

**DEVELOPMENT OF A MODEL OF THE ALPHA / BETA  
765kV LINE FOR THE EVALUATION OF  
AUTO-RECLOSING**

by

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## **DECLARATION**

I, the undersigned declare that the material presented in this dissertation is my own work, except where specific acknowledgement is made in the form of a reference

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## ABSTRACT

The intention of this dissertation is to determine, on the Eskom system, if the pre-insertion closing resistors installed on the Alpha-Beta 765 kV line breakers are preventing overvoltages from being caused during auto-reclosing. Other possible solutions of reclosing protection are investigated. It has been shown on two occasions, from actual field data that overvoltages have occurred on the lines after reclosing. High overvoltages on this network could be the cause of the many reactor failures that have occurred.

A mathematical model of the Alpha-Beta 765kV system was produced on Matlab/Simulink to simulate the resonance of the line during opening and then the effect on the voltage when reclosing takes place. The effects of installing pre-insertion resistors to reduce overvoltages on reclosing were analysed, as well as looking at controlled reclosing at the optimal voltage across the line breakers.

It was shown from the studies, that *pre-insertion resistors do limit the overvoltages to within the surge capabilities of the line (10% overvoltage)* and that the cause of the previous overvoltages were actually due to insertion resistor operations failure. It was also shown that the method of controlled closing at optimal voltage across the breakers is also a successful method of preventing overvoltages. This dissertation also evaluates a design specification for a switching relay for controlled re-closing of the line.

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## **CHAPTER 1: INTRODUCTION & BACKGROUND**

### **1.1 Introduction**

The aim of this project is to determine whether the use of pre-insertion resistors on Eskom's 765 kV, Alpha-Beta transmission line is an effective method of protection against switching transients. This study is brought about due to the excessive damage caused to the line reactors. Other methods of protection are investigated and a model of the Alpha-Beta system is constructed. The model is then used to determine the effect of the different types of protection.

### **1.2 Background**

As mentioned before, this research is focused around Eskom's Alpha-Beta Transmission lines. It is therefore imperative that some background to the lines' configuration, existing protection scheme and problems which have occurred on these lines are discussed. Alternative protection schemes are then discussed.

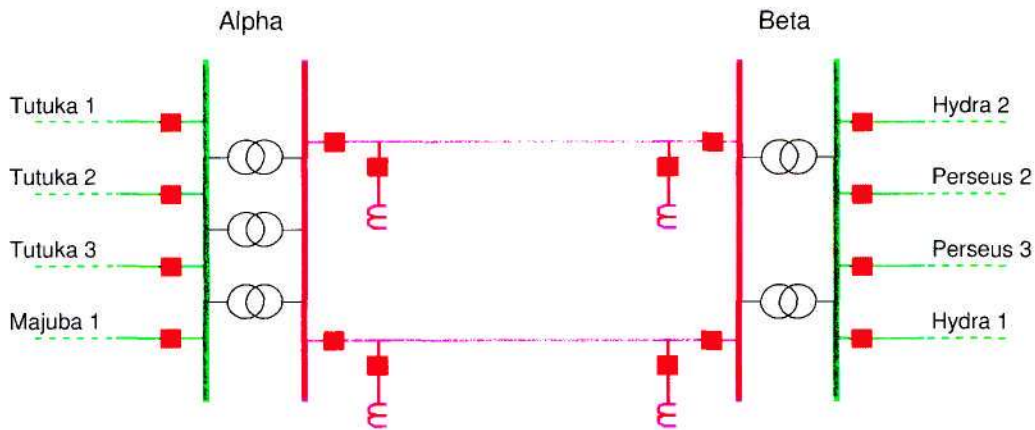
#### **1.2.1 Problem Overview**

Presently in Eskom, the 765 kV, Alpha-Beta transmission line is an important corridor within the South African national grid. Should one of these parallel lines be disconnected, the stability of the entire South African network would be affected. The Alpha-Beta corridor is important because it connects the North-East and Cape Regions. The North-East region contains the majority of the country's generation capacity (a total of approximately 25000 MW) [1]. The Cape region, however, lacks sufficient generation and thus to meet its demand, power is imported from the North-East region via the Alpha-Beta corridor. Should this supply be interrupted, it would result in over 3000 MW of load being shed in the Cape region [1]. It is therefore imperative that these lines are well protected to avoid unnecessary interruptions.

There have, however, been recorded incidents where these lines have tripped and failed to reconnect due to the failure of the existing protection scheme. In order to understand the protection scheme, the configuration of the Alpha-Beta line is first explained.

##### *1.2.1.1 Alpha-Beta Transmission Line Configuration*

The 765 kV Alpha-Beta lines are approximately 435 km long and have a maximum apparent power rating of 6495 MVA [1], [2]. Their long length and Extra High Voltage (EHV) cause the lines to be capacitive under light-load conditions [3]. To compensate for this effect, line reactors are installed on both sides of the line [1]. This can be seen from Figure 1 which shows a one line representation of the Alpha-Beta line. These reactors are then used to prevent overvoltages when the line is lightly loaded or if load is suddenly lost as well as to decrease the Ferranti effect [3].



**Figure 1: One line Diagram of Alpha-Beta 765 kV System**

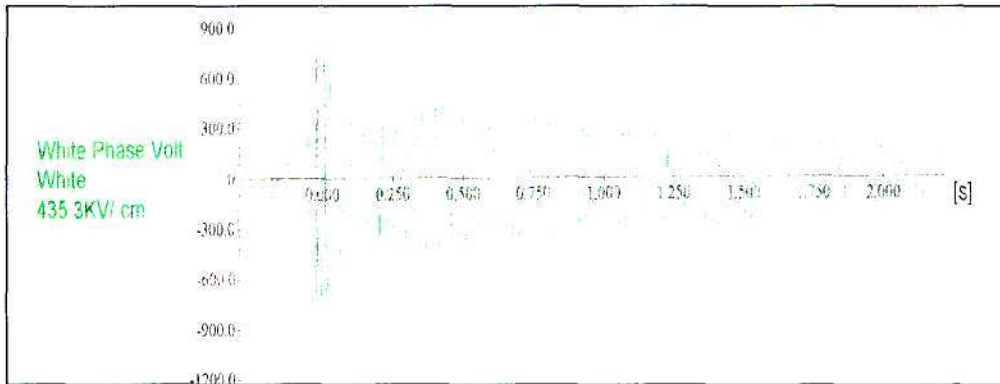
### *1.2.1.2 Alpha-Beta Protection Scheme Overview*

There are breakers at each side of the line which will open, should a fault occur anywhere along the line. These breakers will attempt to reconnect via the Automatic Reclose (ARC) scheme after one second for a single-phase fault, or three seconds for a three-phase fault [1]. However, when the lines are opened, an exponentially decaying transient voltage waveform will remain on the lines. This is due to the capacitive and reactive components of the line causing resonance [3]. The resonant frequency is between 30 Hz and 45 Hz, and is dependant on the line parameters and the level of compensation [4].

This effect can cause an overvoltage surge when the line attempts to automatically reclose. This is because the transient voltage will be superimposed on the source voltage creating dangerous overvoltages along the line and on the shunt reactors. Resistors are therefore switched in parallel with the breakers and will connect 2 to 8 ms before the line breakers close, in order to dampen the overvoltage. These resistors are typically accompanied by surge arrestors which also help to reduce the overvoltage. These resistors are known as Pre-insertion Resistors and are valued at 450 ohms at both ends of the Alpha-Beta line [1].

### *1.2.1.3 Alpha-Beta Pre-insertion Resistor Failures*

Although the use of pre-insertion resistors is a world-wide practice, there are many recorded incidents of them failing to decrease the overvoltage. The steep overvoltages, caused during switching, are unevenly distributed along the reactor winding and thus cause a high risk of insulation failure. There were nine single pole reactor failures on the Alpha-Beta lines between 1999 and 2002. These failures were all due to insulation failure. The costs associated with these failures were in excess of R 30 million.



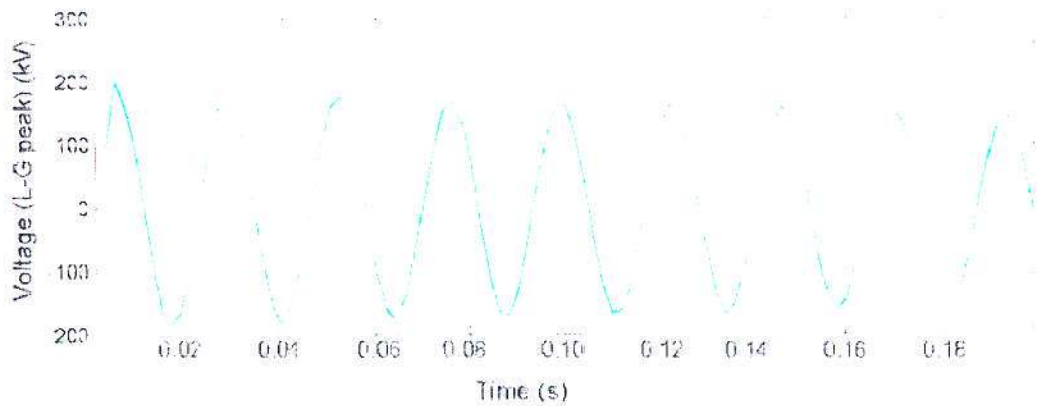
**Figure 2: Actual ring down before and after breaker closed 26/05/2006 [4]**

Two occasions (26/05/1997 and 26/01/1999) where the pre-insertion resistors failed to close before the breaker, on the Alpha-Beta line, are examined. The 26/01/1999 incident occurred due to a three phase line fault, which resulted in all the breakers opening at both the Alpha and Beta end. The line was able to reclose after 3 seconds but an overvoltage, in the order of 1.7 p.u, was experienced. In the 26/05/1997 incident, the breakers at Alpha opened for a fault on the line and reclosed after 3 seconds. However, the breakers on the Beta end failed to close due to an auto-reclose (ARC) relay failure [4].

The transient voltages from an incident which occurred on 26/05/2006 can be seen in Figure 2. It is evident from the figure that a resonant frequency does occur after the line is opened. Figure 3 shows an extract of the ring down voltage from Figure 2. It is then observed that the ring down voltage has an amplitude of 186.4 kV and a resonant frequency of 43.23 Hz. This data was obtained from the field and then manipulated using the methods detailed in Appendix A.

### **1.2.2 Methods for controlling overvoltages whilst switching shunt reactor compensated, EHV lines**

Presently, there are seven countries using or intending to use 765 kV transmission systems. They are Russia, India, China, Korea, Canada, Brazil and South Africa. For these systems, there are two methods which are used to control the surges caused by the resonant frequency on the shunt compensated lines. These can be either the more commonly used method of pre-insertion resistors or the uncommon method of controlled shunt reactor compensated line switching [5]. These methods are discussed and compared below.



**Figure 3: The extracted ring down voltage waveform [4]**

*1.2.2.1 Pre-insertion resistors*

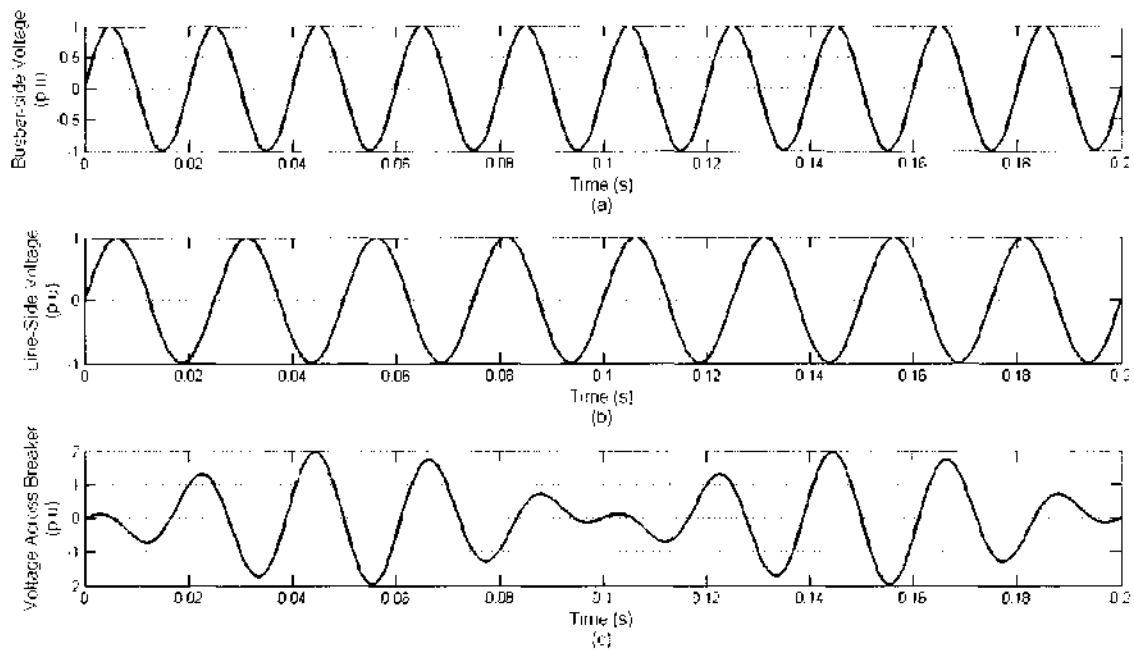
Information was obtained by contacting the above-mentioned power utilities and enquiring as to the method presently in use for the auto-reclosing of their 765 kV shunt compensated lines. Further investigation indicated that all the above utilities make use of pre-insertion resistors whilst closing the breakers.

The most commonly used protection measure for reclosing on EHV shunt compensated lines, is the use of metal oxide (Mol) surge arrestors combined with pre-insertion closing resistors. The problem with this solution is that it is both expensive and mechanically complex. The mechanical complexity results in the solution requiring extensive maintenance and thus it is prone to failure and unplanned outages [5].

*1.2.2.2 Controlled shunt reactor compensated line switching*

As discussed previously, the compensated line will hold a resonant ring-down voltage when opened. This resonant signal has a specific frequency which is typically between 30 and 45 Hz [6]. Since the frequencies of the open line and the busbar (which remains at the grid frequency) differ, a waveform containing beats will occur in the voltage across the open breaker. This can be seen from Figure 4, (a) represents the 50 Hz busbar system frequency, (b) represents the open line's resonant frequency (an example of 40 Hz is chosen) and (c) represents the difference between the two waves. It can be seen in (c) that beats form.

The basic idea behind controlled shunt reactor switching is to close the line, at the point when the voltage difference between the line and busbar is within the minimum of the beat cycle. This should therefore minimise the overvoltage surge which occurs when closing these lines.



**Figure 4:** Theoretical example of a beating waveform (a) 50 Hz sine wave, (b) 40 hz sine wave, (c) difference between waves (a) and (b)

## CHAPTER 2: INVESTIGATION INTO BC HYDRO'S USE OF CONTROLLED CLOSING ON SHUNT REACTOR COMPENSATED LINES

Presently, the Canadian power utility, BC Hydro, is the only utility which makes use of controlled shunt reactor switching. This utility made use of the controlled closing methodology on its 500kV network. BC Hydro has implemented this system over several lines in their 500 kV network, however, only one such transmission line is studied. BC Hydro's latest 500kV transmission line, which was constructed during 1993 and 1994, is discussed [7].

### 2.1 BC Hydro 500 kV line configuration

The 500 kV BC Hydro line is 330km long and the configuration of this line can be seen in Figure 5 [7]. It is evident from the figure that the line is compensated using a mid-line series capacitor bank as well as reactors on either side of the line. The mid-line capacitor bank is rated at 605 Mvar, but is bypassed during auto-reclosing. The shunt reactors are rated as 550kV, 135 Mvar at each end. The lead end is fixed and ungrounded through a metal oxide varistor and the remote end is switchable and grounded through a neutral reactor [5]. The circuit breakers are 500kV single pressure SF<sub>6</sub> type with spring-hydraulic operating mechanisms with required mechanical operating time consistency over the ambient temperature range of -50°C to +40°[7]. The time consistency is relevant because controlled switching is highly dependent on time.

