EVALUATION OF OVERCURRENT PROTECTION PERFORMANCE AND APPLICATION ON THE ESKOM SHUNT CAPACITORS DURING SYSTEM DISTURBANCES

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Date of submission: 24 November 2009

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Om Ganeshaya Namah.

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For my mum and dad.

ABSTRACT

This dissertation report began as an investigation into an overcurrent relay protection operation on a shunt capacitor bank (SCB) at ESKOM's Westgate substation.

Westgate substation has two SCBs, both of which were in service at the time of the 2007 incident. However, only the overcurrent protection scheme applied on SCB No.2 operated due to an external feeder fault on the Eltro feeder at Westgate substation.

In 2004, SCB No.2 had tripped also on an overcurrent relay protection operation for an external fault. The difference identified in the otherwise identical SCBs was the relay technology employed by the overcurrent protection schemes i.e. electromechanical and electronic overcurrent relays were utilised. Therefore an investigation was initiated to determine any difference in the performance and reliability of overcurrent relay technologies in the SCB environment.

The purpose of this work is to present the performance of the different technologies of overcurrent relays (electromechanical, electronic and digital) as applied to an ESKOM SCB during system disturbances and to compare their operation and behaviour.

MatLAB and DigSILENT simulation packages were used to conduct preliminary fault studies to determine overcurrent relay performance, for a definite time overcurrent setting. These simulation results indicated that the simple electromechanical and electronic overcurrent relay could operate incorrectly in the SCB environment, during system disturbances.

Practical laboratory tests were also conducted. This comprised of injecting DigSILENT simulations, comprising of system switching events and external faults, into three technologies of overcurrent relays. These Omicron injection tests found that the Westgate electronic relay would operate incorrectly for certain fault events in the SCB environment.

Due to the results observed, further frequency response tests were conducted. These results suggested that the electronic and electromechanical overcurrent relays were susceptible to harmonics i.e. harmonics impact both the pick-up current setting and operating time of electronic and electromechanical overcurrent relays. The digital relay did not exhibit this vulnerability.

Finally, recommendations were made to address the incorrect operation of the Westgate electronic relay in its SCB application. These recommendations could be applied in other ESKOM SCB overcurrent protection schemes, to prevent incorrect operation for system disturbances.

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GLOSSARY

Overcurrent: This describes fault conditions where the current is above normal current, and is unrelated to load conditions.

Overcurrent protection: The intention of this protection is to prevent thermal damage. An overcurrent relay setting should take into consideration normal and transient load conditions to prevent incorrect relay operation.

Overvoltage: This describes a condition where the voltage is above normal system voltage. An undervoltage state describes the opposite condition.

Protection operation: This is the protection relay initiating a disconnection of a part of an electrical installation. It refers to the relay signal issued to open/ trip its associated circuit breaker.

Protection relay: The protection relay is to issue an alarm and/or trip its associated circuit breaker, under certain fault or abnormal conditions.

Protected zone: This describes the portion of the network protected by a given protection system.

Pick-up: A relay is said to detect or "pick-up" when it changes from an un-energised to an energised state.

Settings: These are the calculated and predetermined energising quantities implemented into a protection relay and for which, under certain conditions, the protection relay is to issue an alarm and/or trip its associated circuit breaker.

Grading/ grades: This describes the time delay or grading margin between relays in a network, to allow the relay closest to the fault to operate first.

1. INTRODUCTION

This chapter provides the background and objectives for this dissertation report. It also includes the research methodology applied and a breakdown of the chapters contained herein.

1.1. Background

This dissertation report began as an investigation into a protection operation at Westgate Substation, which occurred on the 10th October 2007. This entailed an overcurrent relay protection operation on a shunt capacitor bank (SCB) for an external feeder fault on the 132kV Eltro feeder at Westgate Substation. [41]

Westgate substation has two 132kV 72Mvar SCB's, both of which were in service at the time of incident. With both the SCB's in service, only SCB No.2 tripped on overcurrent protection indication for this external feeder fault. [41]

A previous incorrect protection operation occurred on the 13th October 2004 on the SCB No. 2. This was again attributed to an overcurrent indication for an external feeder fault. In this instance the 275kV Hera-Westgate No.1 feeder had tripped and auto-reclosed (ARC) due to a white-to-blue phase impedance earth fault. [41]

ESKOM's Transmission Incident Protection Performance System (TIPPS) database, [41], indicated that an investigation was conducted to determine the cause of the initial overcurrent tripping of SCB No.2 for the 2004 Westgate incident. The investigation feedback comments as per TIPPS were that the overcurrent relay was tested and found to be within acceptable limits. In addition, the root cause could not be established for this overcurrent protection operation. [41]

The TIPPS investigation records for the 2007 incident indicated that each SCB, their associated overcurrent relay and the protection trip indications were tested and found to be correct. Protection personnel indicated that this trip was due to a close-in three phase (3P) fault on the 132kV Eltro feeder. This fault was not cleared by the Eltro feeder protection scheme, which then lead to a long fault duration of 700 milliseconds (ms). The weather was reported as a clear day at Westgate Substation and the loading during the day was approximately 250MVA. [41]

The repeat incident in 2007 highlighted a necessity to investigate further as to why only one of the two parallel SCB's tripped incorrectly for external feeder faults on an overcurrent indication, with both overcurrent relays having identical and appropriate protection settings.

The difference identified in the otherwise identical Westinghouse SCB's was the technology employed by the overcurrent protection scheme. At Westgate substation SCB No.1 employs a GEC CAG39 electromechanical overcurrent relay and SCB No.2 employs a GEC MCGG63 electronic overcurrent relay. [35]

1.2. Problem statement

The research question is to determine whether all overcurrent relay technologies are equally suitable in the difficult fault environment in which SCB's operate, for external system disturbances and fault events.

The findings of this research could impact current SCB performance by removing hidden failures i.e. a root cause that was not previously identified for previous protection operations and possibly enhance future SCB overcurrent protection setting philosophy.

1.3. The objective of this work

The purpose of this work is to observe the performance of the different technologies (electromechanical, electronic and digital) of overcurrent relays as applied to an ESKOM SCB during system disturbances and external faults, and to compare their operation and behaviour for a definite time overcurrent protection setting.

The investigation of the problem statement requires the following tasks:

a) review technical literature on SCB's and the overcurrent relay;
b) review existing setting information of overcurrent relays applied in the SCB environment;
c) review literature on overcurrent relay technologies and their method of operation;
d) conduct preliminary fault simulations using MatLAB and DigSILENT simulation packages to determine if the Westgate protection operations were warranted;
e) correlate MatLAB and DigSILENT findings;
f) conduct fault simulations using the DigSILENT simulation package;
g) inject these fault simulations into the chosen electromechanical, electronic and digital overcurrent relays; and to
h) draw conclusions based on the simulation and practical studies conducted.

1.4. Approach and method

The starting point of this research is to understand the function of the overcurrent relay as applied to the SCB and to understand the principles of operation for the three different types of protection relay technologies.

The literature review will also include a study of published literature on the performance of overcurrent relays in the SCB environment or similar, depending on availability.

Preliminary fault studies will be undertaken to identify the performance of different relay technology under identical external fault conditions, in the SCB environment. MatLAB and DigSILENT software were identified as the most suitable simulation packages for these studies.

The first phase of the practical study employs MatLAB software to conduct a preliminary assessment of the 2007 incident mentioned above. This is done to observe the current output, as seen by the overcurrent relay for an external feeder fault, using a simplified model of Westgate Substation.

These preliminary simulation results could determine whether the overcurrent relay should in fact detect an external fault, and whether this external fault condition could result in the possibility of an overcurrent protection operation or trip.

The second phase of the practical study will be to conduct Electromagnetic Transient (EMT) studies using DigSILENT software to duplicate the studies carried out in MatLAB. These simulations will employ the existing Westgate substation model and the existing DigSILENT CAG and MCGG overcurrent relay models, which are available in the ESKOM Transmission DigSILENT case file [19]. The 2007 incident mentioned above will then be simulated to compare the DigSILENT CAG and MCGG overcurrent relay model operation and performance.

While this appears as an unnecessary duplication of work, the results could determine if the MatLAB and DigSILENT findings are similar, and if the DigSILENT overcurrent relay models perform as they did for the incidents mentioned above. This could be useful information to the ESKOM Transmission Power System Operations Performance (PSOP) Investigation Department where all ESKOM transmission power system incidents are investigated.

The next phase of the research was to use DigSILENT software and the ESKOM Westgate substation model to create a number of fault simulations scenarios i.e. various fault types simulated at numerous locations at Westgate substation. This will be repeated on the common SCB configurations as applied in the ESKOM transmission network to determine if this has an impact on protection performance, as suggested in [58].

In accordance with the IEEE Standard C37.111 Standard Common Format for Transient Data (COMTRADE) files, derived from the DigSILENT fault simulations, will then be injected or 'played back' via an Omicron Test Universe set to the chosen electromechanical, electronic and digital overcurrent relays. The overcurrent relay output trip indications, for each simulation injection, will be captured in an Omicron report format.

These Omicron simulation injection reports will be collated and the findings will be presented. This will provide insight to the problem statement of establishing if all overcurrent relay technologies are equally suitable for the ESKOM SCB environment.

These findings could possibly be used to explain previous incidents where SCBs have tripped, on an overcurrent protection indication, for an external fault.

In addition, possible recommendations to enhance SCB overcurrent protection setting philosophies may be made, which could be implemented in the ESKOM transmission network.

1.5. Dissertation outline

This report consists of eight chapters. Each chapter is briefly described below.

Chapter 1: This chapter provides an introduction and outline to this investigation report and states the background and objectives of this research. It also provides the approach and method to be applied.

Chapter 2: This chapter contains the literature review on SCBs and their application in the power system network. The protection schemes employed by the SCB are also discussed, including the application and settings of overcurrent relays in the SCB environment.

The methods of operation of the three different relay technologies are presented. Also included are calculations for SCB switching events and external fault conditions to determine any impact on the current and frequency of SCB discharge currents.

The various factors affecting the discharge current are also stated. It also presents the findings of previous studies on overcurrent relay performance in harmonic environments.

Chapter 3: Preliminary MatLAB simulation findings are presented in this chapter. This was done to determine if the overcurrent relay protection operation was warranted for the 2007 Westgate incident.

Chapter 4: Preliminary DigSILENT simulation findings are presented in this chapter. The results obtained from both the simulation packages are compared to determine if the findings are similar.

Chapter 5: This chapter contains the Omicron fault injection results for the three technologies of overcurrent relays. The performance of these overcurrent relays are analysed and presented.

Chapter 6: Frequency response test were conducted on the three technologies of relays. The findings of these tests are presented here.

Chapter 7: Recommendations to prevent the operation of the electronic MCGG relay are suggested here. These could be implemented to prevent the relay operation for external fault occurrences.

Chapter 8: The conclusions based on the research findings are discussed here. Possible application of the findings to the ESKOM transmission network and further research is provided.

