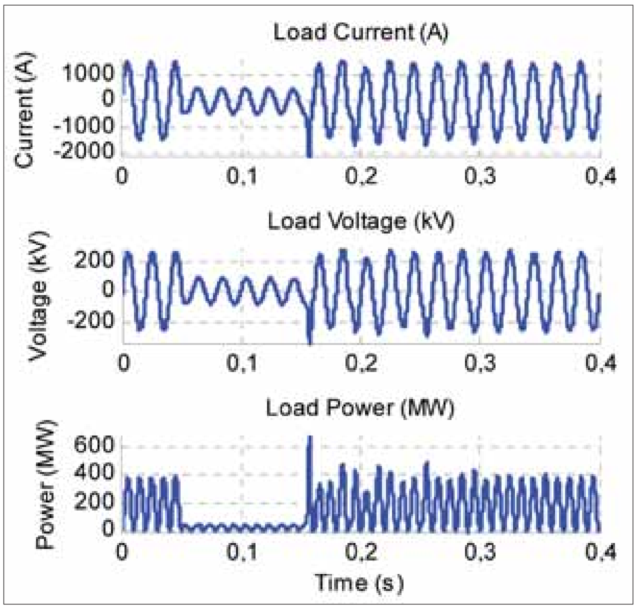

Fig. 8: Load current, load voltage and load power.

adding a series compensation subsystem at the centre of the transmission lines. The model for the series compensation subsystem is presented in Fig. 4. The transmission line is shunt compensated at both ends by means of a 210 Mvar shunt reactance (70 Mvar/phase).

The series compensation subsystem (shown in Fig. 4) consist of a series capacitor and a metal oxide varistor (simulated by means of a 30 column surge arrester block). The series compensation subsystem 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. Bhel and Steinfeld et al. provides more detail on high voltage surge arresters for protection of series compensation networks [2, 9].

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

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

Results

This section provides the simulation results of the simulation model for the following three scenarios:

- Where a line to ground fault occurred on the secondary bus (shown in Figs. 6 to 8),

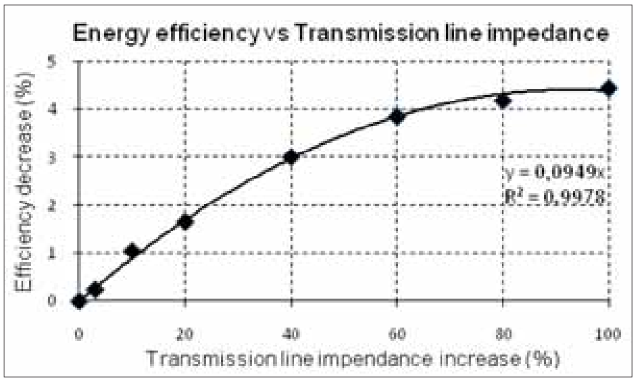

Fig. 9: Efficiency against transmission line impedance.

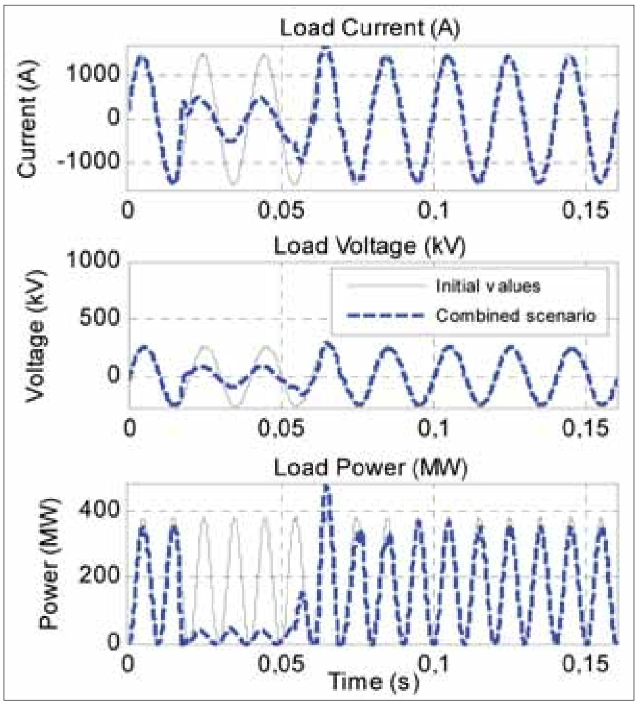

Fig. 10: Initial value and scenario results.