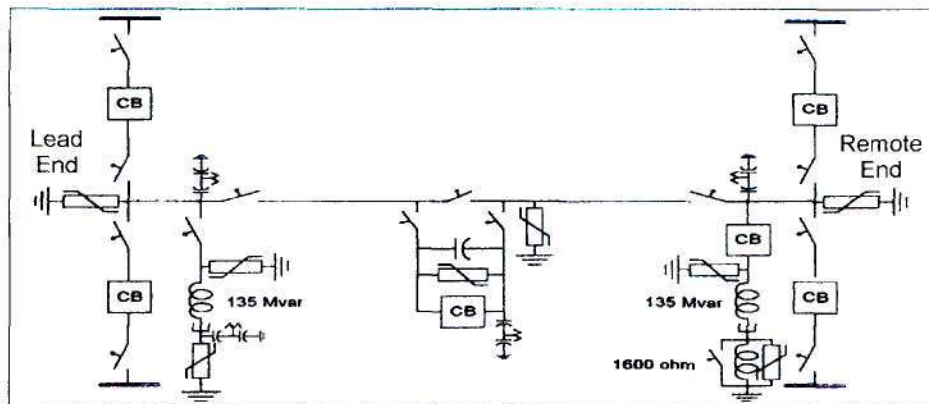
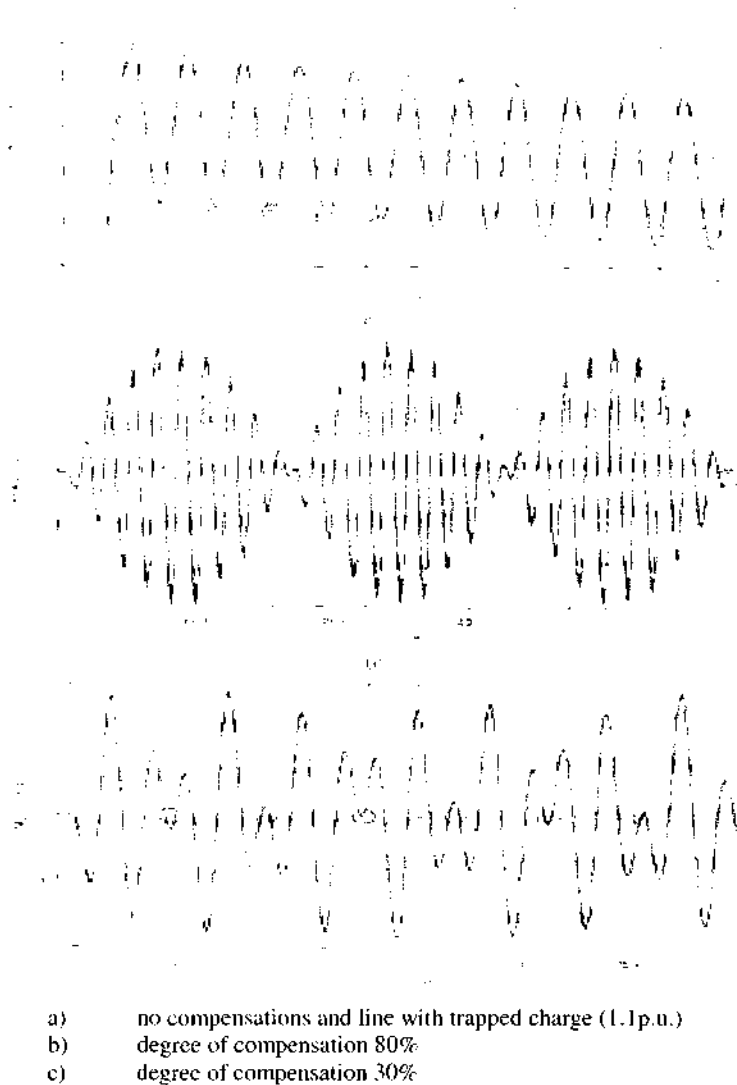


Figure 5: BC Hydro 500kV line arrangement

[7]

## 2.2 Resonant voltage signal produced on the open shunt reactor compensated line

As the line is opened, an exponentially decreasing resonant voltage signal is formed. The resonant frequency of the voltage signal is usually lower than the power frequency and dependent on the inductance of the shunt reactors and the capacitance of the line [7].



**Figure 6: Resonating ring-down voltage signal for various degrees of compensation [7]**

The tripping of an unloaded uncompensated transmission line leaves a d.c. voltage on the line and a voltage minimum across the circuit breaker will occur every half-cycle assuming no decay of the line voltage (Figure 6 (a)) [7].

With both shunt reactors connected on the BC Hydro line, the signal resonates at approximately 45 Hz. In this case, the voltage appearing across the open circuit breaker exhibits a very distinct beating pattern (see Figure 6 (b)) [7].

With only one of the shunt reactors connected, the resonant frequency drops to approximately 33 Hz and the voltage pattern is less distinct than the previous case [7]. This voltage signal is not obviously recognizable as a periodic beating pattern (see Figure 6 (c)). The reason for this is the reduced damping of both the aerial and ground modes due to larger phase impedance and near infinite ground impedance with the ungrounded shunt reactor neutral.

### **2.3 Feasibility study of controlled reactor switching on the B. C. Hydro 500 kV line**

Due to the protection constraints of the line, a decision was made to limit the switching surge level of the line to 1.7 p.u. This limit is defined as a 2 % value, i.e. there is a probability of 2 % or less that the 1.7 p.u limit will be exceeded. Traditionally, pre-insertion resistors would be installed to achieve this constraint [5]. However, due to the mechanical complexity and maintenance associated with pre-insertion resistors, an investigation into a controlled reactor switching scheme was conducted.

#### **2.3.1 Electromagnetic Transient Program (EMTP) Studies**

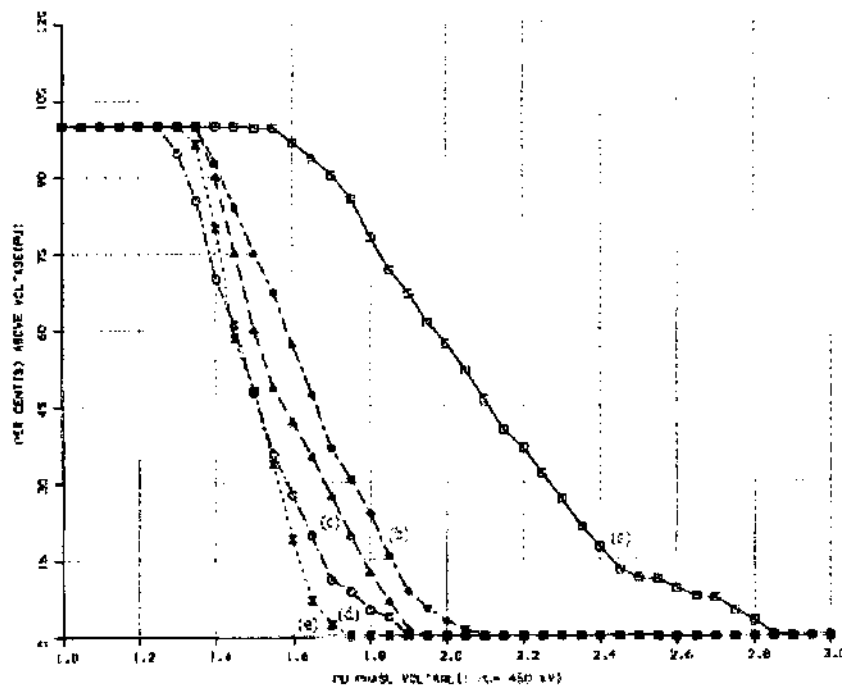
A large number of Electromagnetic Transient Program (EMTP) studies were run to define and specify the requirements for the overall controlled switching scheme [5]. All the protection schemes applicable to the scenario were studied in order to compare results. The following protection scheme cases were studied:

- Closing with no switching surge control
- Closing with the use of pre-insertion resistors
- Control with staggered closing (half-cycle time delay between close signal application to successive poles/phases)
- Control with staggered closing using surge arresters with a 1.5 p.u. protective level, two (at line terminations) or three (at line terminations and mid-line)
- Controlled point-of-wave closing using staggered closing and three surge arresters connected as noted above.

Figure 7 compares the results of the EMTP studies by way of the cumulative frequency distributions of the switching surge overvoltage at the remote end for the different cases (a better description would probably be 'Cumulative Frequency (%)' on the y-axis). In all the cases, a shunt



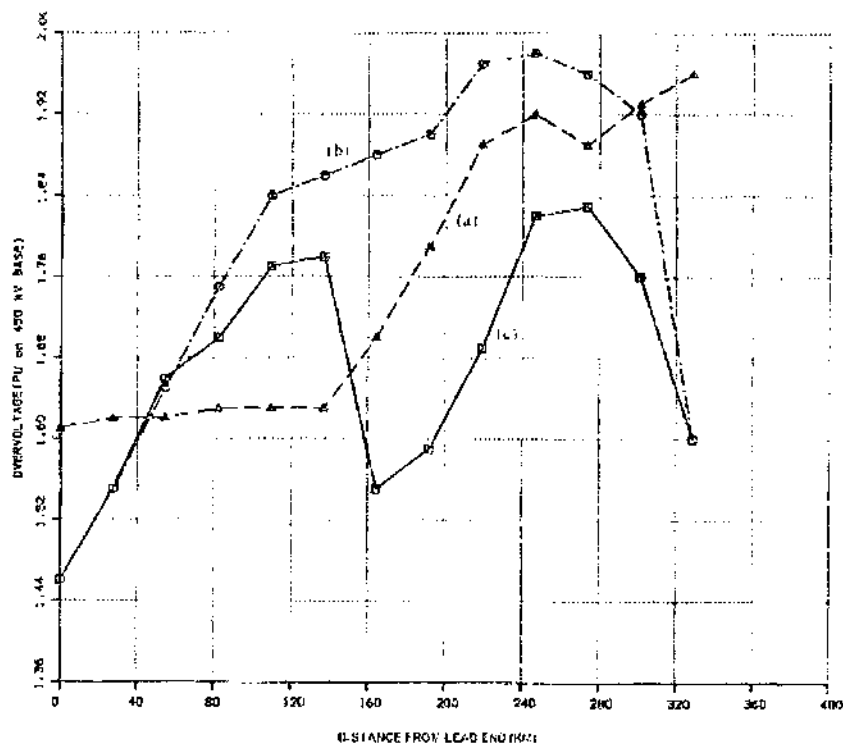
reactor is connected at the lead end only. It is evident from the figure that the value of adding surge arresters is quite significant and with the addition of controlled closing, the 1.7 p.u. surge limit is achieved. Note that for purposes of the study, controlled closing means closing at a 60Hz source side voltage zero crossing, rather than at a minimum beat voltage point across the circuit breaker. The implication of this is that the overvoltage distribution curve for actual controlled closing at the minimum beat voltage across the circuit breaker will show an increase in performance (i.e. it will be to the left of the shown curves). Viewed in terms of mitigation, the curves show that in the extreme case with the control device out of service, the risk of exceeding 1.7 p.u. increases only to 10% which is considered acceptable [5].



- a) no switching surge control
- b) with 400  $\Omega$  closing resistors
- c) with 1.5 p.u. surge arresters at line terminations and staggered closing
- d) as for (c) and additional surge arrester at mid-line
- e) with controlled closing and surge arrester per (d) above

**Figure 7: Cumulative frequency distributions for overvoltages at remote line end [5]**

The voltage profile along the transmission line was also examined in the studies. Figure 8 shows this voltage profile for a number of the studied overvoltage control options. By consideration of both Figure 7 and Figure 8, it is evident that only the controlled closing with the three surge arrester option will meet the 1.7 p.u. limit at every point along the transmission line.



- a) with 400  $\Omega$  closing resistors
- b) with 1.5 p.u. surge arresters at line terminals and staggered closing
- c) as for (b) with additional surge arrester at mid-line

**Figure 8: Overvoltage profiles along transmission lines [5]**

Specialised surge arresters are used compared to standard surge arresters normally applied on a 500 KV system. A comparison of ratings is shown in Table 1 based on IEC 99-4[8].

These surge arresters are considered specialised for a number of reasons:

1. The ratio of system voltage to surge arrester rated voltage is 1.48 versus a typical value of 1.39 or less.
2. The ratio of Continuous Operating Voltage (COV) to rated voltage is 0.8 versus a typical value of about 0.85
3. The switching surge protective level is 1.575 p.u. versus a typical value of approximately 1.8 p.u.
4. The energy absorption capability is higher than that normally required on EHV systems. However, the rating is conservative since two consecutive surges of the noted magnitude are highly improbable.

Requirement	Standard Surge Arrester	Special Surge Arrester
Continuous Operating Voltage (kV rms)	318	318
Rated Voltage (kV rms)	396	372
Switching Surge Protective Level at 2 kA, kV peak	792	709
Line Class	5	6.7 (equivalent at protective level)
Energy Absorption Duty Cycle	1.98 MJ – 60 s – 1.98 MJ	2.5 MJ – 60s – 2.5 MJ
Temporary Overvoltage Capability	Per IEC 99-4 or better at rated voltage	Per IEC 99-4 or better at rated voltage

**Table 1: Comparison of Requirements for Standard and Specialised Surge Arresters on B.C. Hydro 500kV System** [5]

## 2.4 Closing Control Device Strategy

A control device (relay) was designed to measure the transient voltage signal and trigger the breakers to close within the beat minimum on all the phases. The beat minimum is approximately 20 ms in duration and can be seen in Figure 9 as the “window of opportunity”. Closing within the window of opportunity is mandatory. If the control device aims to close the breaker within the window of opportunity but misses, the overvoltage will exceed the surge capabilities of the line [6]. It is therefore important that the control device is accurate and robust.