2. LITERATURE REVIEW

This chapter provides the literature review and gives the reader a brief overview of a SCB and overcurrent relays.

The SCB topics covered include a description of a SCB, their configurations and application in the power system. It also covers the protection schemes employed in the SCB environment.

The introduction of the overcurrent relay begins with a brief history of protection relays as applied in the power system network. The function of an overcurrent relay and its application in the SCB environment is presented.

This chapter also presents the method of operation of the three relay technologies used in the practical injection tests. The methods of operation of the electromechanical, electronic and digital overcurrent relays are discussed.

Also included are calculations for system switching events and external fault conditions of the SCB, to determine the possible impact on the overcurrent relay's performance. This was done by means of current and frequency calculations. The external SCB environment was also evaluated to determine various factors that could influence the SCB discharge current and frequency.

Finally, this chapter also includes extracts from previous research on overcurrent relay performance.

2.1. Shunt capacitor bank construction

A capacitor element consists of two electrodes separated by a dielectric. These elements are grouped together in both series and/or parallel combinations to construct a capacitor unit [6]. The capacitor unit construction is shown below in Figure 2-1.

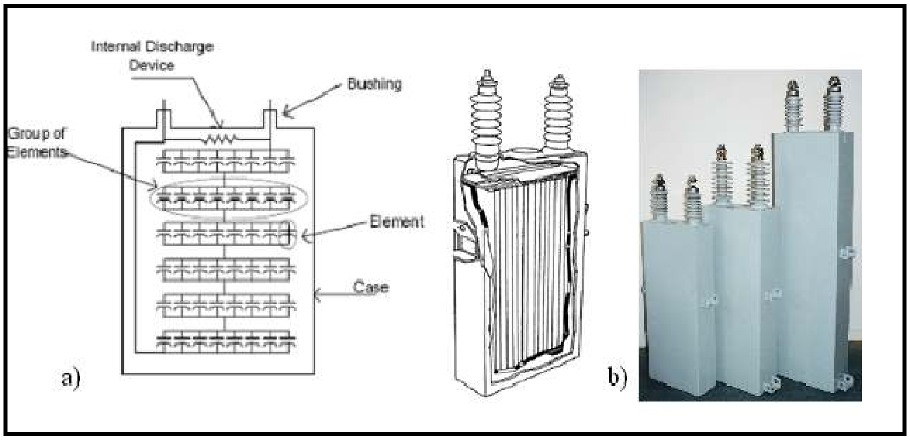


Figure 2-1. a) Construction of a capacitor unit [2] and b) capacitor units of different sizes [40]

A SCB comprises of two or more capacitor units to achieve the capacitance and voltage ratings required [6]. The SCB can be assembled in configurations described in Section 2.1.1. below.

2.1.1. SCB configurations

A SCB can be connected in various configurations on the ESKOM power system network. The SCB configurations used are as follows [2, 6]:

- Single star unearthed seen in Figure 2-2(a);
- Double star unearthed seen in Figure 2-2(b);
- Single star earthed seen in Figure 2-2(c);
- Double star earthed seen in Figure 2-2(d);
- H Configuration (earthed and unearthed)
- C-Filter configuration and delta connected

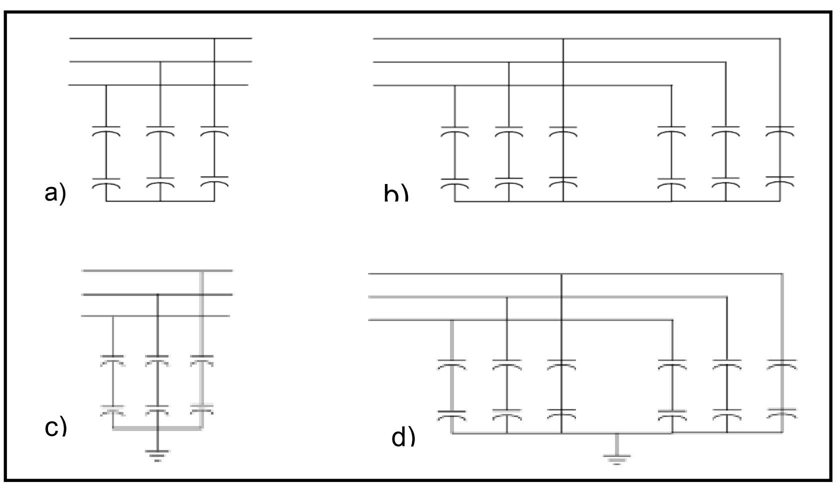


Figure 2-2. Common SCB configurations [2, 10]

The ESKOM Transmission SCB configurations shown in Figure 2-2 above are the most prevalent configurations at the 132kV level. ESKOM Transmission SCB configuration details are presented in Section 5.1.

2.1.2. Application of shunt capacitor banks

Figure 2-3. Shunt Capacitor Bank with current limiting reactor [30]

The SCB provides for the efficiency of the power system by controlling the voltage and providing power factor correction. Voltage control results in reduced line losses and power factor correction results in lower reactive power transmission costs and line losses. [2, 6, 7]

Due to its affordability, a SCB provides an economical solution to improve quality of the electrical supply and can be installed in substations and close to customer loads. [2]

The major shortcoming of SCB is that its reactive power output is proportional to the square of the voltage. The reactive power output of the SCB is calculated by the following equation as per [11]:

$$Mvar_{(output)} = Mvar_{(rated)} \text{ x } [V_{(actual)}/V_{(rated)}]^2 \qquad (2\text{-}1)$$

Where $Mvar_{(output)}$ is the reactive power output of the SCB

$Mvar_{(rated)}$ is the reactive power rating of the SCB

$V_{(rated)}$ is the voltage rating of the SCB

$V_{(actual)}$ is the voltage of the busbar

According to Equation 2-1, when the SCB is most required i.e. when the system/ busbar voltage is low, they are the least efficient. [2]

2.2. Protection relays

The function of a protection relay is to determine when a fault or an abnormal condition occurs. Once a fault condition is detected the relay will generally issue an alarm or a trip signal to the appropriate circuit breaker to remove the fault and thereby protect its associated equipment and personnel in the vicinity. This is achieved by constantly measuring the appropriate parameters, with current and voltage being the most common parameters used. [3]

Fundamental to each relay is that it should operate only for root means square (RMS) current or voltage values, and for a country specific frequency i.e. either 50Hz or 60 Hz. [32]

The simplest relay operating principle is that when a fault occurs, current magnitudes increase and voltage magnitudes decrease. The current and voltage range under normal operation conditions can be calculated and then applied as a setting to a relay. A relay is now capable of determining a fault condition as soon as it measures current or voltage values outside this setting range. [1]

Electromechanical relays were the first relay technology used 80-90 years ago and by late 1950 progressed to electronic or solid state relays [1]. Digital relays are the most recent technology applied in protection relaying.

A relay can have one or more functions i.e. overcurrent, earth fault etc. Each of these functions is called a relay element. [3]

2.2.1. Overcurrent relay function

An overcurrent relay is used to detect currents above a preset current value that is called a pick-up setting. Once the relay has detected the overcurrent condition, it can either issue a protection trip signal instantaneously or after a predetermined time delay [1].

In the SCB environment, the instantaneous overcurrent relay is expected to be stable for feeder faults, transient switching conditions and circuit breaker opening [6].

The characteristics of an overcurrent relay is chosen taking into consideration the other protection relays in the protected zone. The time taken for the overcurrent relay to issue a trip would also be time graded with these other protection devices (such as fuses) so that when a fault does occur, only the relevant relays in the faulted zone initiate a tripping operation [4].

2.2.1.1. Overcurrent relay characteristic curves

The various characteristic tripping curves that are applied to overcurrent relays are illustrated in Figure 2-4 below.

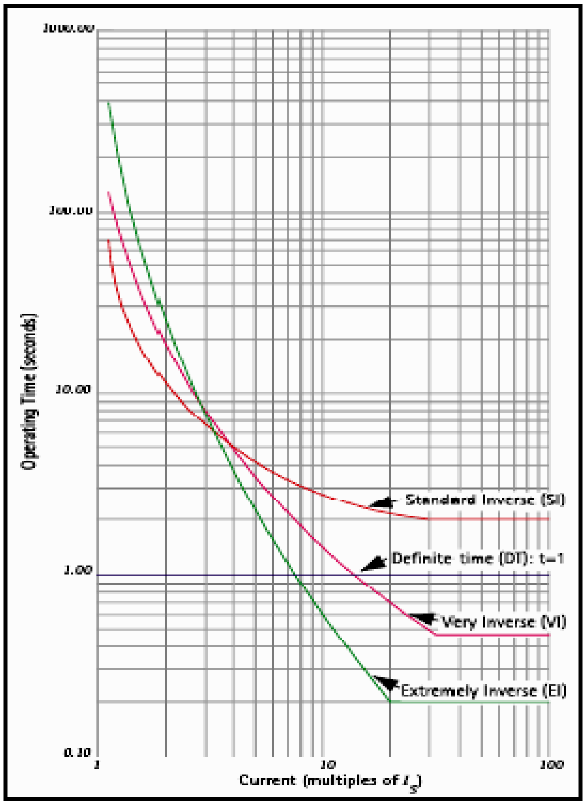


Figure 2-4. Relay characteristic tripping curves [16]

The standard inverse (SI) curve indicated in Figure 2-4 is usually appropriate for most applications. If grading with other protection devices is not adequately achieved, either the very inverse (VI) or extremely inverse (EI) curves can be applied [16].

The characteristic curve normally available on overcurrent relays is the definite time characteristic, which is the straight line ‘curve’ shown in Figure 2-4 above. This characteristic is the focus of the 2007 Westgate incident investigation.

The definite time element of the overcurrent relay indicates that the time for the relay to issue a trip indication is predetermined. As the fault current varies with changes in the source impedance, for co-ordination purposes, this definite time characteristic can be applied in the network where the system fault current fluctuates and a specific current pick-up setting cannot be chosen [14, 16].

When compared to the SI, VI and EI characteristic curves, the definite time characteristic operates faster in the lower current value range, which can be seen in Figure 2-4 [16].

Characteristic curves other than these mentioned above may be provided, including a custom made curve, when a digital relay is applied in a protection scheme [14, 17].

The characteristic curves applied to an overcurrent relay, with the exception of the definite time curve, uses a formula to calculate the relay operation time. This is shown in the Table 2-1 below.

Table 2-1: IDMT tripping time formulas [16]

Relay Characteristic Curve	Equation as per IEC 60255
Standard Inverse (SI)	$T = TMS \times 0.14/(I_r^{\ 0.02} - 1)$
Very Inverse (VI)	$T = TMS \times 13.5/(I_r - 1)$
Extremely Inverse (EI)	$T = TMS \times 80/(I_r^{\ 2} - 1)$
Long time standard earth fault	$T = TMS \times 120/(I_r - 1)$

2.3. SCB protection schemes

This research considers the external system disturbance and fault environment of the SCB.