- Where a impedance fault occurred on the two transmission lines (shown in Fig. 9 and Table 1) and
- Where a combination of the two faults occurred (shown in Fig. 10).

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 (shown in Fig. 3). The fault was induced after 3 cycles and cleared after 9 cycles. Fig. 6 shows the fault current, transformer magnetising 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. Fig. 7 provides the capacitor voltage, surge arrester current and bus 2 voltage which 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.

Fig. 8 shows the 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 follows 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 causes the transformer to saturate and produces magnetizing currents.

Impedance fault on the two transmission lines

For the impedance fault on the two transmission lines, the simulation time chosen 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 was chosen for the transmission line resistance and inductance were 0,011 Ω/km and

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	211,716	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.

8,67 x 10^{-4} Ω/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 Ω/km and inductance increased by 2,66 x 10^{-5} Ω/km. The power consumption of the load decreased to 211,716 MW/time, which resulted in an 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 an total efficiency of 95,541% (or 4,459% decrease in efficiency).

Combined line to ground fault and impedance fault

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 Ω was chosen and an impedance fault with an impedance increase of 100% was chosen. Fig. 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 1 cycle and restored after 3 cycles. From Fig. 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.

Conclusion

The following three scenarios were evaluated: 1) where a line to ground fault occurred at the secondary bus, 2) where a impedance fault occurred on the two transmission lines and 3) where the combination of the two faults occurred. For the 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 Fig. 8. It was therefore decided not to calculate the efficiency loss for this scenario and the scenario was only used for investigative purposes.

For the 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 mΩ/km and inductance increase of 87,6 μH/km). Table 1 and Fig. 9 provides a summary of the efficiency loss with impedance increase. For the third scenario the available load current, load voltage and load power decreased, the moment the two faults were induced. It is again visible from Fig. 10 that almost no power is transferred to the load the moment the line to ground fault (fault from scenario 1) is induced.

Acknowledgement

This paper was presented at the 2011 Industrial and Commercial Use of Energy Conference, Cape Town, August 2011, and is reprinted with permission.

References

[1] T Baldwin and R Adapa, "Phasor Measurement Placement for Voltage Stability Analysis of Power Systems", IEEE Conference on Decision and Control, 1990.

[2] E Bhel, "Handbook of Switchgears: Electric Switchgear Technology & Engineering", Tata McGraw-Hill Education, 2005.

[3] B Gustavsen, G Irwin, R Mangelred, D Brandt and K Kent, "Transmission Line Models for the Simulation of Interaction Phenomena between Parallel AC and DC Overhead Lines", IPST '99 – International Conference on Power Systems Transients, Budapest, Hungary, June 1999.

[4] J P Karamakković, N D Janković and DB Glozić "Transmission-line Equivalent Circuit Model of Minority Carrier Transient Current in Quasi-neutral Silicon Layers Including Effects", International Journal of Numerical Modelling: Electronic Networks, Devices and Fields, Vol. 8, Issue 5, pp. 341 - 356, Sep 1995.

[5] J Lambert, A G Phadke and D McNabb, "Accurate Voltage Phasor Measurement in a Series- Compensated Network", IEEE Transactions on Power Delivery, Vol. 9, Issue 1, Jan 1994.

[6] R Manuel, "Handbook on Transmission Line Parameters", Taylor & Francis group, 2006.

[7] NERSA, "Eskom Revenue Application Document Submitted to NERSA – Annual Report", 2010.

[8] Norconsult, "Power Transmission Line Zimbabwe - South Africa", [Online] Available at www.mozambique.norconsult.com/?aid=9096436, 2011.

[9] K Steinfeld, R Göhler and D Pepper, "High Voltage Surge Arresters for Protection of Series Compensation and HVDC Converter Stations", International Conference on Power Transmission and Distribution Technology, Berlin, 2003.

[10] G Sybille, P Giroux and L Gérin-Lajoie, "Effect of Subsynchronous Resonances on Hydro-Québec Static Var Compensators", Mathematics and Computers in Simulation, Vol. 38, Issue 4-6, August 1995.

[11] Zimbabwe Report, "Rehabilitation and Recovery in the Power Sector – Chapter 8", 2011.

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