The strategy for the closing device is to delay the closing command appropriately such that closing or prestrike of the contacts occur in the desired time window [6]. The control device utilises an algorithm that recognises and analyses the voltage signal across the circuit breaker and then predicts the occurrence of future optimal instants for closing (i.e. the beat minima) [6]. After de-energization of the line, up to 300 ms are available for the control device to analyse the characteristics of the voltage signal across the circuit breaker [6]. Possible closing windows can then be predicted. The scheme must incorporate mitigation measures to cover all possible contingencies within the allocated computation time (approximately 300 ms) [6]. These contingencies range from control device unavailability to failure to determine the optimal closing instant [6]. Every circuit breaker has a certain closing time in the range of 50 ms. This means that after the control device issues the closing command, it takes another 50 ms until the contacts actually close [6]. Hence, the control device has to predict the shape of the voltage signal at least 50 ms into the future. The signal across the circuit breaker is periodically repeated at least two to

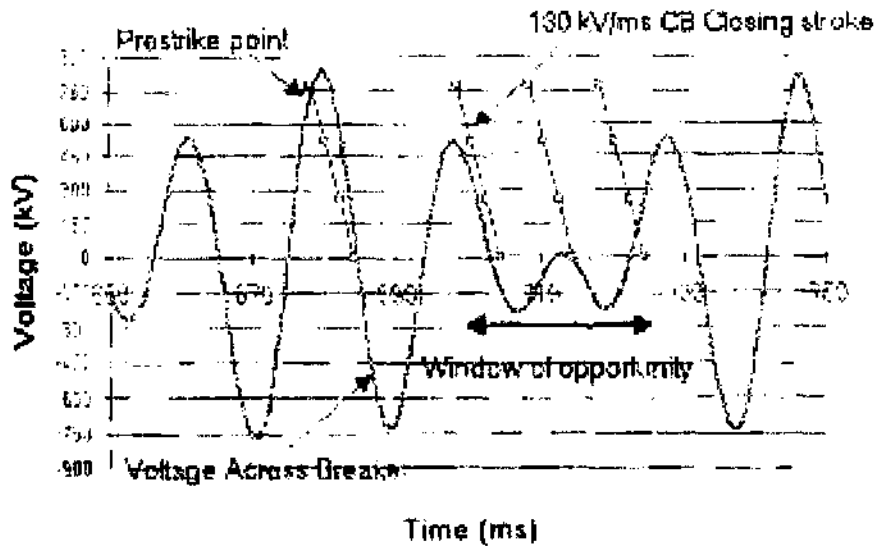


Figure 9: Closing stroke for system breaker superimposed on measured voltage across circuit breakers [7]

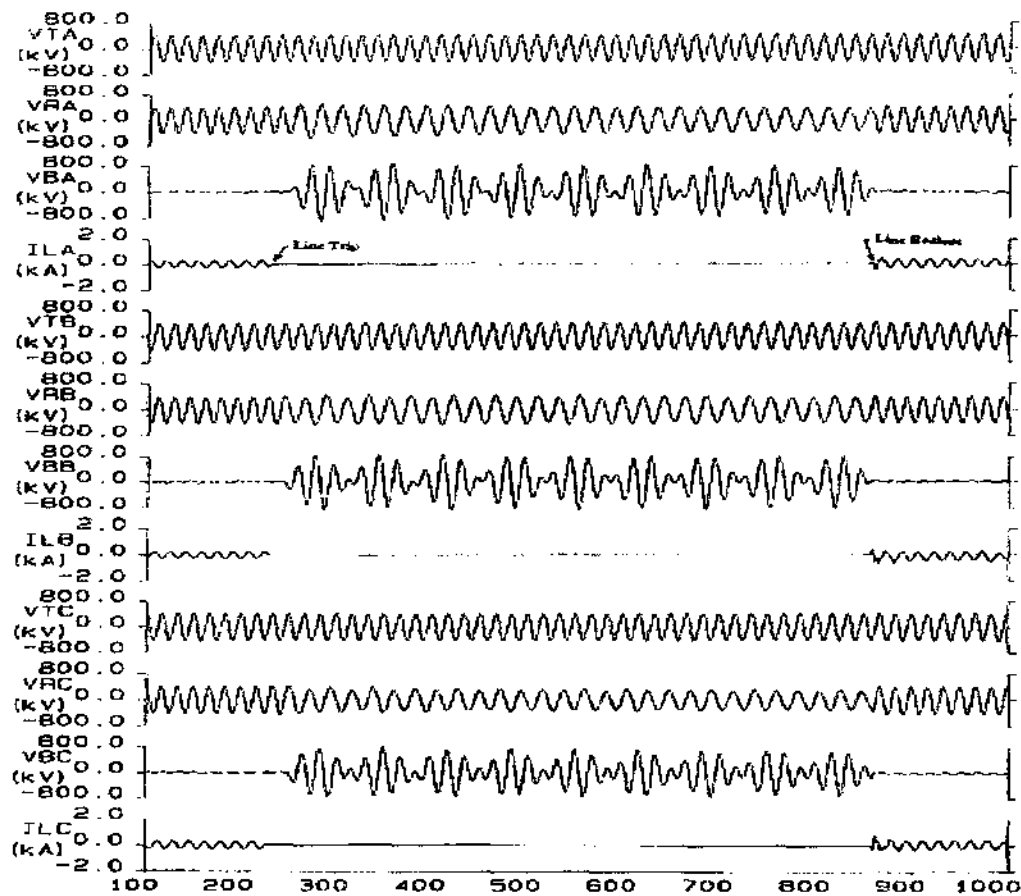
three times during the acquisition time of 300 ms after the line is de-energised; therefore, a fairly accurate prediction of the future waveform can be made [7].

In terms of functionality and of being fail-safe with respect to auto-reclosing of the circuit breaker, the control device is required to meet the following requirements:

- Work when either one and two shunt reactors are connected
- Bypass in the event of control device failure (e.g. loss of power, malfunction of the process, etc.)
- Reclose at 60 Hz source side zero crossing, if the optimum closing instant is not selected on application of the close signal
- Successfully complete Transient Network Analyser (TNA) and EMTP based testing before installation.

## 2.5 Line Switching Tests

A series of line switching tests were carried out to verify the performance of the design concepts and associated hardware [5]. Two line condition cases were considered, in the first case, the shunt reactors were connected at both line ends; in the second case, only the fixed shunt reactor at the lead end of the line was connected.

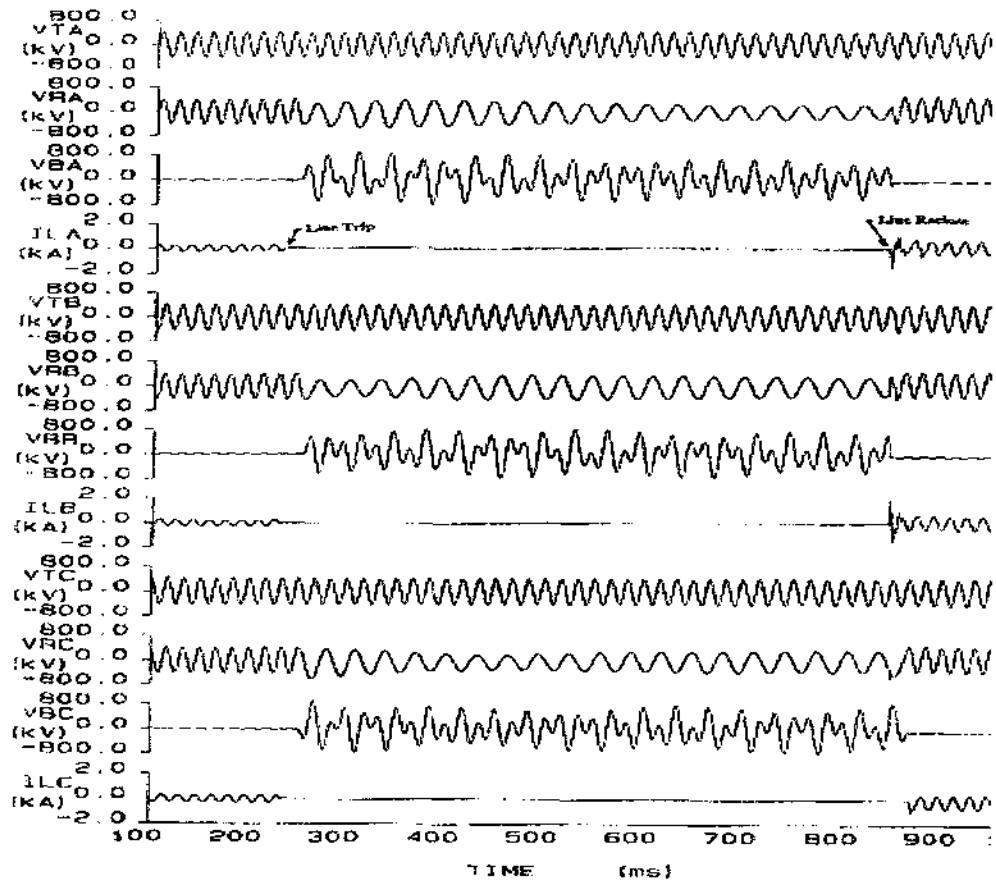


VTA, B, C	source side phase voltages
VRA, B, C	line side phase voltages
VBA, B, C	voltages across circuit breaker poles
ILA, B, C	line currents

**Figure 10: Controlled auto-reclosing with two shunt reactors connected [5]**

With two shunt reactors connected, the line oscillates at about 45 Hz on being switched out. The voltage across the circuit breaker has a very pronounced beat with distinctive and repetitive maximum and minimum amplitude points. The control device closed each pole of the circuit breaker independently at a zero crossing within the beat minimum. As seen in Figure 10, this resulted in no overvoltages and thus no energy was absorbed by the line surge arresters [5].

With one shunt reactor connected (low compensation as discussed earlier) the line oscillates at approximately 33 Hz on being switched out. However, the voltage across the circuit breaker has a less pronounced beat making it difficult to determine the periodic maximum and minimum amplitude points. The control device therefore experienced difficulty in achieving optimal closing on two poles (see Figure 11).

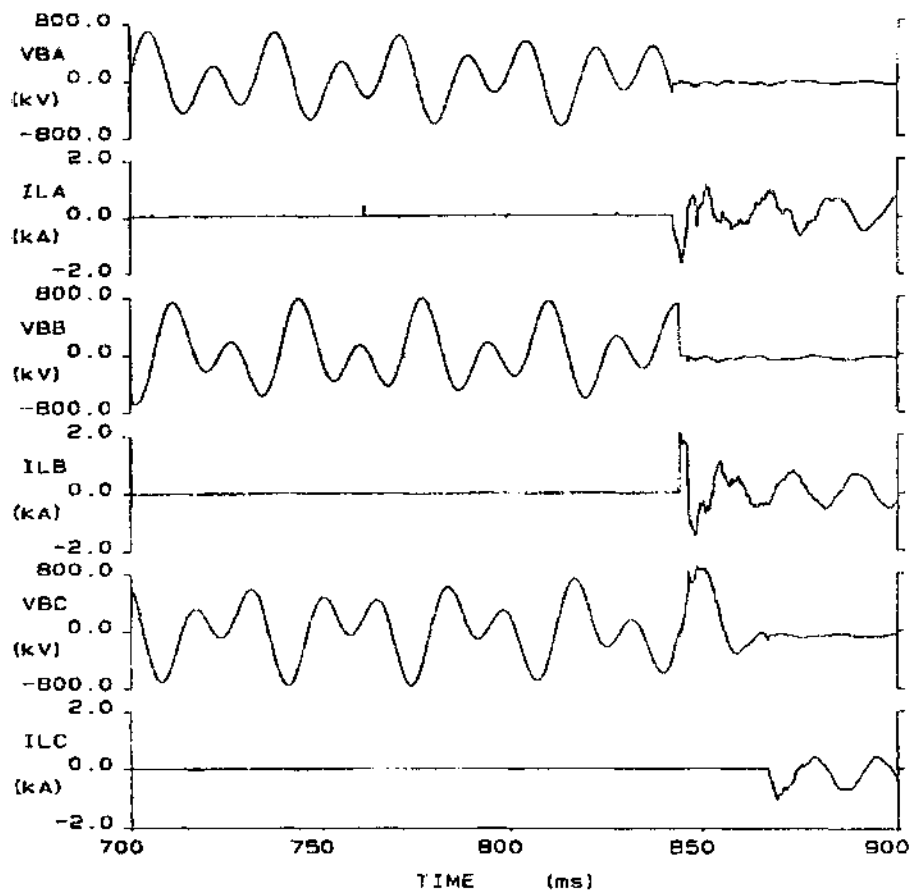


VTA, B, C      source side phase voltages  
 VRA, B, C      line side phase voltages  
 VBA, B, C      voltages across circuit breaker poles  
 ILA, B, C      line currents

**Figure 11:      Controlled auto-reclosing with one shunt reactor connected at lead end      [5]**

The reclosing in all such instances was successful, however, overvoltages did occur. As expected, the measured overvoltages did not exceed 1.7 p.u. in any instance and the worst case single-shot energy absorption by a line surge arrester was approximately 1 MJ [7]. This is well below the rated energy absorption capability of the surge arrester. This was because of the one feature of the control device. That is, if the device has not chosen an optimal closing instant by the time the close signal is applied, then a special default mode is activated to mitigate this circumstance. In this mode, the closing target is a zero crossing of the source side voltage.

The control device and overall controlled switching scheme has been in-service since March 1995 and has functioned correctly without incident at the time that the paper was published (April 1997) [7]. To improve performance for the one shunt reactor case, the control device software was upgraded and successfully tested in November 1997 [7].



VBA, B,C - source side phase voltage  
 ILA, B,C - line currents

Figure 12: Example of coupling between phases [5]

## 2.6 Interphase Coupling Phenomena

Interphase coupling phenomena are caused by capacitive coupling and by coupling through the neutral of the reactors, for the case where the reactor is grounded through a neutral reactor. This means that as the first phase is reenergized during the reclosing operation, a phase shift due to coupling occurs in the second and third phases. Figure 12 shows an example of the circuit breaker closing on one phase and influencing the oscillation on another phase [6]. The same effect occurs in the third phase again when the second phase is reenergized. The second and third phase voltages show a dynamic phase shift. This causes a significant deviation from the original signal used by the control device to predict the optimum closing instant which means that a signal measurement error could possibly occur [6]. This deviation is shown in Figure 13. It is evident from the figure that the coupling effect is significantly less in the second phase to close than this in the third (healthy) phase to close [6].

Compensation of this error can be done only by adding a correction factor programmed into the control device provided that the deviation from the optimal closing moment is consistent. However, numerous EMTP simulations showed that the considered effect scatters statistically. This means that neither a simple nor more complex systematic correlation between line characteristics, switching angles and deviation from the optimal closing is derivable [6]. The value of increase in the second phase is negligible and that in the third phase to close is not more than 20%. Both values are not too high and thus the maximum possible error will still allow the breaker to close within the surge limits of the line [6]. The effect of coupling becomes relevant only if all three phases are unfaulted during auto-reclosing, which is rarely the case. Therefore, for the development of the control device such coupling effects were neglected [6].

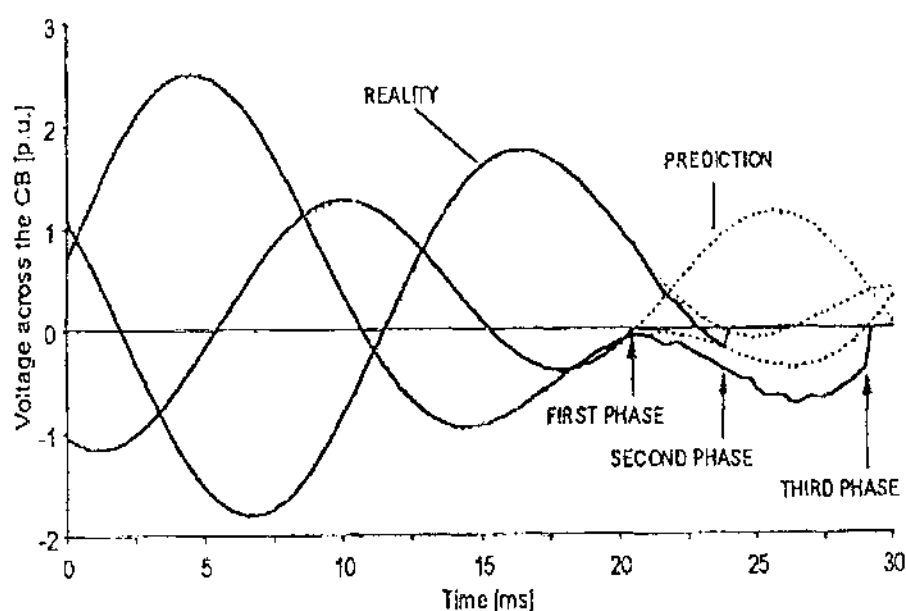


Figure 13: Interphase coupling between phases during contact closure [6]

## 2.7 Conclusions

The following conclusions are drawn about the use of pre-insertion resistors or controlled breaker closing using surge arresters on the BC Hydro 500 kV line.

Switching surge limitation on EHV systems can be achieved by making use of pre-insertion resistors with line surge arresters and traditionally, pre-insertion resistors are used. Switching surge limitation on systems can, however, be achieved through the combined use of line surge arresters and controlled circuit breaker closing. This scheme displaces the use of circuit breaker closing



resistors. Specific requirements are placed on the components of the scheme and the control device provides fail-safe or default modes to guarantee that the circuit breaker will close. In the event of such mode closing, a higher than design risk for exceeding the switching surge limitation level must be accepted. The controlled closing scheme allows for the use of lower line insulation levels which induces cost savings. Extensive field testing provided evidence of the scheme's robust design and operation.