Therefore a brief description of the protection scheme applied to SCB's for external fault protection is listed below as per ESKOM's Distribution Standard [6], Technology Reference for Power Capacitor Application and Protection [7], and Protection Setting Philosophy for Transmission and Sub-Transmission Grids [10].

2.3.1. Overcurrent protection

The overcurrent relay is used to detect internal short circuits and external faults. The relay should have a minimum current pick-up level of above 135% of the load [6, 10].

The overcurrent relay has two time settings that it could be set to. This is as per [6, 10]:

- Low-set definite time setting:
  This is set to 1.5 times full load current, with a 200 millisecond (ms) time delay setting to prevent operation of the relay for transient conditions.
- High-set instantaneous setting:
  This is set to 3 times full load current if there is only one SCB on the busbar. If two or more SCB's are on the busbar, this is increased to 4 times full load current. Hi-set instantaneous setting has no intentional time delay and is intended for the fast clearance of faults.

2.3.2. Overvoltage protection

Overvoltage protection is required to ensure that the SCB would be removed from the system when the system voltage value exceeds 110% of the manufacturer's continuous voltage rating of the SCB [10, 15]. This is important as overvoltage events severely ages the SCB, especially if the frequency and duration of these overvoltage events are excessive. [7, 10]

To prevent any operation for transient overvoltage conditions and to co-ordinate with overvoltage protection of the system and/or feeder, the overvoltage protection on SCB's is set in definite time mode with a minimum time delay of 200ms. [7, 10]

When a few SCBs are in the same vicinity of the power system, all SCBs cannot be removed simultaneously for overvoltage conditions as this could then cause an under voltage condition.

To cater for the cascade tripping that would be required, the first stage is set to 120% of rated voltage with a 200ms time delay. The second stage would have a time delay increased to 500ms. [10]

2.3.3. Earth fault protection

An overcurrent relay is used on each phase element and frequently an additional current element or relay is used for earth fault protection. This current element or relay measures the neutral current [6, 16].

The pick-up setting value for the earth fault relay is usually between 20%-40% of the full load current or is set to the minimum earth-fault current of the protected zone [14, 35].

The time grading of the earth fault relay is similar to that of the overcurrent phase relays i.e. this relay is co-ordinated with other earth fault devices in the network [14].

The earth fault relay as applied to earthed and unearthed SCB's is described below.

2.3.3.1 Earthed SCB

The earthed SCB's earth fault relay is set as fast as possible, however still graded with the other protection schemes on the bus. This co-ordination would prevent the earth fault relay from operating for external system faults. [10]

The low set earth fault pick-up current value is 20% of the current rating of the SCB. [10]

The high set instantaneous setting should be 3 times the current rating of the SCB if there is only one SCB on the busbar. This is increased to 4 times the SCB current rating if two or more SCBs are on the busbar. This setting has no intentional time delay and is intended for the fast clearance of faults. This is identical to the overcurrent high-set settings so as to cater for high switching currents and back-to-back switching of the SCB's. [10]

2.3.3.2 Unearthed SCB

The residually connected earth fault element, which is derived from the three phase current measuring elements, should be insensitive to harmonics and inrush conditions. [6]

The low-set earth fault pick-up current setting is 20% of the current rating of the SCB. As the setting is measured from the star point, this setting detects earth fault currents higher than 1,2 p.u. on each SCB leg. This setting has an associated definite time mode setting of 200ms. This time delay allows for current transformer (CT) transient behaviour on energisation of the SCB. [10]

The high-set current setting, if available on the relay, should be set 3 to 4 times the low-set setting described above. This amounts to 60% to 80% of rated current of the SCB. Grading with other earth fault protection schemes is not required in the unearthed SCB environment, as the SCB is not connected to earth. [10]

2.4. Electromechanical relays

Electromechanical relays are so named due to the mechanical force it generates from the current flow in one or more windings of a magnetic core/s. This mechanical force is used to then operate a contact. [14]

The different classifications of electromechanical relays are thermal, motor operated, mechanical, moving coil, attracted armature and the induction disc type. [14]

The construction and principles of operation of the two types of electromechanical overcurrent relays used in the practical injection tests i.e. the attracted armature and the induction disc type relays are described below.

Of the electromechanical relays used in the practical injections, the CAG is of an attracted armature type and CDG is of an induction disc type. The difference in operation is as explained below.

2.4.1. Attracted armature type relay

A General Electrical Company (GEC) overcurrent relay was used for the practical portion of this research. A photograph of the CAG39 relay used in the injection tests is shown below.

Figure 2-5. CAG39 Electromechanical overcurrent relay

The CAG39 electromechanical relay is of the attracted armature classification type with a typical construction shown in figure below. [43]

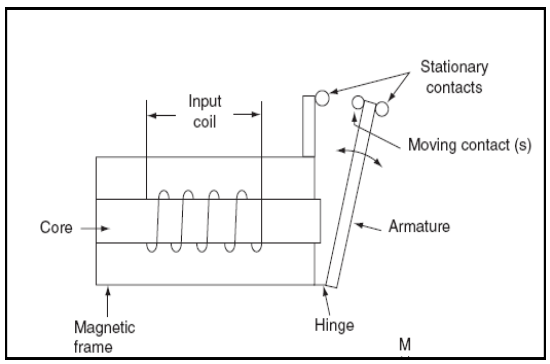


Figure 2-6. Typical electromechanical attracted armature relay [13]

The figure above illustrates a simple solenoid. The CT transforms the input current into a safe levels for the relay. When the input coil exceeds the certain threshold or setting value of the relay, the force induced in the solenoid attracts the armature and its associated moving contact, closing the circuit. [22]

The speed of the relay depends on the magnitude of the input current. However, with no intentional delay, this relay is often referred to as an instantaneous relay. [22]

2.4.2. Induction disc type relay

A GEC earth fault relay was used for the practical portion of this research. A photograph of the CDG16 relay used in the injection tests is shown below.

Figure 2-7. CDG16 Electromechanical earth fault relay

The electromechanical CDG16 relay is of the induction disc classification, with the typical construction shown below. [42]

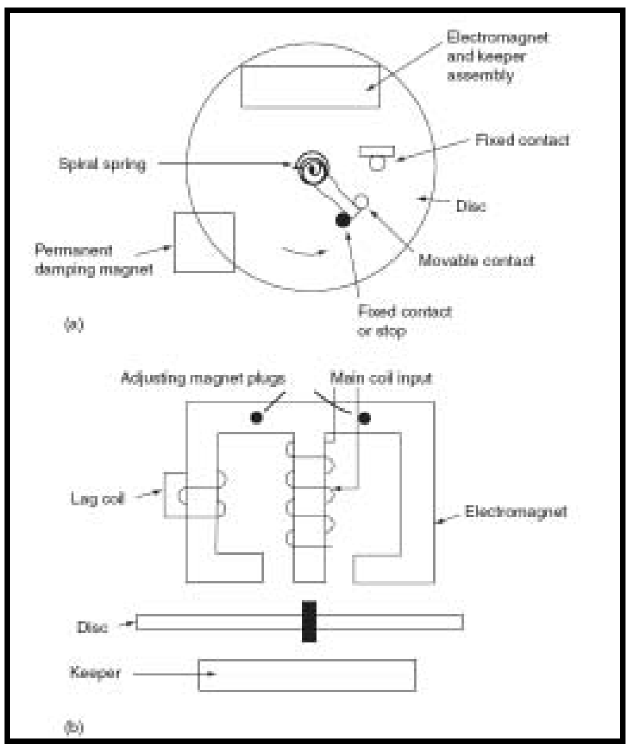


Figure 2-8. Typical induction disc type overcurrent relay: (a) top view; (b) side view [13]

A phase current from a CT is injected into the main coil input via a plug bridge also commonly called the plug setting multiplier (PSM). The PSM varies the number of turns on the main coil and can be adjusted according to the current setting of the relay. [13, 17, 22]

This current sets up a magnetic flux in the electromagnet and consequently induces a current on the lag coil, found on same core. This results in a magnetic flux around each coil, which is out of phase. The magnetic fields established by the coils subsequently induce eddy currents in the disc. [17, 22]

Once the input current into the relay is greater than the spring torque pressure on spindle and the damping magnet, this will now be sufficient to generate a torque that causes the disc to rotate. [17, 22, 34]

The basic current/torque equation as per [34]:

$$\tau = K.\ Im_1\ .\ Im_2\ .\ \mathrm{Sin}\theta \qquad (2\text{-}2)$$

Where K is a constant;

Im_1 and Im_2 are the currents in each coil; and

θ is the phase angle between the currents.

Since the lag coil carries a current that is proportional to the input current, Equation 2-2 can be further simplified as per [34]:

$$\tau = K_1.\ I^2 \qquad (2\text{-}3)$$

Where K_1 includes the term sin θ, which is a constant for the relay [34].

The disc rotates in the direction of the torque, which is from the coil with leading current to the coil with lagging current. It takes with it the movable contact until it closes onto the fixed contact, subsequently issuing a trip indication. The time taken for the contacts to make is dependent on the position of the spindle stop contact, also known as the time multiplier (TM). [17, 22, 34]

The speed of the disc is calculated as per [17]:

$$\text{Speed} = \text{Distance/ Time} = 1/\ I^2 \qquad (2\text{-}4)$$

Equation 2-4 indicates that the speed of relay operation is inversely proportional to the current i.e. for high currents the relay disc would rotate faster and therefore issue a trip signal faster than at low currents [17]. This also explains the characteristic tripping curves seen in Figure 2-4.

In summary, the PSM setting therefore determines the current setting for which the relay disc begins to rotate and the TM setting determines the time in which the relay issues a trip signal.

Once the relay has started to rotate, if the input current should decrease to below the pick-up setting, or drop off altogether, the disc would reverse into its start position due to the pressure of the spring on the spindle [17].

However, there is the possibility that the disc does not reverse direction immediately, due to stored kinetic energy in the disc, possibly causing the electromechanical relay to overshoot and issue an incorrect trip indication [16].

2.5. Electronic relay

A GEC overcurrent relay was used for the practical portion of this research. A photograph of the MCGG63 relay used in the injection tests is shown below.

Figure 2-9. MCGG63 electronic Relay

For the purpose of this work, an electronic relay is defined as a relatively simple analogue-to-digital static or solid-state relay.

The relay response is determined by the use of electronic circuits comprising of elements such as diodes, transistors, transformers, resistors, capacitors, inductors, operational amplifiers and comparators, etc. [17, 22, 23].

A circuit configuration of a solid-state overcurrent relay can be seen in Figure 2-10 below.