## CHAPTER 3: SIMULATION MODEL OF THE ALPHA-BETA 765KV SYSTEM

### 3.1 Simulation Model Design

In order to predict the effects of faults and the reclosing of the Alpha-beta line with or without pre-insertion resistors, a simulation model was designed. The distributed parameter line model was used to represent the transmission line, as this is the preferred model for greater accuracy over longer length lines (>250km) [10]. The distributed line parameters are determined from the physical line parameters, i.e. resistivity, length, Geometric Mean Radius (GMR), etc. These parameters are obtained from the manufacturer, and the model parameters are calculated by the program detailed in Appendix B.

A Matlab-Simulink model is then constructed using the line parameters. The Simulink model is shown in Figure 14. The two parallel transmission lines are clearly visible from the figure and both lines use the distributed parameter model. To emulate the voltage transformer (VT) measurement, a 3 phase V-I measurement model was used to measure the voltage across the breakers.

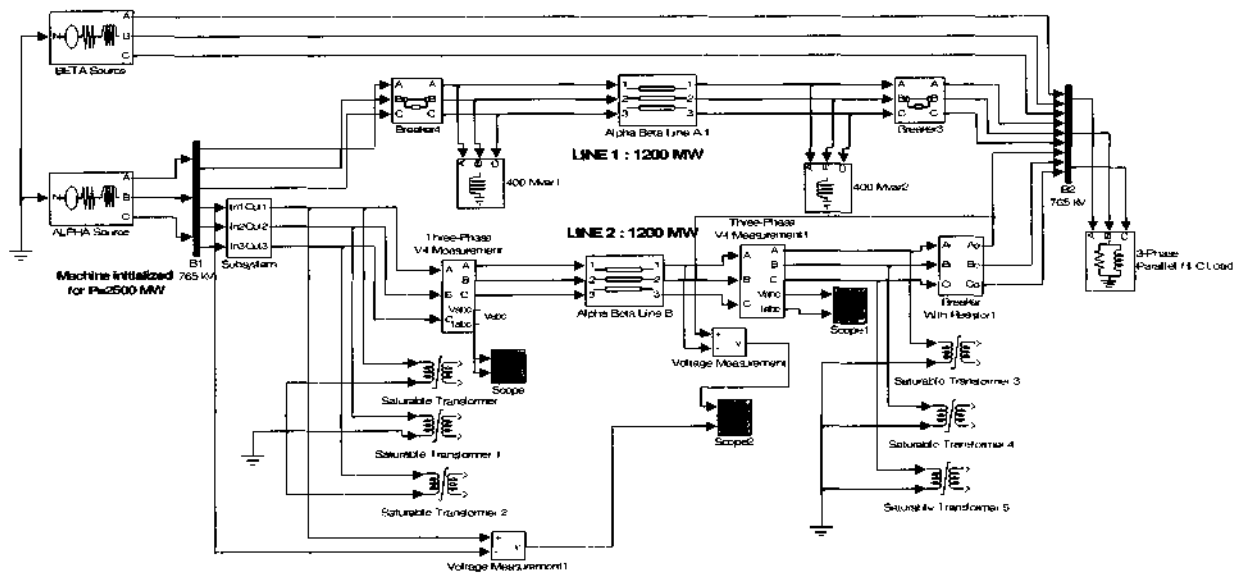


Figure 14: Alpha-Beta 765kV system model in Simulink

The top line is compensated using two line reactors, whereas the bottom line is compensated with the primary windings of saturable transformers. This is done to represent the effects of the reactors saturating because there is no saturable reactor model in Simulink. The transformer is open circuited on the secondary side and star connected to earth on the primary side. The parameters used for the saturable transformers are obtained from the saturation curve provided by ABB.

A load of 2500 MW and 500 Mvar is attached to the Beta substation, and a generating input of 2600 MW is supplied to the Alpha substation. The source block models at the Alpha and Beta substations implement 3 voltage sources connected in star with the neutral internally grounded. The inductance value is specified by the source inductive shunt circuit X/R level ratio. These values were obtained via the PSS/E system model presently representing the Eskom transmission network and are based on a typical operating condition for the line [1]. The breaker models on either side of the line were adapted by putting two breakers in parallel, one with an internal resistance of 450 ohms. This parallel branch represents the pre-insertion resistor which closes 8 msec. before the source breaker. The breaker block is shown in Figure 15. A further description of the block parameters and model configuration is detailed in Appendix C.

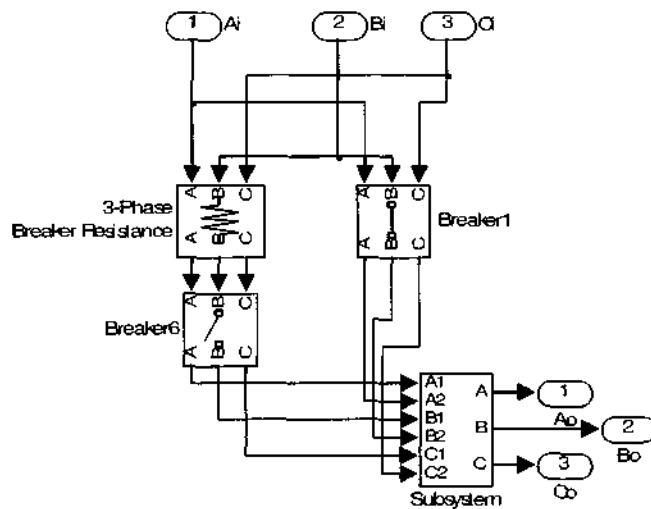
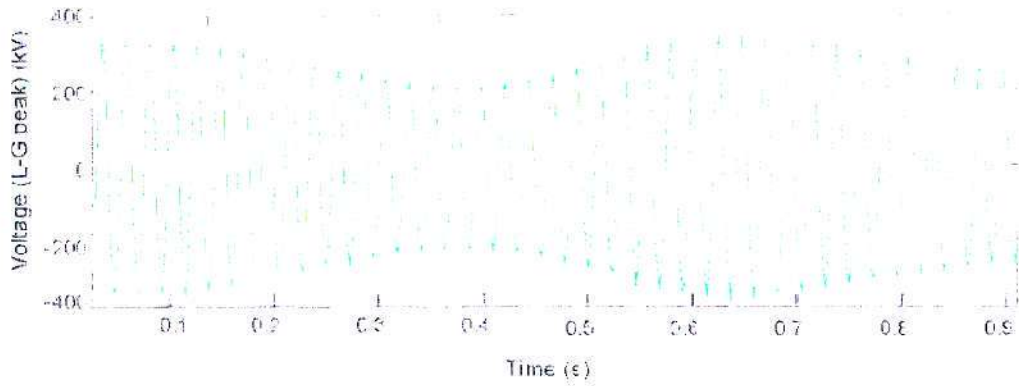


Figure 15: Model breaker with a 450 ohm pre-insertion resistor connected in parallel

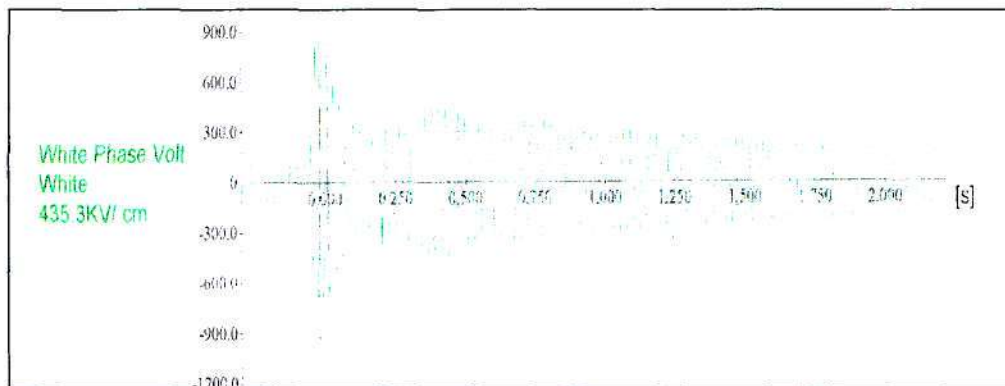
### 3.2 Testing of the Simulation Model

In order to ensure that the model's output is accurate, a past incident must be recreated. The measured and simulated values can then be compared to determine the simulation error. The incident which occurred on 26/01/1999 was chosen [4]. During this incident, a three phase line fault caused all the phase breakers to open at both Alpha and Beta substations. The ring down voltage waveform was extracted and is displayed in Figure 16.



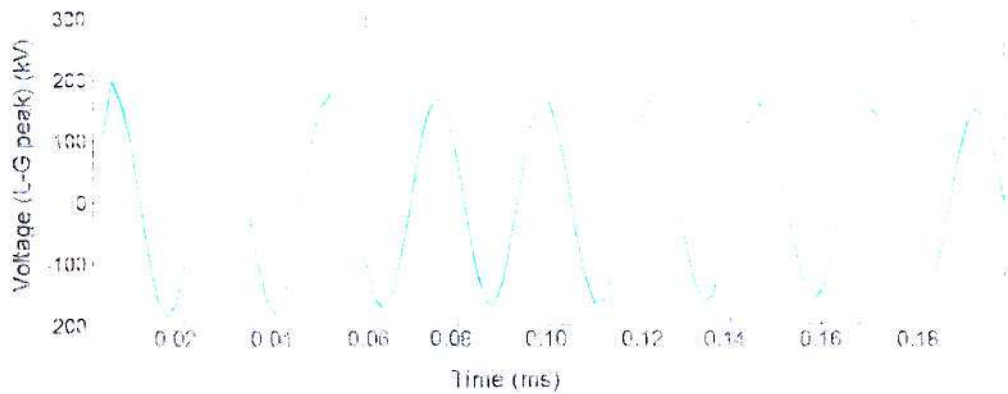
**Figure 16: Resonant ring down voltage after opening [4]**

Data from another incident (26/05/2006) was recorded [4]. Figure 17 shows the actual reclosing of the Alpha breaker onto the ring down voltage after 3 seconds. The breaker opened for a fault on the line and reclosed after 3 seconds. However, the Beta breaker failed to reclose and thus the Alpha breaker reopened. Figure 18 shows an extract from the ring down voltage shown in Figure 17.



**Figure 17: Actual ring down before and after breaker closed 26/05/06 [4]**

The amplitudes and frequencies from each incident are calculated using Matlab and the program code appears in Appendix A. The actual ring down frequency from the two incidents is calculated to be 43.23 Hz. Running the simulation under the same conditions yields a ring down frequency of 42.5 Hz as seen in Figure 20. Therefore, the simulation results differ from the measured results by 0.73 Hz ( $\pm 1.7\%$  error). This provides confidence in the accuracy of both the simulation model and simulation results.

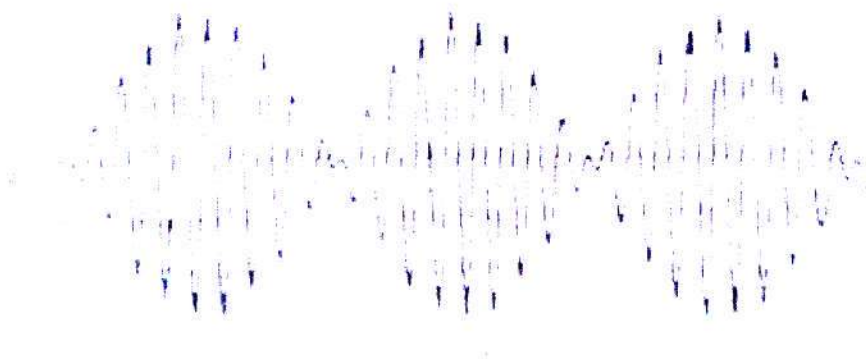


**Figure 18:** The extracted ring down voltage waveform [4]

### 3.2.1 Comparison between study and case study results

The figures (Figure 19 and Figure 20) below show the comparison between the voltage measured across the breakers of the BC Hydro 500 kV system in the case study and the Eskom 765kV system in this study. The BC Hydro 500 kV system is 80% compensated and the Eskom 765kV system is 60% compensated, explaining the slight difference in the resonant frequency of 45Hz on the BC Hydro system and 43Hz on the Eskom system.

The overvoltages resulting from the compensation are not compared, as the purpose of this study is to find where the minimum voltage occurs to enable the closing of the breakers without the use of pre-insertion resistors. The case study presented was performed to investigate how compensation affects the closing voltage for controlled switching.



**Figure 19:** Voltage across open circuit breaker – Degree of Compensation 80% Case Study (BC Hydro) [6]

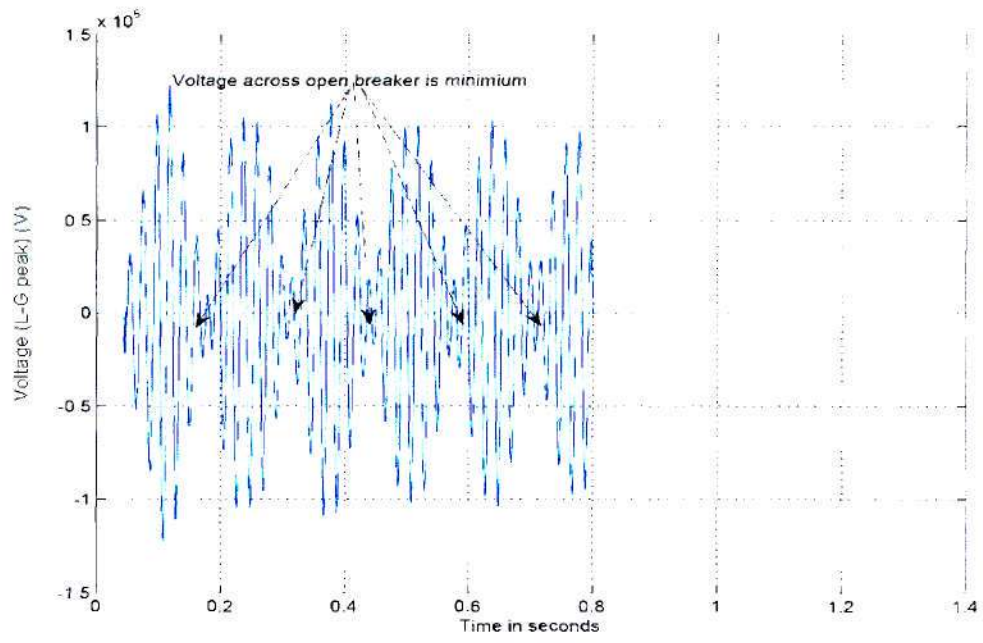


Figure 20: Voltage across open circuit breaker – Degree of Compensation 60% (ESKOM)

## CHAPTER 4: ALPHA-BETA 765KV SYSTEM SIMULATION

### 4.1 Simulation Aim

The aim of the simulations is to determine what effects the various protection schemes will have on the transient voltages. Both the pre-insertion resistor and controlled shunt reactor switching schemes will be simulated to determine which scheme yields the best results.

### 4.2 Simulation Methodology

Several simulations are undertaken to emulate the various protection schemes and system conditions. In each case a fault is simulated by simply opening the breakers at both the Alpha and Beta sides of the line. For the purpose of the line reclosing, only two frequencies are relevant: the power system frequency on the breaker source-side and the fundamental ring down frequency on the line-side. The voltages at the source and at the line breaker sides are of similar magnitude, and the voltage measured across the breaker has a beating form. The following conditions are simulated.

- Reclosing at minimum differential voltage between busbar and line with pre-insertion resistors included.
- Reclosing at minimum differential voltage between busbar and line without pre-insertion resistors included.
- Reclosing at maximum differential voltage between busbar and line with pre-insertion resistors included.
- Reclosing at maximum differential voltage between busbar and line without pre-insertion resistors included.

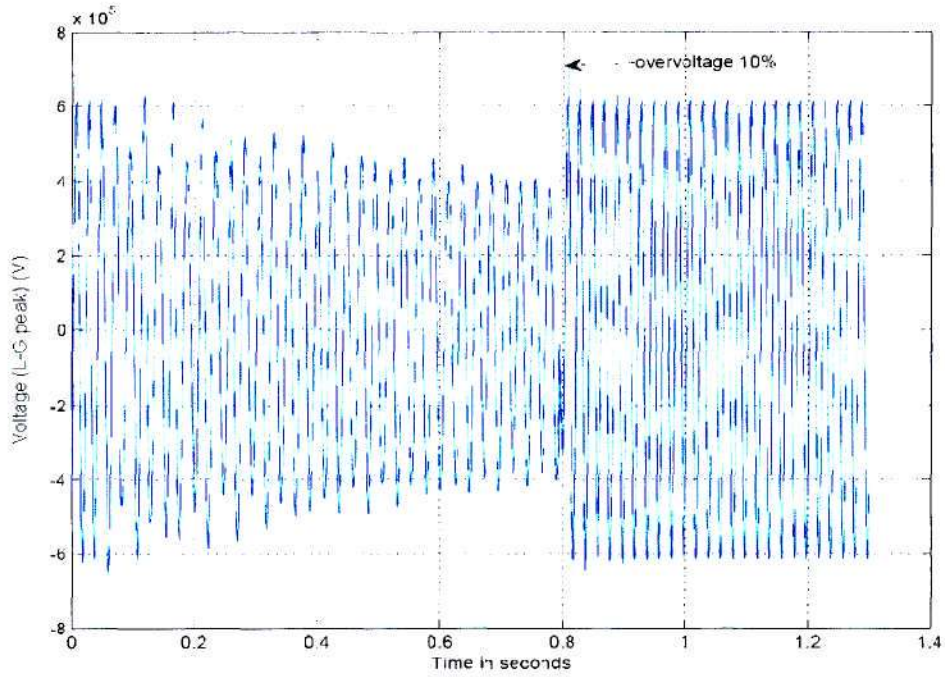
Note that when the pre-insertion resistors are used, they are connected 8 ms before the line breakers are closed.

### 4.3 Simulation Results

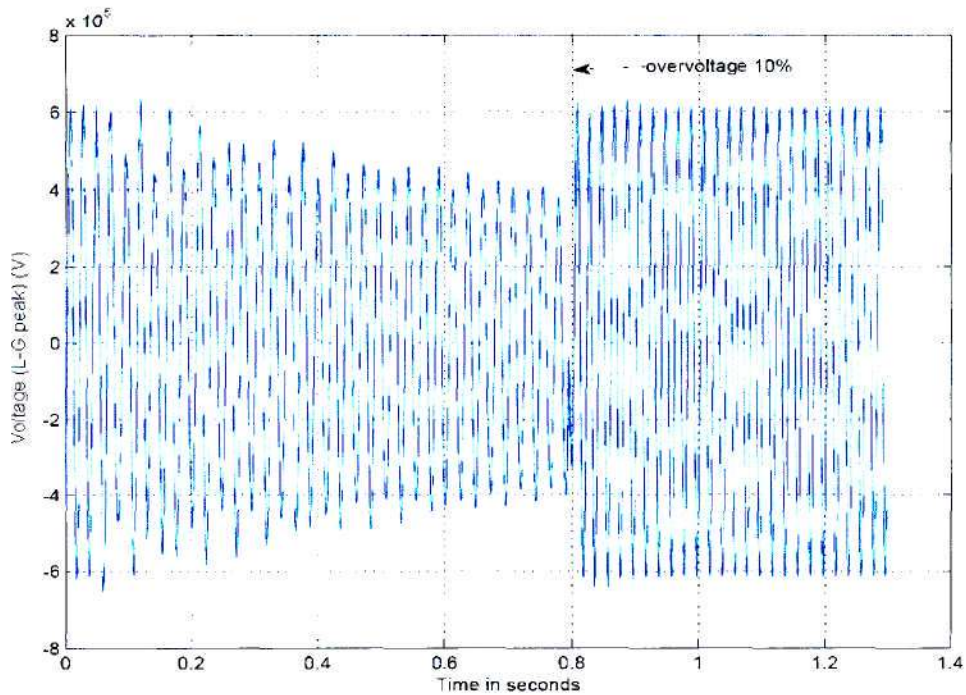
#### 4.3.1 Simulation 1 - Reclosing at minimum differential voltage with pre-insertion resistors included

This simulation is used to determine the voltage transient effects caused when the pre-insertion resistors are used. The line breakers are closed at 0.8 sec. when the beating differential voltage across the line breaker (Seen in Figure 23) is at a minimum. It is evident from both Figure 21

and Figure 22 that the overvoltages are +10 % of the system voltage at Alpha and Beta. This overvoltage is within the surge capabilities of the equipment on the line [2].



**Figure 21:** The Alpha breaker reclosing at minimum voltage with the inclusion of pre-insertion resistors



**Figure 22:** The Beta breaker reclosing at minimum voltage with the inclusion of pre-insertion resistors



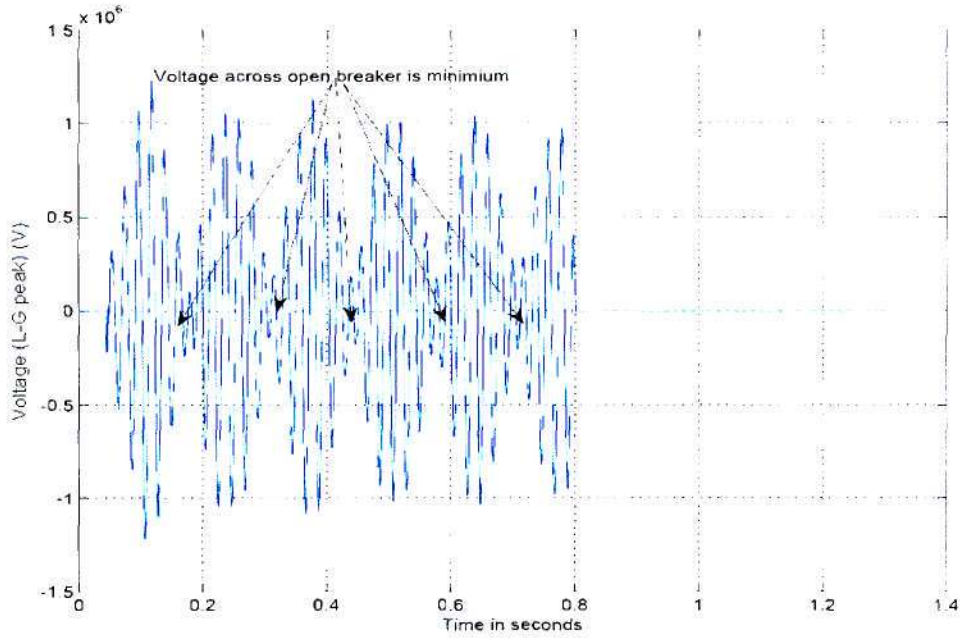


Figure 23: Difference in voltage between line and busbar at Alpha

#### 4.3.2 Simulation 2 - Reclosing at minimum differential voltage without pre-insertion resistors included

This simulation is used to determine the voltage transient effects caused when the pre-insertion resistors are not used but the line is reclosed when the differential voltage across the breaker is at a minimum. The line breakers are closed at 0.8 sec. when the beating differential voltage across the line breaker (Seen in Figure 26) is at a minimum. It is evident from both Figure 24 and Figure 25 that the overvoltages are +10 % of the system voltage at Alpha and Beta. This overvoltage is within the surge capabilities of the equipment on the line[2].

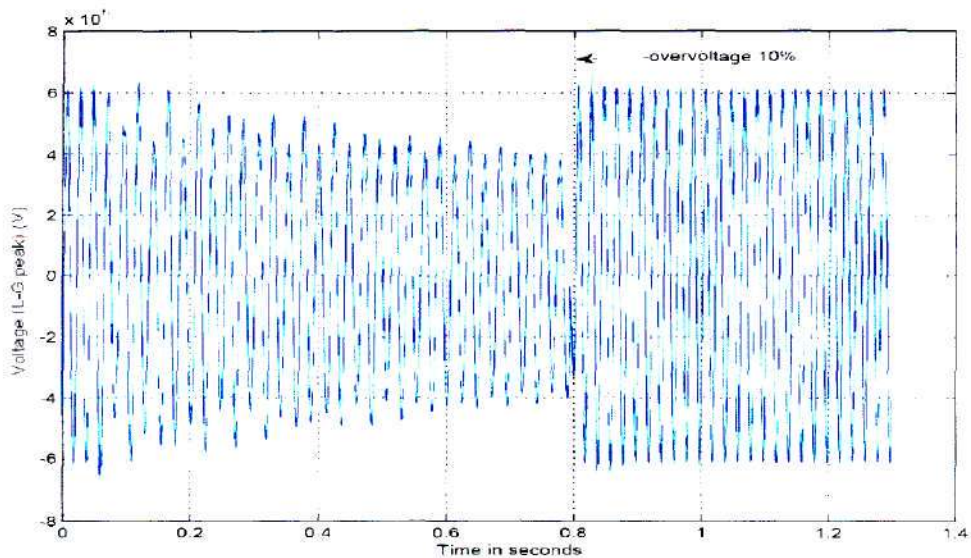
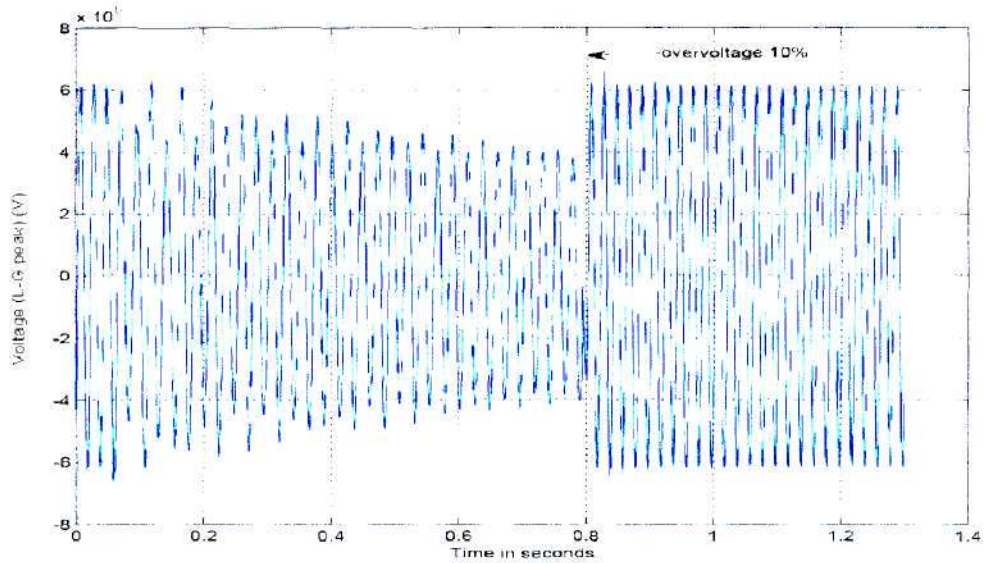
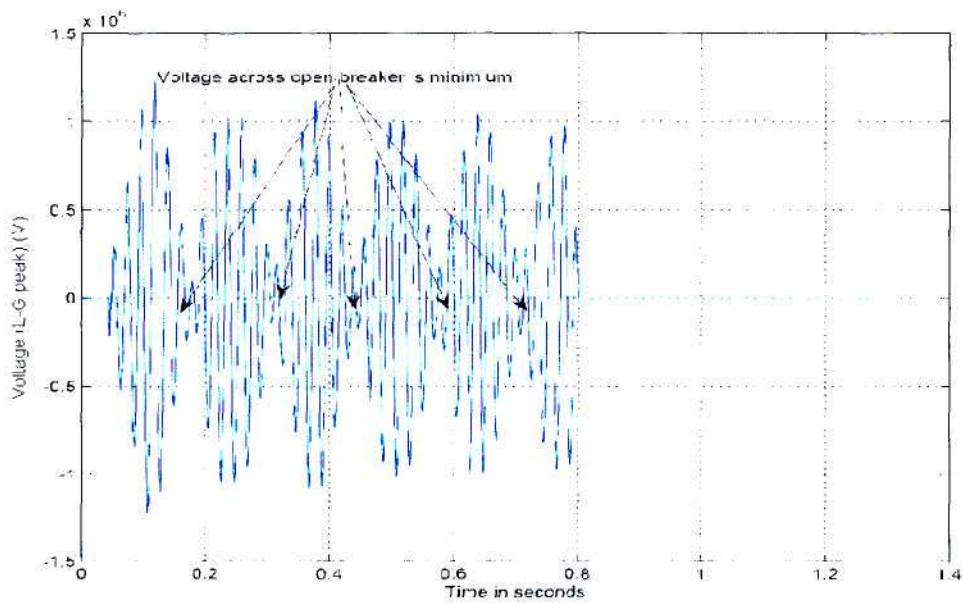


Figure 24: The Alpha breaker reclosing at minimum voltage without the inclusion of pre-insertion resistors.



**Figure 25:** The Beta breaker reclosing at minimum voltage without the inclusion of pre-insertion resistors

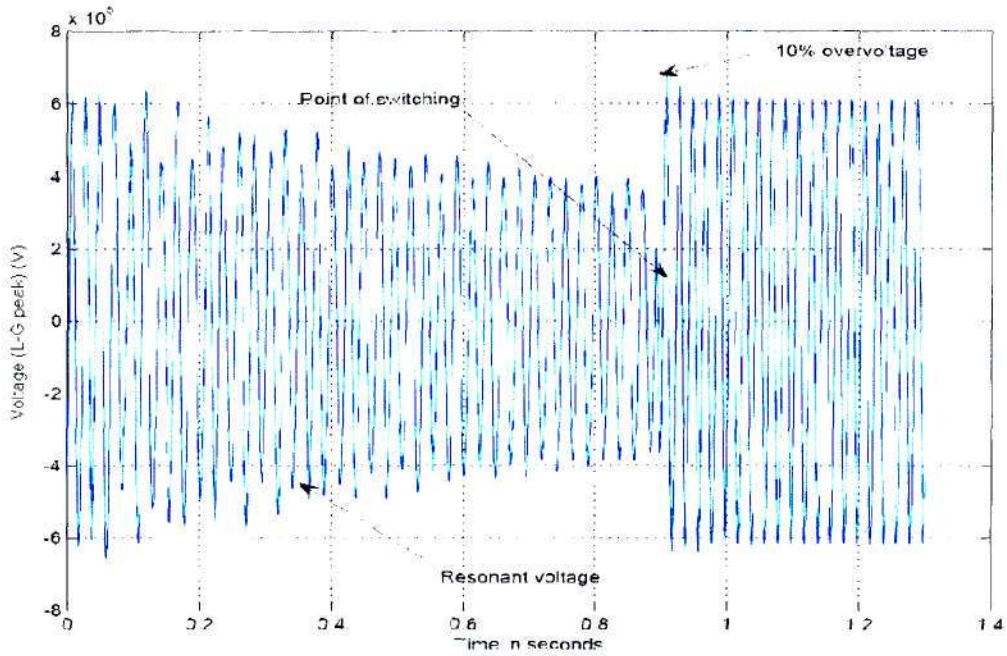


**Figure 26:** Difference in voltage between line and busbar at Alpha before reclosing

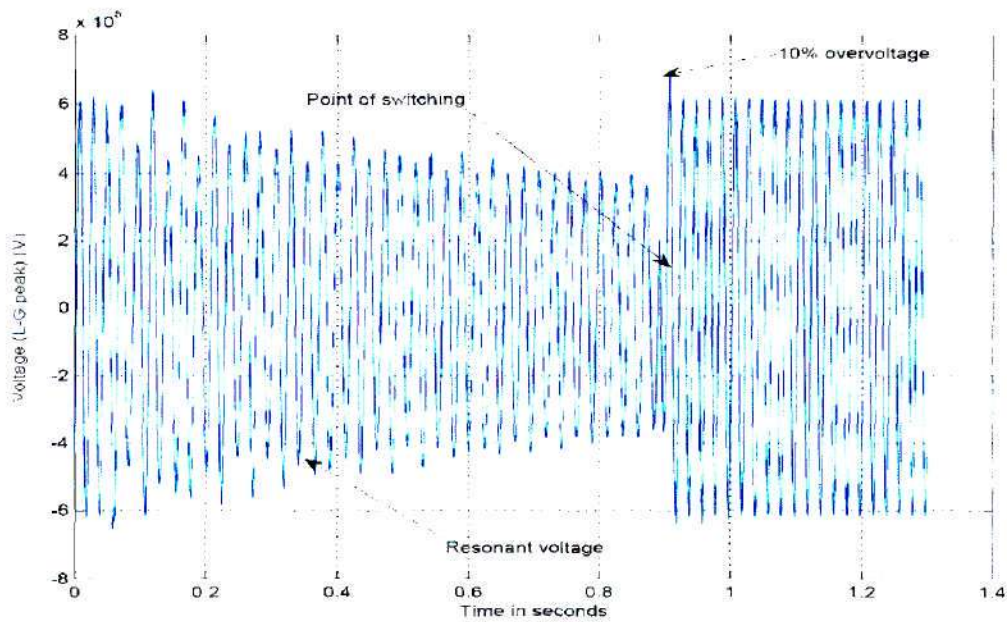
#### 4.3.3 Simulation 3 - Reclosing at maximum differential voltage with pre-insertion resistors included