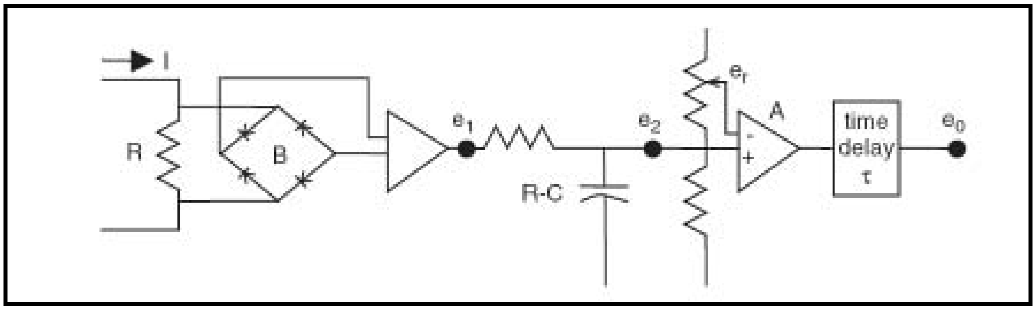


Figure 2-10. Possible circuit configurations of a solid-state overcurrent relay [34]

For this type of relay, the input alternating current (AC) is sometimes converted into an isolated and smaller AC value via a transformer [1, 22]. In the case of Figure 2-10, a shunt resistor is used to reduce the input current [34].

The voltage across the resistor is then converted, via a full-wave bridge rectifier, into a direct current (DC) value proportional to that of the AC input. This output waveform of the relay can be identified as e_1 in Figure 2-11 below. [1, 22, 34]

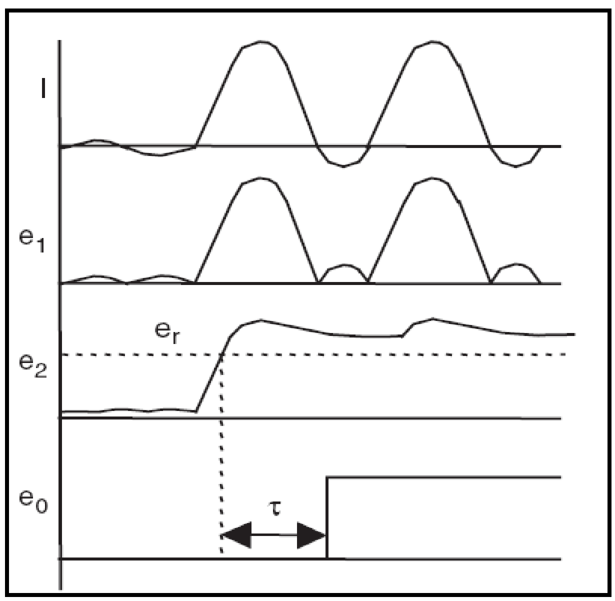


Figure 2-11. Output waveforms of a solid-state overcurrent relay [34]

A filter circuit is then incorporated to eliminate all frequencies except the fundamental frequency that the relay has been designed to operate for i.e. 50Hz or 60Hz. This filter circuit contains a resistor and capacitor [1, 22, 34].

The integral of the filtered and rectified waveform, represented as e_2 in Figure 2-11, is then compared to the relay reference or threshold settings (e_r). If e_2 remains above the e_r value for a predetermined and user defined time delay (τ), the relay would issue a trip indication. [1, 22. 34]

The major advantages of static relays are the increased speed and reliability due to the absence of mechanical parts as found in electromechanical relays [17]. They also have a lower burden, lower maintenance requirements and are more compact in size [22].

Due to their components however, electronic relays are designed to operate in controlled temperature and humidity environments to prevent mal-operations. They also require independent power supplies. [17,22]

2.6. Digital relay

A Schweitzer Engineering Laboratories (SEL) relay was used for this research. A photograph of the relay used in the injection tests is shown below.

Figure 2-12. SEL387 Digital relay

For the purposes of this work, a digital relay is defined as relay that uses a microprocessor with software based protection algorithms (series of instructions and calculations) for the detection of power system faults. Certain manufacturers and resources refer to the digital relay as a numeric relay. [1, 17]

Similar to the electronic relay, the digital relay uses a CT to transform the AC current input into an isolated AC value. The input voltages are also reduced to a safe level by surge filters to protect the internal components of the relay [1, 17, 22].

This relay is very compact and can have more than one protection function or element [1, 22].

The architecture of a typical digital relay is indicated in the image below [24].

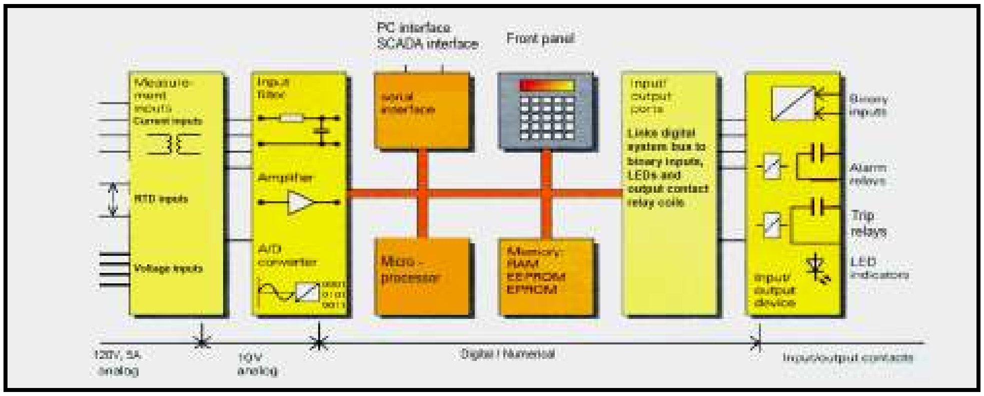


Figure 2-13. Components of a typical digital relay [24]

The input sine wave is also filtered via anti-aliasing filters. This is to remove all unwanted high frequency components for which the relay is not designed to operate. [1, 3, 17, 22]

The filtered signal is fed to an analogue to digital converter. The relay then samples the data. This sampling frequency takes into consideration the Nyquist criterion. [1, 3, 17]

The Nyquist criterion as per [3, 14]:

$$f_s = 2 \,.\, f_h \qquad (2\text{-}5)$$

Where f_s is the sampling rate; and

f_h is the highest frequency to be sampled.

The relay algorithms then process the sampled data into digital outputs. In the memory component storing the relay algorithms, the relay can use Fourier Transforms or Discrete Fourier Transforms to calculate the RMS magnitudes and phase angles of the input signal. [1, 3, 17]

As with all protection relays, the digital relay can compare the measured (and calculated) values to a predefined parameter of the relay settings to determine whether a trip operation is warranted. The digital relay goes a step further in that the relay logic can be used to identify the fault type. [1, 3, 22]

Under normal, balanced power system conditions only positive sequence currents and voltages exist. The relay continually measures the new positive sequence values and compares these to the normal condition (in its sample-and-hold circuits) to determine if a fault exists. Negative phase sequence currents occur when system conditions are unbalanced and therefore can be used for more sensitive, faster and improved fault clearance. [1, 3, 26]

As the digital relay logic can be used to identify the fault type, once the fault type is determined, it can operate appropriately. [2 3, 26]

One advantage of the digital relay is that its logic can be user-defined by means of a configuration file. This can be transferred to the relay via a personal computer (PC). [1]

Another major advantage is the fault event recording capability. This fault record, usually in an oscillograph format, includes input/output changes and the progression of key logic decisions. The record can be downloaded via PC or remote access and is beneficial for fault analysis. [1, 22]

The digital relay also has a self-diagnostic functionality built-in, with warning indications of impending or possible malfunctioning [1, 17]. It also contains advanced metering and communication protocol ports, allowing the relay to be incorporated into the Supervisory Control and Data Acquisition (SCADA) system as per IEC Standard 61850 [24].

The digital SEL relay used in the practical injection tests has one instantaneous, one definite-time and one IDMT element for each phase. It also incorporates negative-sequence, and residual ground currents for measuring purposes [25].

More in depth information regarding the computer relaying algorithms, which does not form part of this work, can be found in [22], [23] and [26].

2.7. Current and frequency calculations

In the literature review of SCB's it was suggested that the normal switching operations of a SCB, and a fault occurrence in the vicinity of the SCB, would cause inrush, discharge and outrush transient conditions consisting of high currents with harmonic content [12, 47, 53].

This phenomenon was investigated to determine its possible effects on an overcurrent relay.

A simplified system illustrated below is used to explain SCB normal switching operations and fault events. This has been adapted from references [8] and [18].

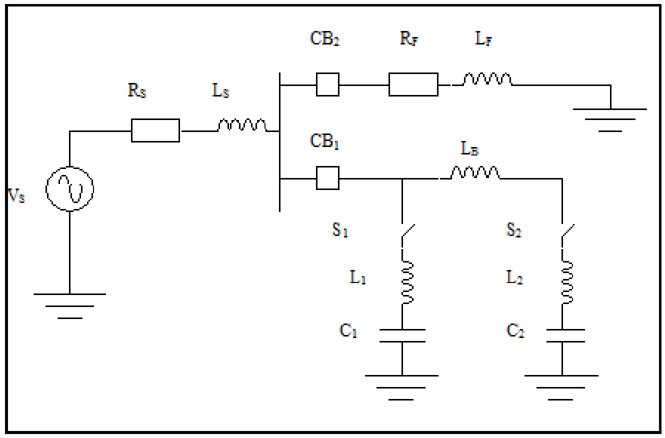


Figure 2-14. Simplified system diagram [8, 18]

The simplified system diagram in Figure 2-14 is further simplified to the circuit representation below. [18]

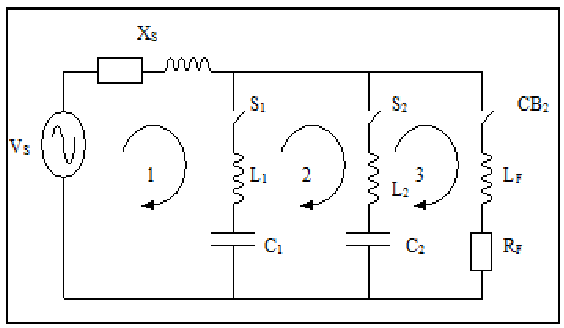


Figure 2-15. Circuit representation to illustrate SCB transients

2.7.1. Single SCB switching

The first transient condition investigated is the switching event of the first SCB, C_1. In Figure 2-16 switch S_1 is closed to determine the inrush current as seen by C_1.

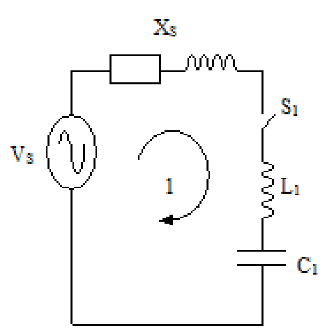


Figure 2-16. Single SCB switching circuit

The inrush current for a single SCB switching operation is calculated below, with equations as per [21]:

$$I_{pk} = \sqrt{2}\ \sqrt{(I_{SC} \cdot I_1)} \qquad (2\text{-}6)$$

Where I_{pk} is the peak inrush current in amperes

I_{SC} is the three-phase fault current in amperes

I_1 is the SCB current in amperes

The I_{pk} current of the capacitor bank to be energised is calculated using the following:

I_1 = 315A as calculated by Equation 2-1; and

I_{SC} = 16,83kA, as determined by EMT fault study on DigSILENT

$$I_{pk} = \sqrt{2}\ \sqrt{(I_{SC} \cdot I_1)}$$
$$= \sqrt{2}\ \sqrt{(16{,}83 \cdot 10^3 \cdot 315)}$$
$$= 3256\text{A}$$

It can be seen that for a single SCB switching event, the inrush current into the bank being energised would exceed the definite time overcurrent pick-up setting of 472A and the instantaneous overcurrent pick-up setting of 1260A.

The frequency of this inrush current can be calculated as per [21]:

$$f_{(hertz)} = f_s \cdot \sqrt{(I_{SC} / I_1)} \qquad (2\text{-}7)$$
$$= 50 \cdot \sqrt{(16{,}83 \cdot 10^3 / 315)}$$
$$= 365{,}5\text{ Hz}$$

Where f_s is the power system frequency of 50Hz is used.

It can be seen that for a single SCB switching event produces a high frequency inrush current of the seventh harmonic order.

2.7.2. Back-to-back SCB switching calculations

The term back-to-back switching as applied to SCBs refers to the switching in of a second SCB when an existing SCB is already energised [21].

This event is depicted in Figure 2-17 where switch S_1 is already closed and C_1 has achieved steady state operation conditions. Switch S_2 is to be closed to energise C_2.

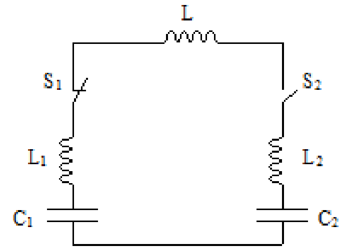


Figure 2-17. Back-to-back SCB switching circuit

The calculations for the inrush current and frequency for a back-to-back SCB switching operation is presented below, with equations as per [21]:

$$I_{pk} = 13500 \sqrt{[V_{LL} . (I_2.I_1) / (f_s . L_{eq} (I_1 + I_2))]} \qquad (2\text{-}8)$$

Where I_{pk} is the peak inrush current, in amperes

V_{LL} is the maximum line-to-line voltage, in kV

I_1 is the current in SCB being switched, in A

I_2 is the current of the SCB already energised, in A

L_{eq} is the total equivalent inductance per phase between SCB's, in µH

Equation 2-8 can be simplified further when the SCB to be switched is equal to that of SCB already energised, as per [21]:

$$I_{pk} = 9545 \sqrt{[V_{LL} . I_1) / (f_s . L_{eq})]} \qquad (2\text{-}9)$$

The I_{pk} current of the capacitor bank to be energised is calculated using Equation 2-9:

$$I_{pk} = 9545 \sqrt{[132 . 315) / (50 . 200)]}$$

$$= 19,46 \text{ kA}$$

Where L_{eq} = 200µH (assuming a 200m cable between the SBC's); and 1µH/m [21].

It can be seen that for a switching event of a second SCB, with C_1 already energised, causes an extreme inrush current into the second bank. This is a more onerous scenario than the single SCB switching event. Again, this would exceed a definite time overcurrent pick-up setting of 472A and the instantaneous overcurrent pick-up setting of 1260A.

The frequency of the transient inrush current is calculated in kHz, with an equation as per [21]:

$$f_t = 13,5 . \sqrt{[f_s .V_{LL} / (L_{eq}.I_1)]} \qquad (2\text{-}10)$$

$$= 13,5 . \sqrt{[50 .132 / (100. 315)]}$$

$$= 6\,200 \text{ Hz}$$

Again it is noted that the back-to-back SCB switching event produces a high frequency inrush current of a high harmonic order.

2.7.3. Outrush current and frequency calculations

The term "outrush current" is used to describe the high magnitude and high frequency discharge current of the SCB due to external fault in the vicinity of the SCB [12].

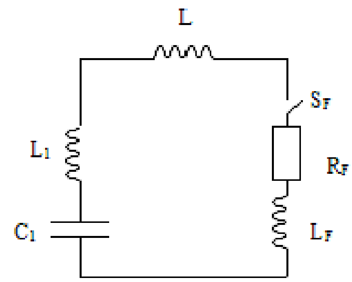


Figure 2-18. External fault in SCB vicinity

An external fault is depicted in Figure 2-18 where C_1 is already in service and has achieved steady state operation conditions. Switch S_F is to be closed to simulate the fault condition. The associated fault impedance, R_F and L_F, is ignored in the calculation below so as to determine the peak current.

The calculations for the inrush current and frequency for this system disturbance is presented below, with equations as per [12]:

$$I_{pk} = V_0 \, . \sqrt{(C_1 / L_{eq})} \quad (2\text{-}11)$$

Where I_{pk} is the peak inrush current, in amperes

C_1 is the capacitance of the SCB, in μF

V_0 is the initial voltage on C_1, in kV

L_1 is the self-inductance of C_1, in μH

L is the inductance of between the fault location and C_1, in μH

L_{eq} is the sum of L_1 and L_2, in μH

To determine C_1, with equations as per [18]:

$$X_c = V / (\sqrt{3}. I_1) \quad (2\text{-}12)$$

$$= 132 \, . \, 10^3 / \, (\sqrt{3} \, . \, 315)$$

$$= 242 \, \Omega$$

Also, $X_c = 1 / (2. \pi .50. C_1)$

therefore, $C_1 = 13{,}2$ μF.

The peak inrush current can now be calculated by substituting the above into Equation 2-11:

$$I_{pk} = 132.\ 10^3\ .\ \sqrt{(13{,}2\ .\ 10^{-6}\ /\ 300\ .\ 10^{-6})}$$

$$= 27{,}69\ kA$$

Where L_{eq} = 300μH (assuming a 300m distance between the SBCs and the fault location); and 1μH/m [18].

It is noted that the peak outrush current is determined by the SCB voltage at the instance of circuit breaker opening, the SCB capacitance and self inductance, and the inductance between the SCB and the fault location [48].

Transient discharge current frequency is calculated assuming a distance of 300m to the fault, with equations as per [21]:

$$f_t = 1/\ [2\pi\ \sqrt{(L_{eq}.C_1)}] \qquad (2\text{-}13)$$

$$= 1/\ [2\pi\ \sqrt{(13{,}2\ .\ 10^{-6}\ .\ 300\ .\ 10^{-6})}]$$

$$= 2529\ Hz$$

The calculation for an external fault event in the SCB environment indicates a high frequency inrush current. It is noted that the frequency is significantly affected by the inductance between the SCB/s and the fault location.

Therefore, for an unearthed SCB, a close-in 3P bolted fault would be worst-case scenario to generate a high discharge current. For an earthed SCB, the worst-case scenarios could be a 3P-to-earth or a SLG fault. [21]

2.8. Factors that influence SCB discharge current

2.8.1. Source impedance

In the case of a single SCB switching operation, the source impedance plays a crucial role in determining the inrush current and inrush current frequency. This is as the source impedance is greater than the SCB inductance. [21]

The affect of the source impedance is less significant on the back-to back switching events and on the external fault occurrences, where the impedance of the discharge loop is lower than that of the source impedance [18, 54]. These discharge loops can be seen in Figure 2-17 and Figure 2-18.

2.8.2. Point on wave of fault occurrence

A simulation of a fault occurrence at system voltage zero, extracted from [38], is presented below. No harmonics can be seen on the current waveform.

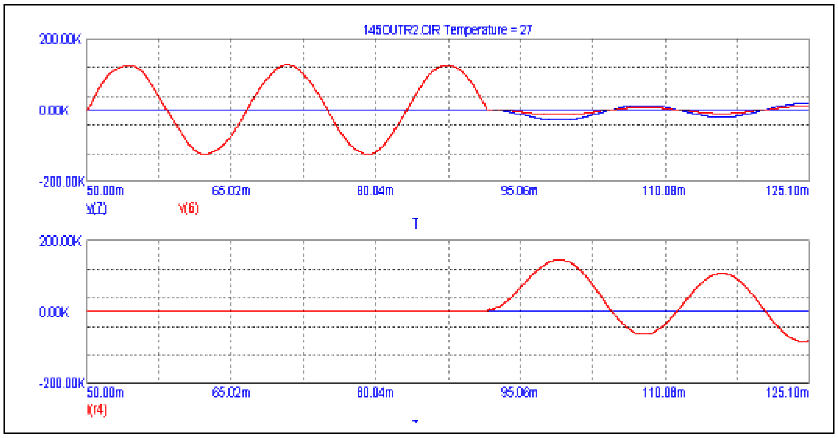


Figure 2-19. Fault at voltage zero [38]

As most faults occur when the system voltage is at the peak of the sinusoidal waveform or near a voltage peak [49], the above is usually unlikely.

A simulation of a fault occurrence at a system peak voltage, extracted from [38], is presented below.

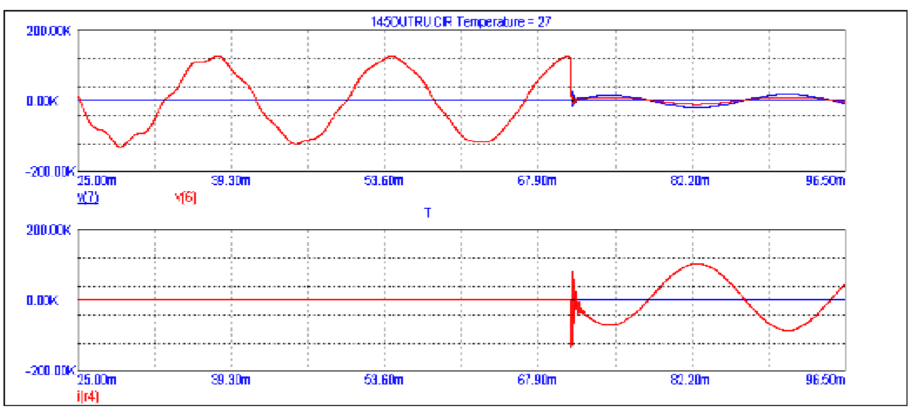


Figure 2-20. Fault occurrence at voltage peak [38]

Harmonics can be seen on the current waveform at the instance of the fault occurrence. The current can be seen exceeding the maximum 20kA allowed by ANSI/ IEEE Standards C37.012. As the high current decreases within a half cycle, the current would still be within the associated circuit breakers peak current capability [38].

However in practice, a current limiting reactor (CLR) would need to be installed to limit the current [38].

2.8.3. Application of a CLR

This section of research was conducted to determine if the discharge current of a SCB changed significantly with the use of a CLR.