This simulation is used to determine the voltage transient effects caused when the pre-insertion resistors are used but the line is reclosed when the differential voltage across the breaker is at a maximum. The line breakers are closed at 0.9 sec. when the beating differential voltage across

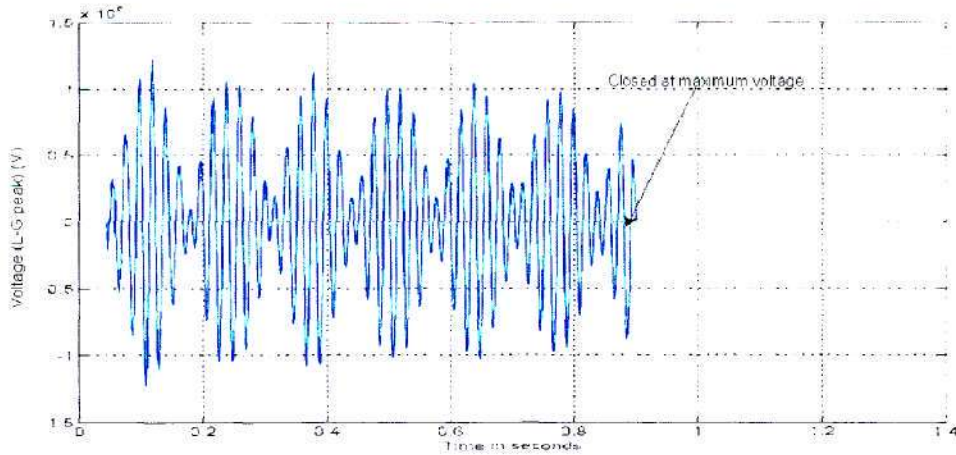
the line breaker (Seen in Figure 29) is at a maximum. It is evident from both Figure 27 and Figure 28 that the overvoltages are +10 % of the system voltage at Alpha and Beta. This overvoltage is within the surge capabilities of the equipment on the line [2].



**Figure 27:** The Alpha breaker reclosing at maximum voltage with the inclusion of pre-insertion resistors



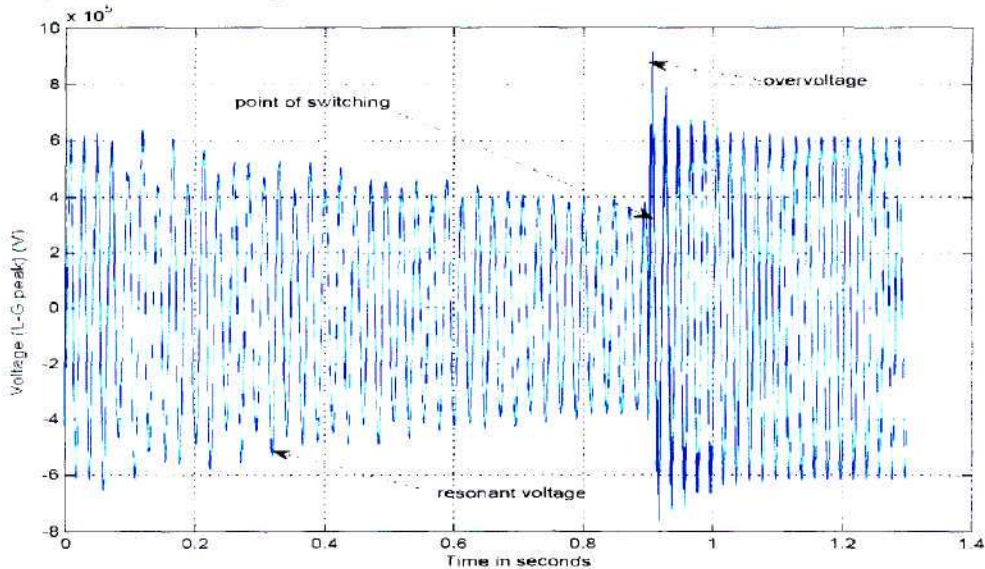
**Figure 28:** The Beta line breaker reclosing at maximum voltage with the inclusion of pre-insertion resistors



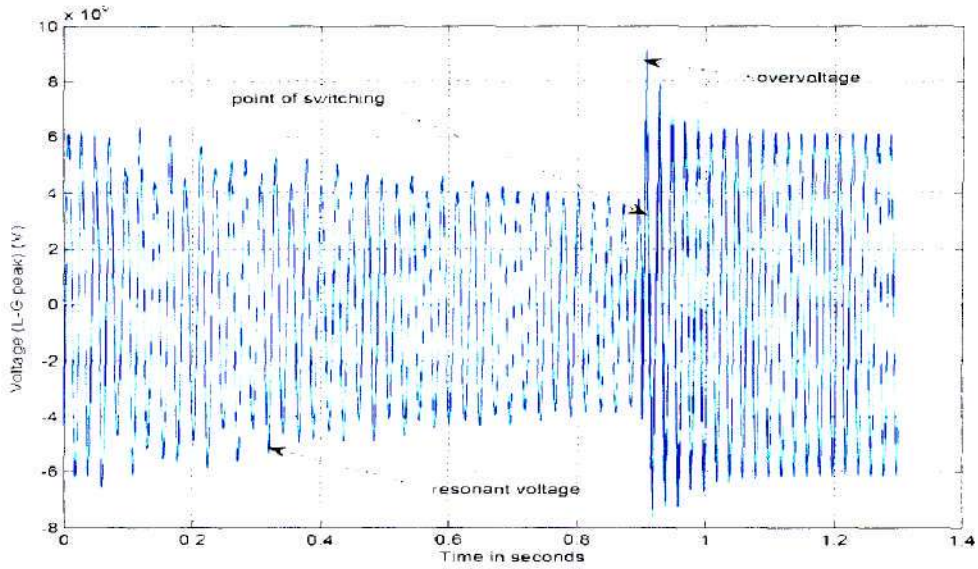
**Figure 29:** Difference in voltage between line and busbar at Alpha before reclosing

#### 4.3.4 Simulation 4 - Reclosing at maximum differential voltage without pre-insertion resistors included

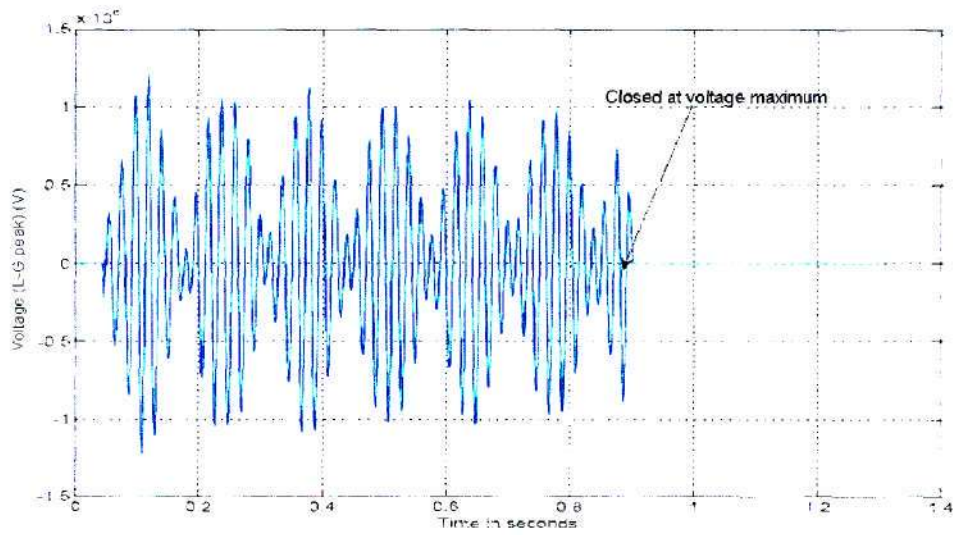
This simulation is used to determine the voltage transient effects caused when the pre-insertion resistors are not used (i.e. the pre-insertion resistors fail to close) but the line is reclosed when the differential voltage across the breaker is at a maximum. The line breakers are closed at 0.9 sec. when the beating differential voltage across the line breaker (Seen in Figure 32) is at a maximum. It is evident from both Figure 30 and Figure 31 that the overvoltages are approximately +50 % of the system voltage at Alpha and Beta. This overvoltage is not within the surge capabilities of the equipment on the line and therefore there is a chance that the components will be damaged [2]



**Figure 30:** The Alpha line breaker reclosing at maximum voltage without the inclusion of pre-insertion resistors



**Figure 31:** The Beta breaker reclosing at maximum voltage without the inclusion of pre-insertion resistors



**Figure 32:** Difference in voltage between line and busbar at Alpha before reclosing

#### **4.4 Interpretation of Simulation Results**

Several conclusions can be drawn from the four simulations presented above. It is concluded that pre-insertion resistors are able to reduce the transient overvoltage to within the surge capabilities of the line. However, should the resistors fail to close, the overvoltage exceeds the line surge capabilities and damage can be done to its components. Controlled switching within the beat minimum without the use of pre-insertion resistors, also yields an overvoltage which is within the surge capabilities of the line. It is therefore concluded, from a theoretical perspective, that controlled switching is a viable means of transient protection on the Alpha-Beta lines.

## CHAPTER 5: DESIGN SPECIFICATIONS FOR A CONTROLLED SWITCHING RELAY

The convenience of controlled switching devices for use on the Alpha-Beta line is evident from the discussion in the previous chapters. Such a device is not yet readily available and must therefore be designed. A design specification for this device is given in order to initiate the design process of such a device. These devices will possibly be used for the future 765 kV transmission network in South Africa.

### 5.1 Switching Constraints

There are several criteria which must be met in order for the proposed protection scheme to function correctly. The relay must measure the differential voltage across the line breaker and attempt to reclose within the beat minimum for each phase. This objective is highly dependent on time and thus all possible time errors and constraints must be considered.

It is evident from Figure 33 that the beat minimum or reclosing period exists for approximately 50 ms on the Alpha-Beta line when it is compensated by both reactors on each end of the line. This means that if the breaker is set to close in the middle of the beat minimum, a closing error of up to  $\pm 25$  ms can occur without stressing the line equipment. The errors due to the sampling and measurement of the voltage signal must therefore not produce a closing error of more than  $\pm 25$  ms.

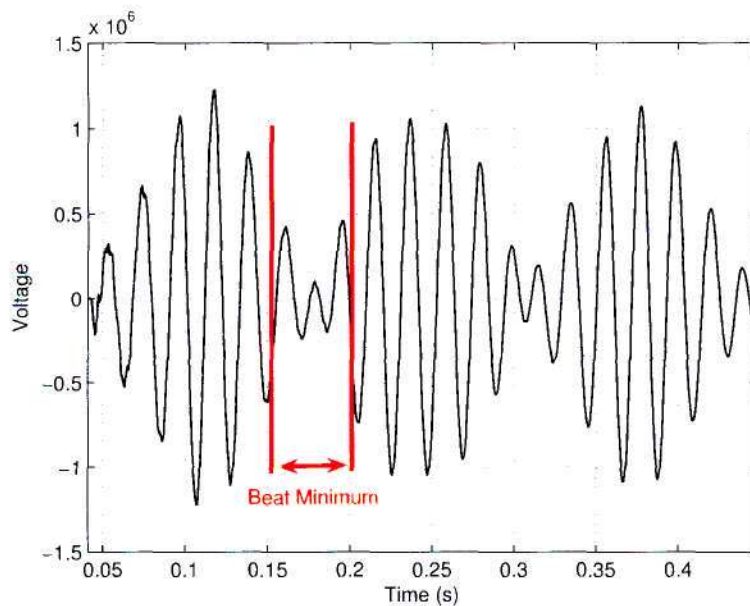


Figure 33: Differential voltage across the breaker at Alpha with the line compensated by both line reactors.

Other errors could occur due to the varying time taken to close a breaker. The relevant breakers have a closing time of approximately 50 ms [7]. This means that there is a 50 ms gap between the issuing of the close command by the relay, and the closing of the breaker. However this time can vary by as much as  $\pm 1$  ms with a standard deviation ( $\sigma$ ) of 0.6 ms for a compensated line [7].

## **5.2 Relay Functional Overview**

A relay consists of three main functions as well as a group of auxiliary functions where the main functions are the input sampling of the voltages on the busbar and line side, the hardware filtering of these quantities to cutoff any unwanted frequencies, frequency tracking of the waveforms, computation of the phasor quantities, computation of decisional variables and lastly the computation of the close logic output. The auxiliary functions include the control logic, auto-verification, event recording, synchronization and communication.

A description of the primary functions is presented hereunder.

### **5.2.1 Analogue Input Quantities**

These consists of three busbar voltage transformer input quantities and a single channel line side voltage transformer input quantity connected as a phase-to-phase measurement. The analogue input circuitry is responsible for converting these power system voltage waveforms into digital form for use by the relay processors. These consist of hardware filters and analogue to digital converters with appropriate sampling circuitry.

### **5.2.2 Frequency Tracking and Phasor Calculation**

Frequency tracking is an essential component of any relay to ensure that the sampling period for digitally calculating the phasor quantities is correct as the power system frequency varies. The phasor quantities are typically calculated using techniques such as the full cycle Discrete Fourier Transform.

### **5.2.3 Relay Algorithm and Output Decision Logic**

This is the main software function of the relay and consists of various signal processing, logic operations, level detection techniques that allow the algorithm to be fine tuned for a wide range of applications.



### 5.3 Algorithm Functional Design and Implementation

A Matlab Simulink model has been developed for the proposed algorithm based on the design criteria discussed earlier. The Simulink model is shown in Figure 34.