A simulation conducted in [38] for a fault occurrence at a voltage peak without a CLR was shown in Figure 2-20. It indicates harmonics and an extreme peak in the current waveform [38].

This simulation was repeated with a CLR to limit the discharge current. The current limiting effect of the CLR can be seen in Figure 2-21.

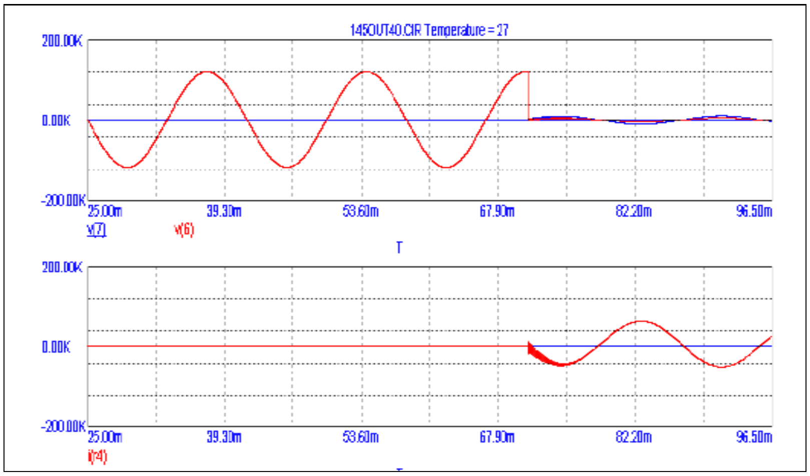


Figure 2-21. Fault occurrence at voltage peak with CLR [38]

This figure suggests that there is no extreme peak current and confirms the current limiting effect of the CLR when compared to Figure 2-20. However, harmonics are still present for a number of cycles [38].

2.9. Summary of factors affecting SCB discharge current

In summary, as per [21, 38, 48 and 57], the peak current and the frequency of this transient current are determined by the following factors:

- source impedance;
- the point on wave of the voltage waveform at which the fault occurs;
- the charge of the capacitor bank at the instance of switching;
- the inductance, capacitance and damping resistance of the circuit for the specific switching event or system fault; and the
- vicinity to distribution loads that contribute to harmonics.

These factors highlight that EMT simulations studies would be the most appropriate method to determine the transient current for new and existing SCBs. These simulations would have to be injected into the overcurrent relays to determine their performance in the SCB environment.

2.10. Previous research on relay performance

The literature review conducted to attain information for the exact topic of overcurrent relay performance, or a comparison of overcurrent relay technologies, as applied to the specific environment of SCB's was not readily available.

The scope for the literature review was therefore increased to find a comparison of overcurrent relay technology and their performance in a harmonic environment. In the SCB environment these harmonics are due to the switching inrush currents and the discharge currents for external fault occurrences [8, 28, 31].

The following inverse time overcurrent relays (ITOCR) performance was extracted from [9] where an ITOCR was injected with a current containing harmonics.

Each numbered mode in the tables below reflects a change in the harmonics of the inject current. The corresponding total harmonic distortion (THD) is also shown for each current injection.

Table 2-2: Pick-up values of ITOCR at different modes [9]

Mode	α	I_1 (A)	I_{rms} (A)	THD_i(%)
0	0°	1.0975	1.10	6.0010
1	30°	1.1422	1.20	35.3101
2	60°	1.2177	1.30	46.0880
3	90°	1.3352	1.60	68.9976
4	120°	1.3888	1.68	70.6527
5	150°	1.4583	1.90	85.8677

It can be seen from Table 2-2 above that the RMS pick-up current of the ITOCR increases for each mode or current injection with increased THD.

Table 2-3: Operating time of ITOCR at different modes [9]

Mode	I_{rms} (A)	THD_i (%)	t (s)
0	2.00	6.43	4.634
1	2.00	27.45	5.268
2	2.00	35.12	5.984
3	2.00	59.50	8.682
4	2.00	65.23	9.582
5	2.00	85.20	14.964

It can be seen from Table 2-3 above that the operating time of the ITOCR increases for each mode (current injection of increased THD).

These research results are incorporated in Figure 2-22 below.

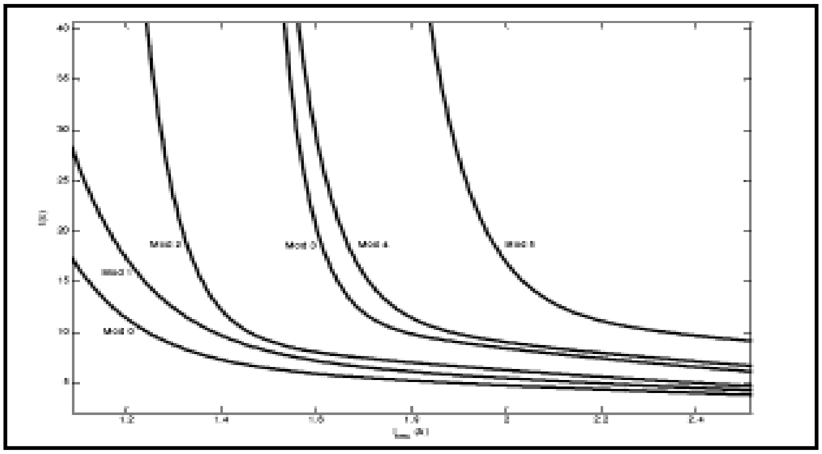


Figure 2-22. ITOCR Operating time vs. RMS current for various modes [9]

These curves show that the electromechanical ITOCR were susceptible to current harmonics in practical studies undertaken by Dalci et al [9]. This experiment concluded that both "*the pick-up current and the operating time of the ITOCR increase proportionally to the THD value of the non-sinusoidal current*". [9]

Yumurtaci et al [27] conducted a similar study on electromechanical instantaneous overcurrent relays and this again showed that the pick-up current would increase as the harmonics in the injected current increased. [27]

Another research paper conducted by Wichita State University, [32], investigated how harmonics affected relays. This research showed that 30% of the relays tested would fail to meet manufacturer specifications when injected with a 20% distortion in current. This practical research was carried out in 1994 on 29 relays widely used in the Kansas Electric Utility and included all relay types. [32]

It should be noted however that the technology applied to the digital relay technology has improved greatly since 1994, and most digital relay designs can calculate the 50Hz fundamental waveform from the input waveform. [1, 13]

2.11. Summary

This chapter provided a brief overview of a SCB, its construction and the reasons for their application in the power system network. The protection schemes used to protect SCBs were identified, including the function of an overcurrent and earth fault relay, which were also explained.

The basic measuring principles of the different technology of relays applied in the ESKOM SCB environment were presented. Modern digital relays have advanced sampling and filtering circuits while electronic relays have simple filter circuits comprising of capacitors and resistors. Electromechanical relays have no special filtering circuits. It is therefore concluded that the technology of the overcurrent relay determines it's vulnerability to harmonics.

Also presented were current and frequency calculations showing the impact of normal switching events of a single SCB, back-to-back switching and external system fault occurrences. These calculations showed transient currents with high peak values and containing high frequencies.

The literature review indicated that electromechanical and some electronic overcurrent relays were vulnerable in a harmonic environment. This suggests that the application of these overcurrent relays in the SCB environment could lead to incorrect and unreliable protection operations.

In addition, the various factors affecting the SCB discharge transient currents were presented above. These factors highlight that EMT simulations studies would be the most appropriate method to determine the transient current for new and existing SCBs.

Finally, the findings from previous research on the performance of different relay technologies, including the overcurrent relay technology, were presented. From this literature survey it is concluded that the electromechanical and the electronic (pre 1994) overcurrent relays were susceptible to harmonics.

3. MATLAB RMS SIMULATIONS

This chapter presents the MatLAB preliminary fault study for the Westgate SCB No.2 that tripped on 10th October 2007. It also presents the overcurrent relay settings as applied at Westgate substation.

The objective of presenting the MatLAB simulations to determine if the overcurrent relay operation for the 2007 incident at Westgate substation was warranted, when compared to the definite time overcurrent relay settings. Further simulations were conducted to identify possible protection operations of the overcurrent relay, due to a definite time overcurrent protection settings.

3.1. Westgate substation layout

Illustrated in the figure below is the single line diagram of the Westgate Substation, as per DigSILENT [19].

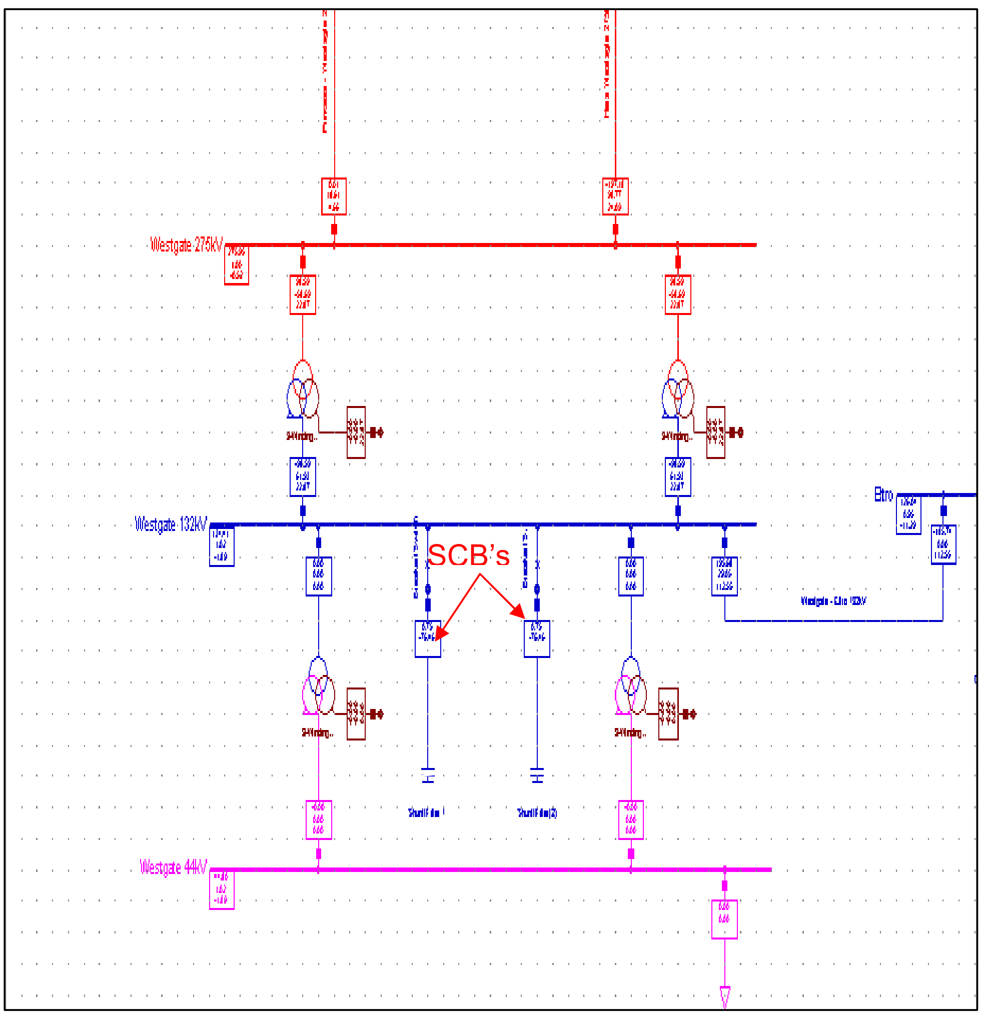


Figure 3-1. Westgate substation layout [19]

The SCB's can be seen in the Westgate Substation layout above on the 132kV busbar. Westinghouse was the manufacturer of each SCB, with a nameplate rating of 72Mvars.