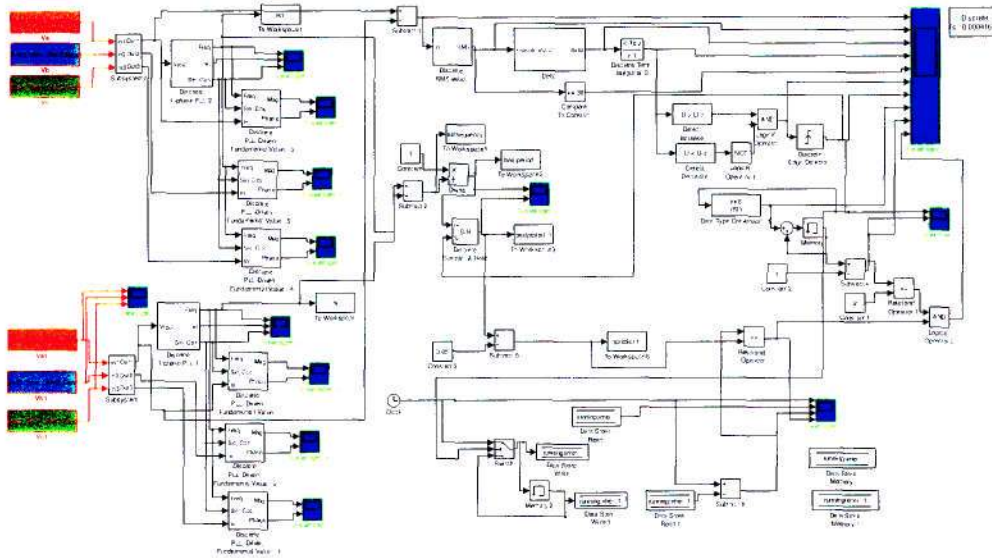


Figure 34: Relay model in Simulink

The busbar and voltage input waveforms are generated from the Matlab-Simulink power system model discussed in Chapter 3. These quantities are then passed to a low-pass filter and then frequency tracked using a phase locked loop Simulink block for the A phase only. This provides the frequency for correct calculation of the phasor voltage quantities which represents the system voltages in terms of rms magnitude and angle quantities. These quantities are used to calculate the beat frequency of the difference voltage across the circuit breaker. The function also calculates a rms voltage from the discrete sample values for the beat voltage. These filtered analogue quantities are used to calculate decision variables such as the delta voltage (rate of change of voltage over a set period), closing time predictor and threshold detector which feeds the control close output logic decision. These components are discussed below:

#### 5.3.1 Analogue Input Design

The voltage inputs are sampled at 48 samples/cycle, which is typical for a modern numerical relay, passed through a gain function which represents the voltage transformer ratio for the application and a low pass filter with a cut-off of 200Hz which is up to the 4<sup>th</sup> harmonic. The performance of the filter is shown below showing a small phase error at nominal frequencies.

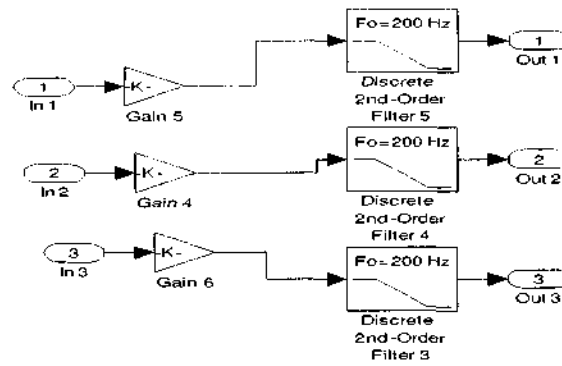


Figure 35: Filter design parameters

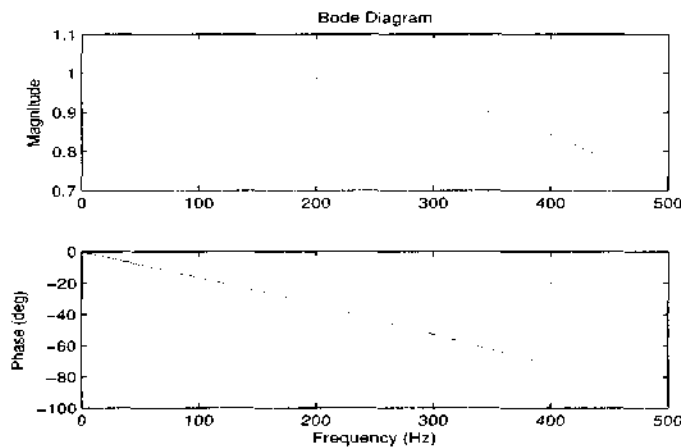
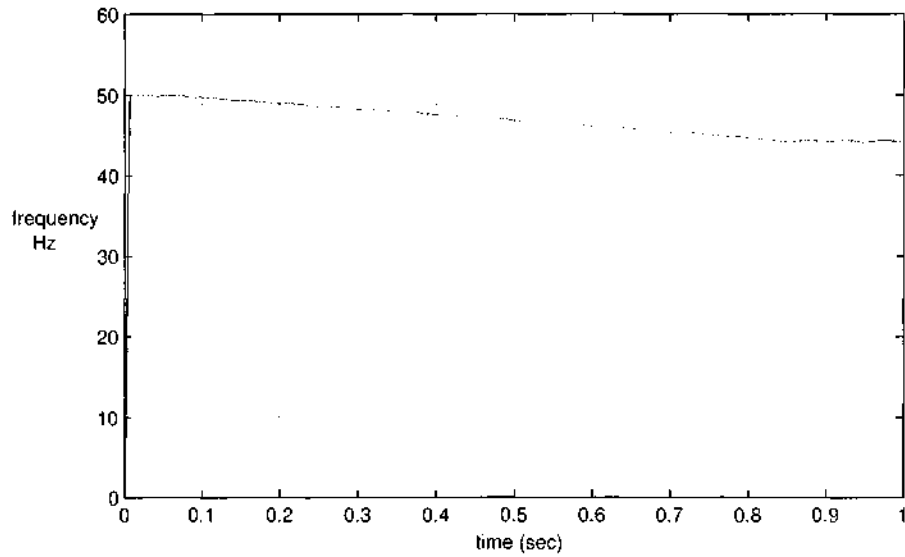


Figure 36: Filter Performance

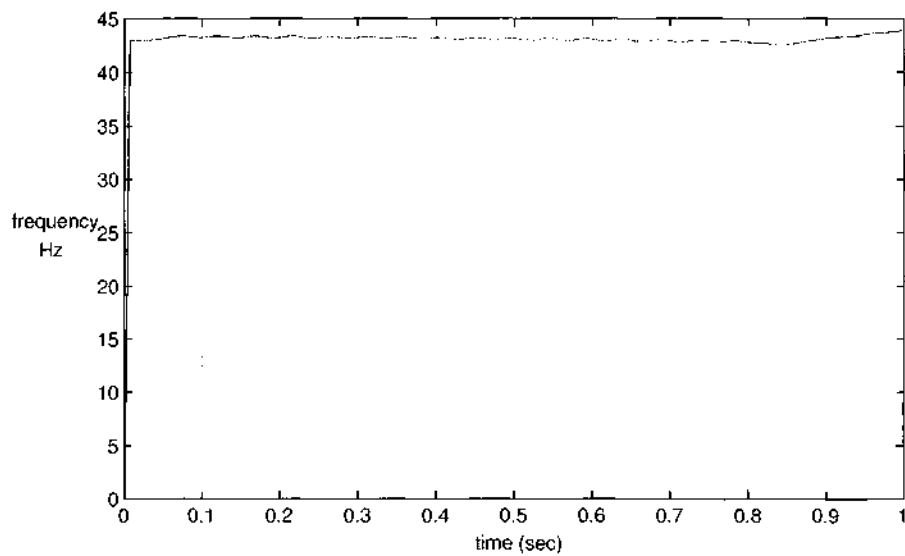
### 5.3.2 Frequency Tracking

The frequency on the line side on breaker opening is at nominal 50Hz and immediately after breaker opening is at frequencies of between 30Hz and 45Hz depending on the level of compensation. Simulation results for the Eskom example shows frequencies in the order of 33Hz and 43Hz for the condition where one or two reactors are in service. The frequency tracking algorithm starting from an initial frequency of 50Hz would take time to track to the resonant frequency as shown below for the 43.23Hz example. Here the breaker is opened for 0.8 seconds and the initial frequency was at 50Hz and as can be seen the function struggles to track the frequency very quickly. In fact the requirement is that the tracking algorithm should lock onto the frequency by the arrival of the first minima which could be within 150msec. It is

proposed that the breaker status trip and reactor status bits be mapped to the function to change the initial frequency estimate on breaker opening. The performance is shown below where the breaker is opened for 0.8 seconds and the initial frequency was estimated at 43Hz so therefore the function quickly locks onto this frequency.

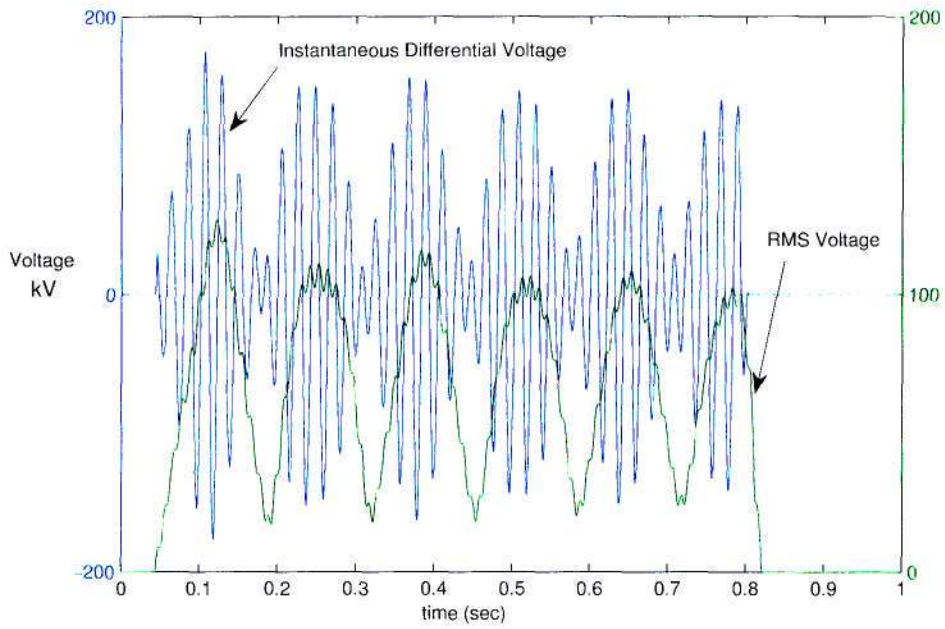


**Figure 37:** Frequency tracking performance with an initial estimate of 50Hz on breaker opening



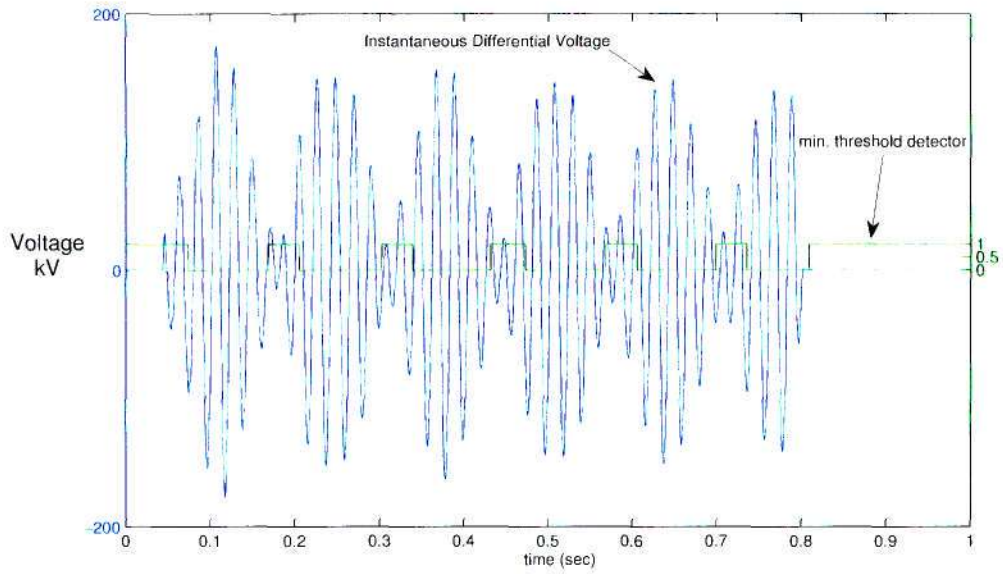
**Figure 38:** Frequency tracking performance with smoothing function and good initial estimate of frequency





**Figure 40: Instantaneous and RMS Differential Voltage comparison**

The voltage minimum of the rms value corresponds very well to the instantaneous differential voltage and is used to track and provide a robust signal for when the voltage minimum occurs. It is also used as minimum rms voltage threshold detector below which the voltage must be to allow the closing logic to proceed. This is a settable threshold which can be modified depending on the application requirements. The performance of the minimum threshold detection logic is shown below.



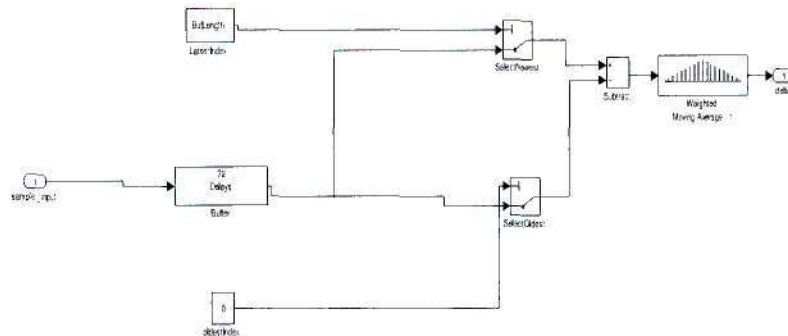
**Figure 41: Minimum rms differential threshold detector performance**

5.3.3.2 *Delta Differential RMS Voltage*

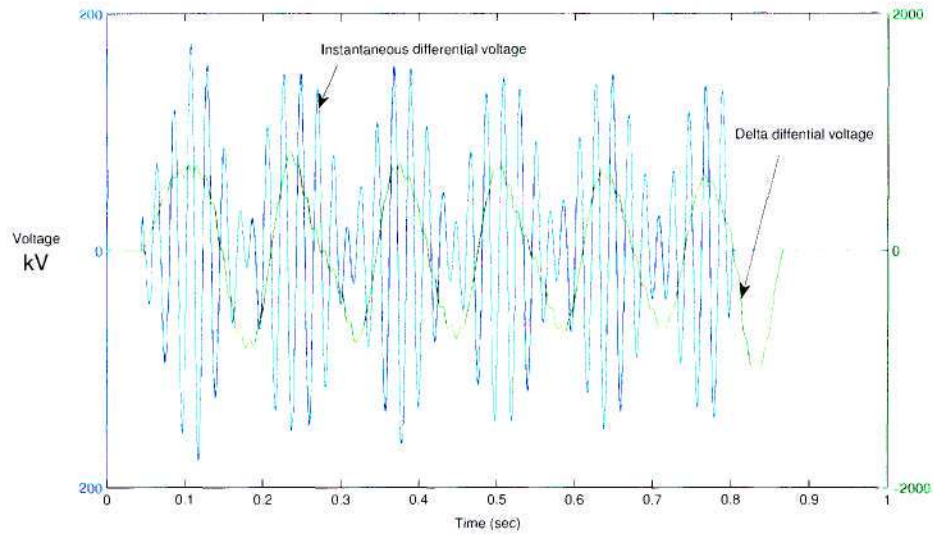
This function calculates an average rms differential voltage over a user settable buffer size (in cycles), stores it and then calculates a delta measurement as the difference between two consecutive average values as follows:

$$\Delta V / \Delta T = V_{\text{ave. buffer}}(T) - V_{\text{ave buffer}}(T-1)$$

This tracks the changing measurement and provides a means to check for a gradient change or zero crossing. The function with its performance is shown in the following figures:

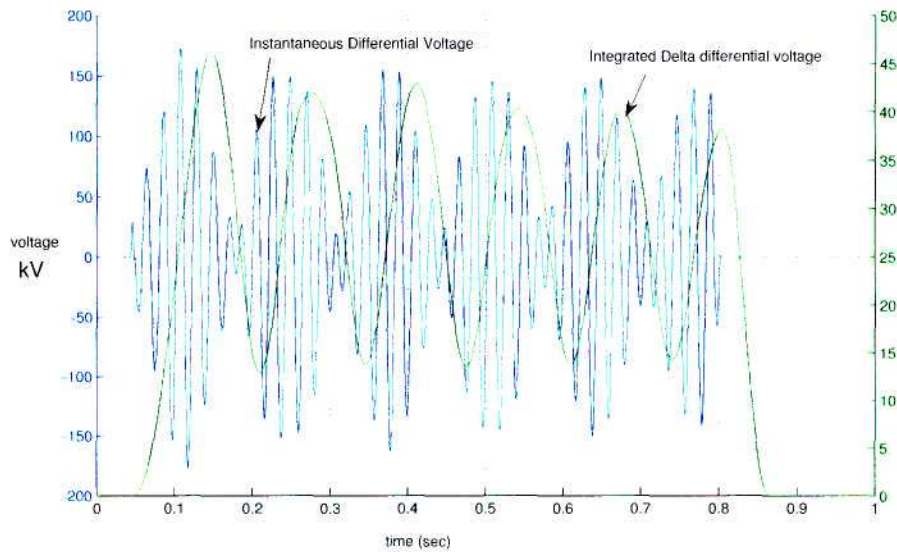


**Figure 42: Delta differential voltage measurement logic**



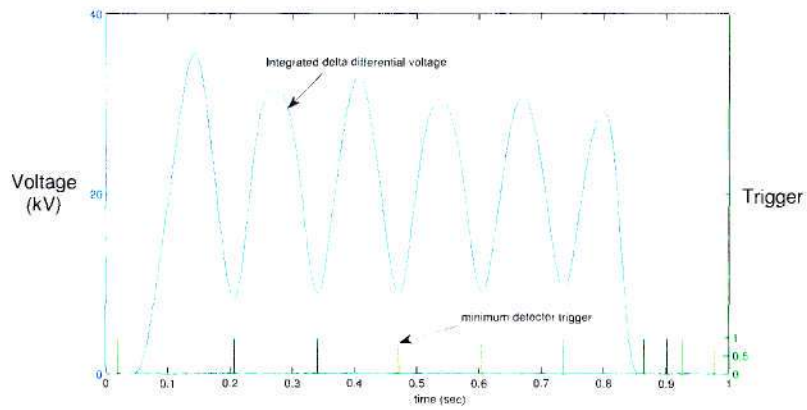
**Figure 43: Delta differential voltage measurement comparison**

The delta measurement quantity is further integrated to provide a robust signal for detecting the minimum differential voltage point and provides a trigger input for the resonant frequency function discussed next. The integrated signal is delayed by a cycle but this is compensated for in the output logic decision.

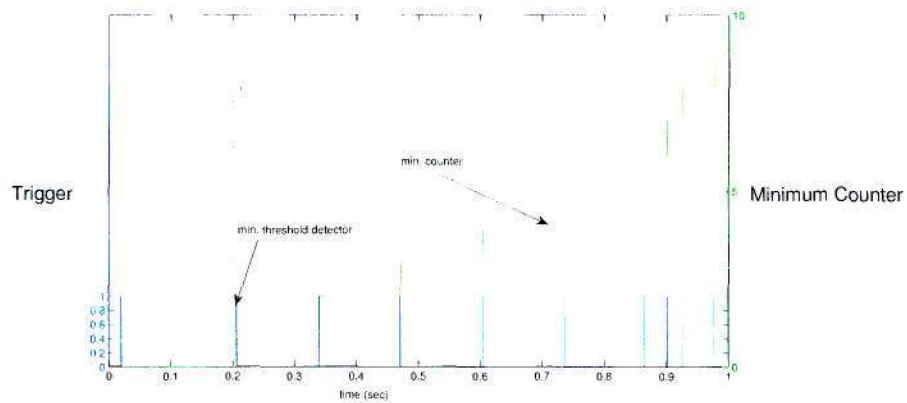


**Figure 44: Integrated delta differential voltage measurement comparison**

The trigger is determined from the voltage minimum of the integrated waveform and provides a consistent signal for detecting the voltage minimum. This in turn is used to trigger a counter which is used to determine a minimum number of counts before the output logic is allowed to issue a close command.



**Figure 45: Integrated delta differential voltage minimum detection**

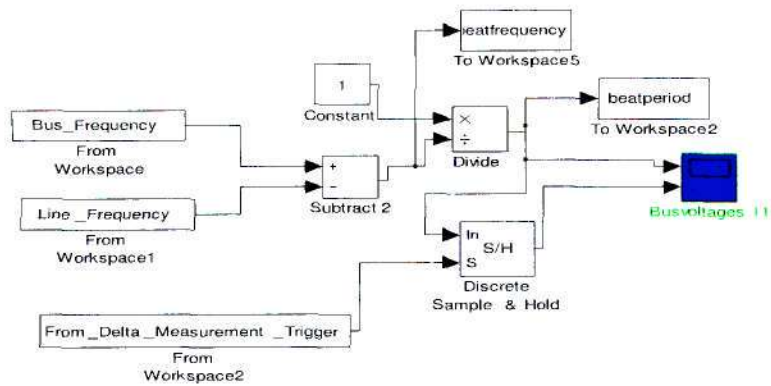


**Figure 46: Minimum number of counts before the output logic**

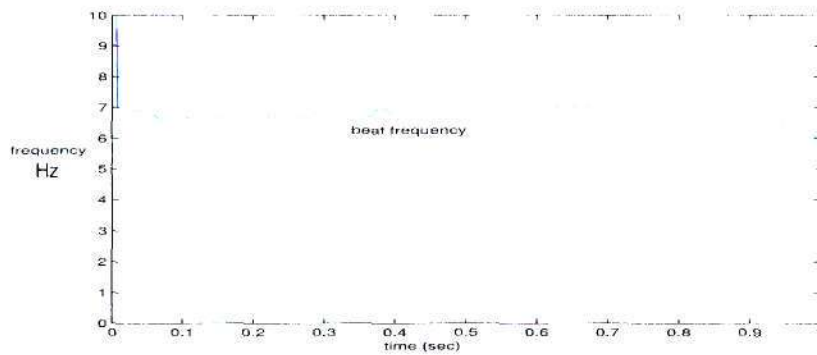
### 5.3.3.3 Beat frequency and period function

This is calculated as the difference in frequency of the busbar frequency and line frequency, which is the beat frequency and represents the resonant frequency of the ringdown voltage (i.e. the beat frequency). This is shown as follows:

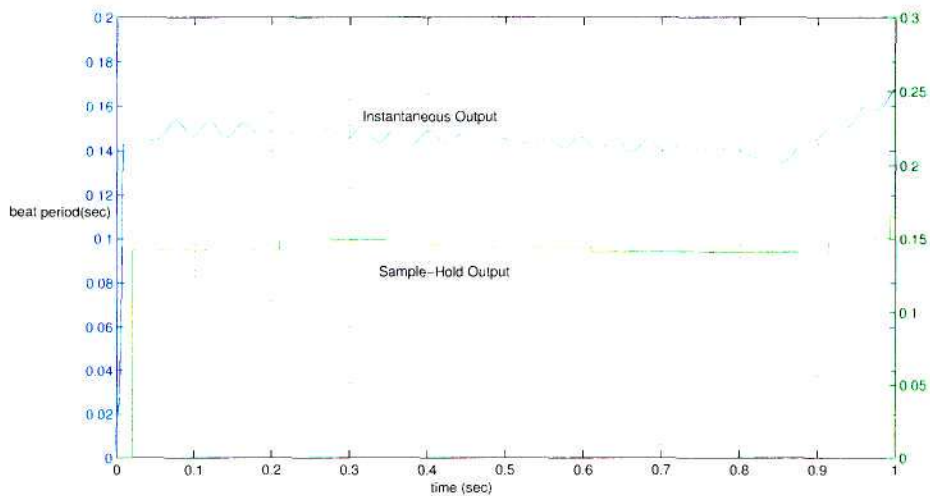




**Figure 47: Logic for calculating the beat frequency**



**Figure 48: Calculated Beat frequency**



**Figure 49: Instantaneous and sampled results for the beat frequency period**

The actual beat frequency varies with time as seen in Figure 48 thus the instantaneous value for its period follows the same trend. The actual beat period value used in the decision logic is

sampled at the instant the minimum differential voltage occurs using a trigger from the delta differential rms voltage function and then using a sample and hold logic to provide an average measurement over the beat period.

#### 5.3.3.4 Closing Logic Function

The final closing logic is shown below and combines the output from the counter function and the predicted closing time which is the beat period minus the compensation time with a running timer which starts on a voltage minimum detection trigger and resets on the next trigger. This allows the running time to be compared to the predicted closing time and a closing decision is allowed if the running timer has exceeded the predicted closing time.

The closing condition is therefore only valid if the following conditions are met:

1. The number of minimum counts has exceeded a set value of two
2. The rms voltage is below the set threshold
3. The running timer has exceeded the predicted closing time and therefore allows a close command

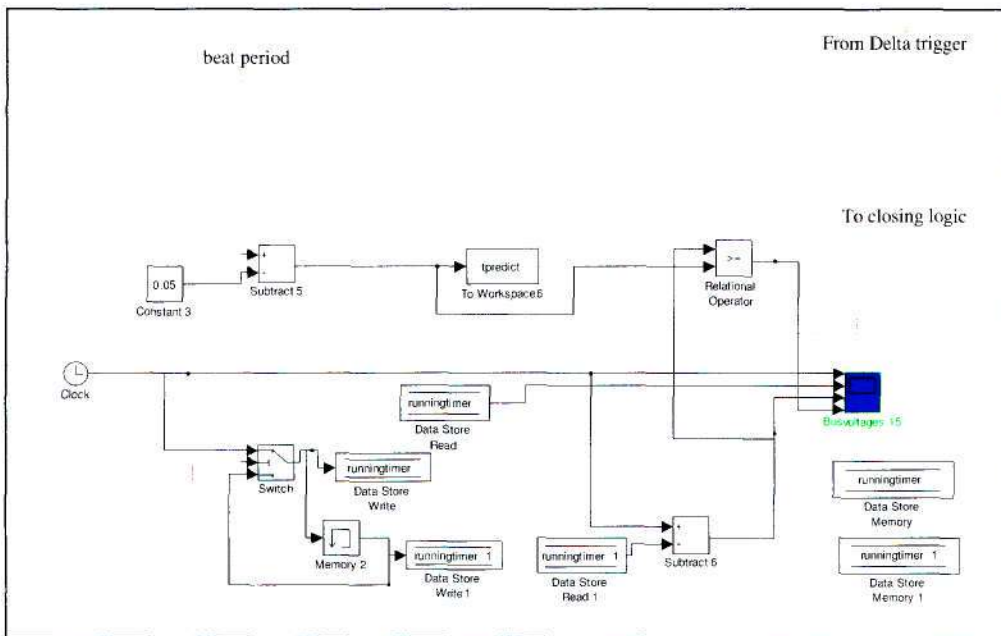
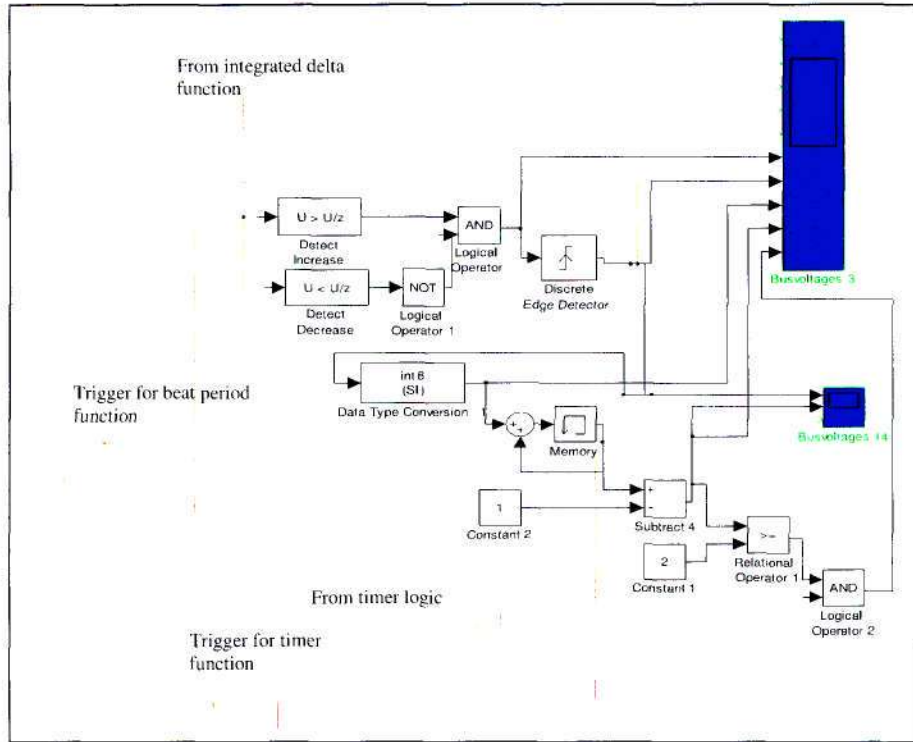
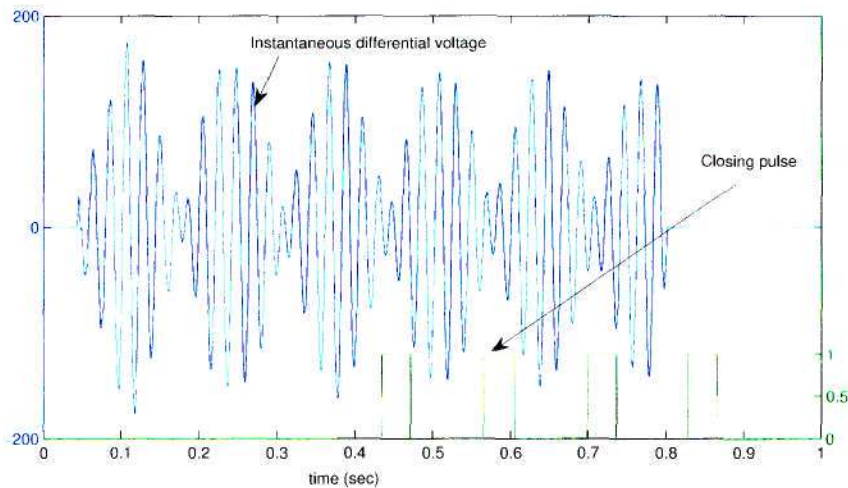


Figure 50: Logic to calculate closing time based on the predicted time



**Figure 51: Counter logic and final closing logic**

The overall performance of the closing logic is shown in the Figure 52 taking note that this is based on a counter setting of two which means the closing pulse is only given after two minimum thresholds are detected.



**Figure 52: Closing logic performance with a count of two setting**

## CHAPTER 6: CONCLUSION

Automatic reclosing on the Alpha-Beta, 765kV, shunt-reactor compensated line can cause very high transient overvoltages. These overvoltages are caused due to a resonance voltage remaining on the open line. The resonant signal is caused due to the capacitive and reactive components of the line and its frequency is therefore dependent on the degree of compensation used. Traditionally, pre-insertion resistors are used to reduce the transient overvoltages to within the surge capabilities of the line. A Simulink model of the Alpha-Beta 765kV line was constructed and used to study the performance of the existing pre-insertion resistor protection scheme. It has been shown that the resistors are able to reduce the overvoltages to within the surge capabilities of the line. However, if the pre-insertion resistors fail to operate, the line components are exposed to dangerous overvoltages. Several such incidents on the Alpha-Beta line were recorded and analysed.

An alternative protection scheme, which has been used by the BC Hydro utility, was investigated. The protection scheme involves closing the line breakers at the moment when the differential voltage between the busbar and line is at a minimum. Simulations of the controlled closing scheme, on the Alpha-Beta line, proved that it is able to reduce the overvoltages to within the surge capabilities of the line without the use of pre-insertion resistors. A relay must be designed to facilitate the controlled closing. This relay will be able to predict the optimal reclosing moment and then issue the close command to the breaker. The relay must be robust because the resonant voltage signal is dependent on the specific conditions of the line such as the degree of compensation and faulted phase.

Since pre-insertion resistors are currently installed on the Alpha-Beta 765kV system, the controlled closing relays could be installed in conjunction with the resistors. This can be done to facilitate field testing without jeopardising the stability of the network. Should the solution prove to be feasible after field testing, the controlled closing methodology could be implemented throughout Eskom's future 765 kV network. This would directly save costs because the use of expensive pre-insertion resistors would be unnecessary.