The capacitor banks are externally fused and consist of 4 stacks in series, with 9 capacitor units per stack [41]. Further SCB details were obtained from TIPPS [41] and are provided in Appendix A-9.

The simulation results show the current as seen by the overcurrent relay CT's of SCB No.1 and SCB No.2.

3.2. Overcurrent protection scheme and settings

The overcurrent settings for the Westgate SCB's are presented below in Table 3-1.

Table 3-1: Westgate Overcurrent Protection settings [35]

SCB	Protection Description	Relay Type	Current Pick-up Setting	Time Setting
1	Overcurrent (Definite Time)	GEC CAG39	1.2A	0.2 Sec (via external timer)
2	Overcurrent (Definite Time)	GEC MCGG63	1.2A	0.2 Sec
2	Overcurrent Instantaneous	GEC MCGG63	4A	Instantaneous

It is noted that the CAG39 overcurrent relay is of the instantaneous type. However, at Westgate substation this relay is applied in series with an external overcurrent timer RXKT 22. The timer is set in definite time configuration with a time delay of 200ms. [35]

3.2.1. Time delay current pick-up setting calculation

The current pick-up settings as per the Transmission Protection settings database are identical for both the Westgate SCB's [35].

The rated current of the SCB is calculated below:

$$I_{Rated} = \text{Mvar}/ (\sqrt{3}.\text{kV}) = 72/ (\sqrt{3}.132\text{kV}) \quad (2\text{-}1)$$
$$= 314{,}92 \text{ A}$$

Where the Mvar rating of the SCB bank is 72Mvar and the voltage level is 132kV.

The maximum primary current permitted is 150% of the rated current and is calculated below:

$$I_{Prim} = 1{,}5 \,.\, I_{Rated} \quad (2\text{-}2)$$
$$= 1{,}5 \,.\, 314{,}92$$
$$= 472 \text{ A}$$

This 472A is the pick-up current setting for the time delay element of the overcurrent relay, as seen on the primary side of each phase CT.

3.2.2. Instantaneous current pick-up setting calculation

The instantaneous current pick-up setting is calculated as per the Transmission Protection settings database [35]. This states that the maximum overcurrent permitted when two banks are in parallel is 400% of the rated load current.

$$I_{Prim} = 4 \cdot I_{Rated} \qquad (2\text{-}3)$$
$$= 4.\ 314{,}92$$
$$= 1259{,}68A$$

This is the value of current, as seen by the CT primary, for the instantaneous element setting of the overcurrent relay.

3.3. MatLAB simulations

In MatLAB, a simplified model of Westgate Substation comprising of two unearthed 72Mvar SCB's with a three phase source and the 132kV Eltro Feeder was created. The Westgate Substation is illustrated below is as modelled in MatLAB [45].

Westgate SCB No.1 is indicated by a yellow oval on Figure 3-2. On the same figure, the three phase fault applied on the 132kV Eltro feeder is indicated by the blue oval. This replicates the 2007 Westgate incident.

The oscilloscope associated with SCB No.1, Scope 3, is used to view the root mean square (RMS) values of all three phase primary currents, as seen by the overcurrent relay CT's. The purple oval on Figure 3-2 highlights Scope 3.

Similarly, the RMS current waveforms of the SCB No.2 can be viewed using Scope 4 for the different fault scenarios indicated below.

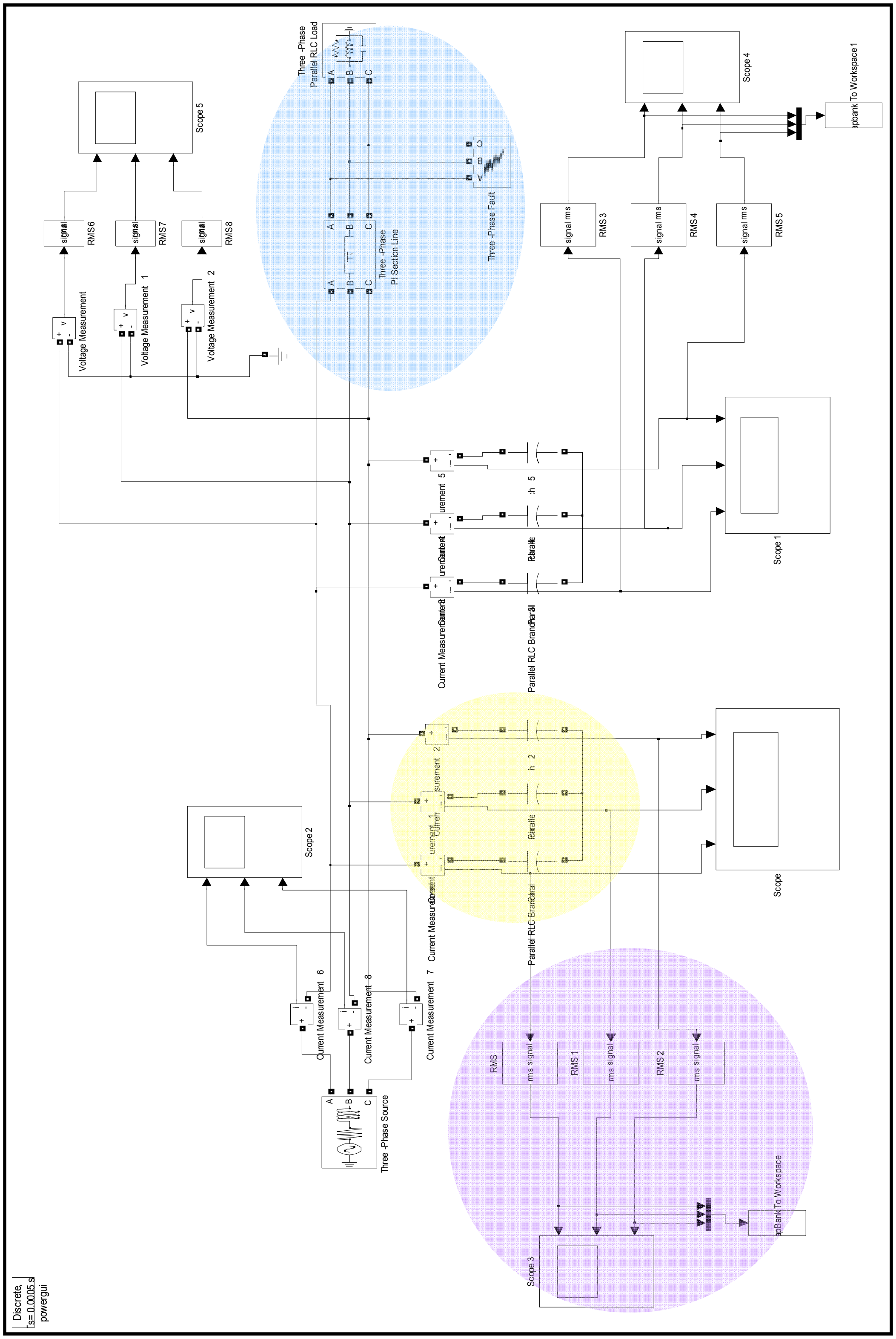


Figure 3-2. Equivalent Westgate substation layout in MatLAB

(This drawing is shown in a larger print in Appendix A-1 and A-2)

3.4. MatLAB simulation findings

3.4.1. A three phase fault on the Eltro Feeder as seen by SCB No.2

This simulation recreates the 2007 incident of a close-in three phase (3P) fault at Westgate substation.

The graph below shows the RMS phase currents for a 3P fault at 1km from Westgate substation, on the 132kV Eltro feeder. A fault duration of 700ms was used for this simulation as the Eltro feeder protection failed to operate and clear the feeder fault as expected.

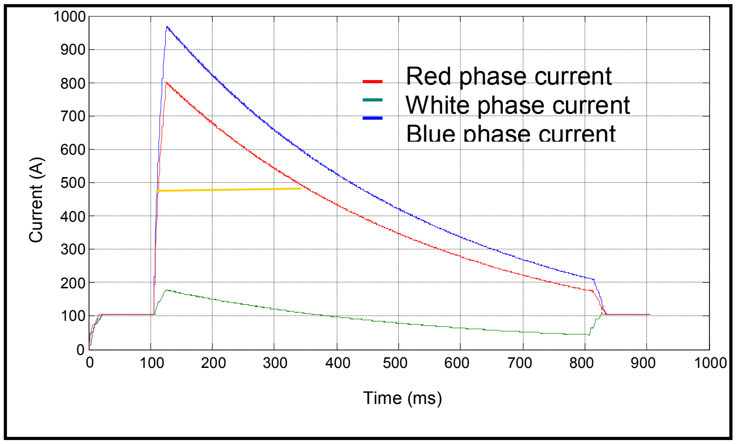


Figure 3-3. SCB No.2: 3P fault, 700ms fault duration 1km from Westgate

The yellow bar indicated on the graph is an approximation of the overcurrent relay pick-up level of 472A and a time of 200ms to correspond to the overcurrent relay's definite time delay setting.

The simulation shows that the overcurrent relay's definite time element would detect the current above 472A and would issue a protection operation after the 200ms time delay. This can be seen for both the red and blue phases.

The instantaneous element of the overcurrent relay was not relevant in this simulation as a primary current level of 1260A was not reached. This indicates that the instantaneous element of the relay would not issue a protection operation. A protection operation is commonly referred to as a trip operation.

This simulation provides some confirmation that an operation of definite time delay element of the overcurrent relay would be possible i.e. it operated according to the definite time overcurrent settings for a close-in three phase fault with a 700ms fault duration.

The simulation above was repeated with a 100ms fault duration. This is to show a comparison of SCB input current in the event that the Eltro feeder protection had operated within 100ms and cleared the feeder fault as expected. This simulation is shown below in Figure 3-4.

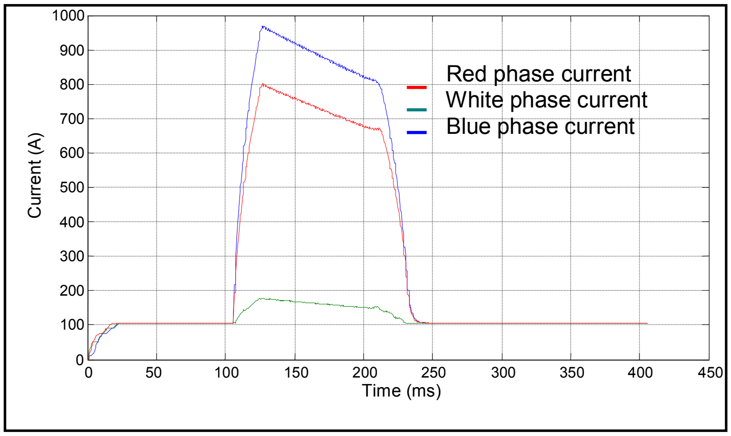


Figure 3-4. SCB No.2: 3P fault, 100ms fault duration 1km from Westgate

This simulation indicates that the overcurrent relay would detect the currents above 472A but would not issue a trip output for a short duration fault and/or if the Eltro feeder protection cleared the fault in time.

3.4.2. A three phase fault on the Eltro Feeder as seen by SCB No.1

The graph shows the RMS phase currents for a close-in 3P fault on the 132kV Eltro feeder, with the 700ms fault duration. The current seen by SCB No. 1, seen in Figure 3-5 below, is identical to the currents as seen by SCB No. 2 in Figure 3-3.

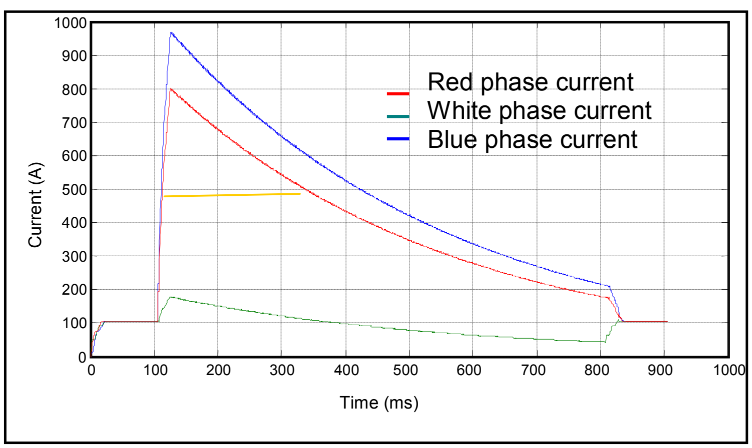


Figure 3-5. SCB No.1: 3P fault, 700ms fault duration at 1km from Westgate

The RMS currents in Figure 3-3 and Figure 3-5 indicate that an overcurrent relay would detect the current above 472A and would issue a trip after 200ms. This simulation indicates that the overcurrent relay would operate according to the overcurrent protection settings. However, the GEC CAG39 overcurrent relay utilised by SCB No. 2 did not issue a trip output for the 2007 fault incident at Westgate substation.

The RMS phase current for a close-in 3P fault on the 132kV Eltro feeder, with fault duration of 100ms, is shown above in Figure 3-6.

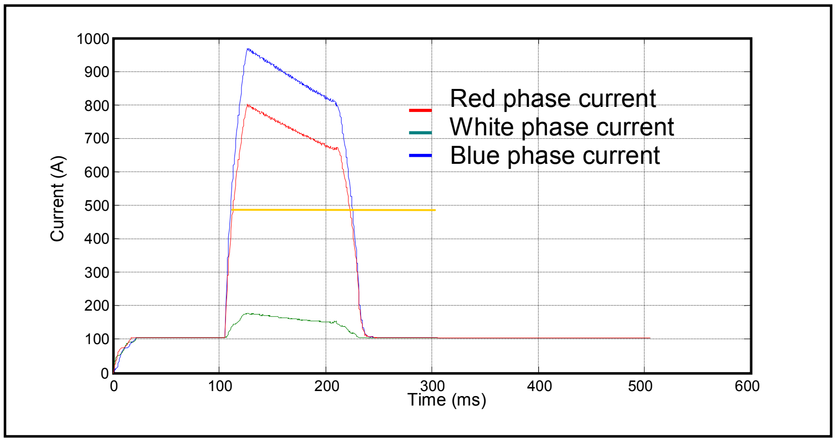


Figure 3-6. SCB No.1: 3P fault, 100ms fault duration 1km from Westgate

This is identical to Figure 3-4 as seen by SCB No.2 and the same findings would apply.

3.4.3. Faults on the 132kV Eltro Feeder

3.4.3.1 Single-phase earth fault

The graph below shows the RMS phase currents for a close-in single-phase earth fault (SLG) on the 132kV Eltro feeder. A fault duration of 100ms was used as the 700ms fault duration had no impact on this simulation.

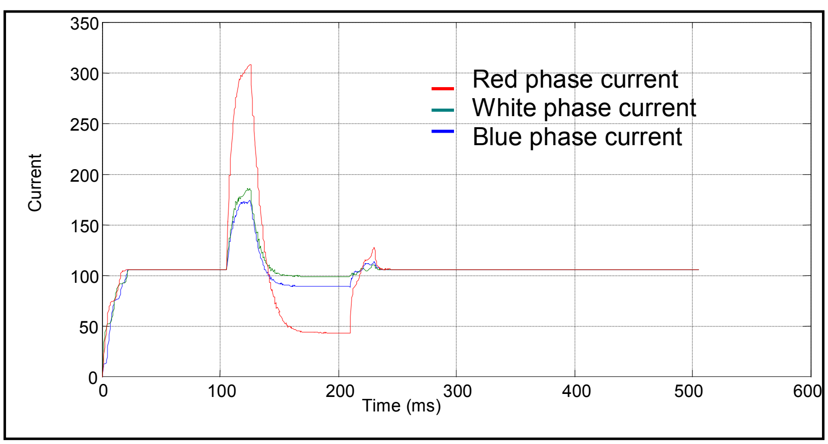


Figure 3-7. SLG fault; 100ms fault duration at 1km from Westgate

The figure above indicates shows that the overcurrent relay would not detect a fault as the currents are below 472A. It would therefore not issue a protection operation trip for short duration SLG faults and/or if the Eltro feeder protection cleared the fault in time. This simulation and analysis thereof is the same for SCB No.1.

3.4.3.2. Double line-to-ground fault

The graph below shows the RMS phase currents for a close-in double line-to-ground (DLG) fault on the 132kV Eltro feeder. A fault duration of 700ms was used for this simulation, as the Eltro feeder protection failed to clear the fault in time.

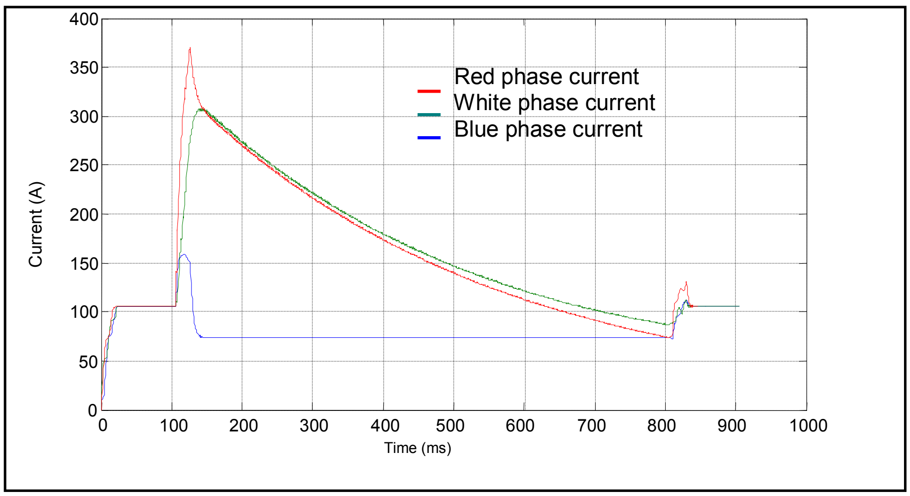


Figure 3-8. SCB No.2: A DLG fault, 700ms fault duration at 1km from Westgate

The simulation shows that the overcurrent relay would not detect currents below 472A and would therefore not issue a trip for this DLG fault. This simulation and analysis thereof is the same for SCB No.1.

3.5. Summary

This chapter presented the MatLAB simulations of the Westgate incident.

The analysis of these results indicated that all overcurrent relays could issue a protection trip for a long duration close-in 3P fault i.e. the overcurrent relay would operate according to the 200ms definite time overcurrent settings.

This was deduced from RMS currents, as seen by the CT's, when compared to the definite time overcurrent relay settings implemented at Westgate substation. This finding was applicable to both the overcurrent relay applications for Westgate SCB No1. and SCB No.2.

The short duration fault simulations of a close-in 3P fault indicated that the overcurrent relay would not operate or issue a protection trip signal. This finding was again applicable to both SCB overcurrent relay applications.

Further MatLAB simulations indicated that no other overcurrent protection operations where likely for other fault types or locations.

DigSILENT EMT simulations where conducted to compare with the MatLAB results and are presented in Chapter 4.

4. DIGSILENT EMT SIMULATIONS

DigSILENT EMT simulations were completed using the Westgate substation model from the ESKOM transmission file, [19], and the DigSILENT overcurrent relay models available. The layout for Westgate substation was shown in Figure 3-1.

The 60km Eltro feeder involved in the fault simulations was modelled using distributed line parameters for each fault location. This was done for an accurate calculation of the impedance to the fault.

The objective of this chapter is to present the following:

- provide an understanding of DigSILENT overcurrent relay models
- determine the operation of the DigSILENT overcurrent relay models due to a definite time overcurrent protection settings; and to
- compare DigSILENT and MatLAB simulations results. This is to determine which simulation package could be used for by ESKOM PSOP department for future fault investigations that may require overcurrent relay simulations.

4.1. DigSILENT relay models

Indicated in Figure 4-1 and 4-2 below are the relay logic diagrams of the MCGG and CAG overcurrent relays as extracted from [19].

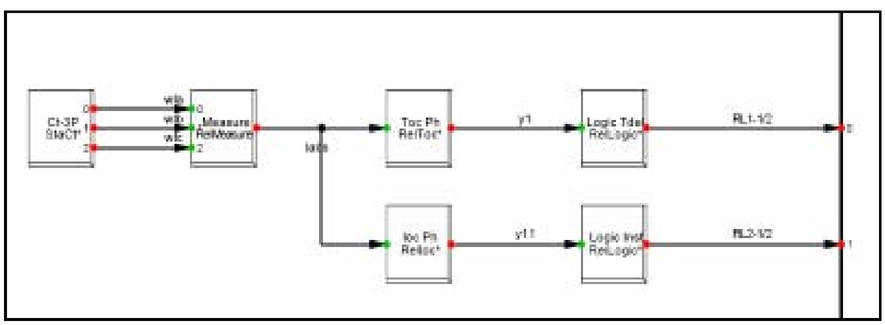


Figure 4-1. DigSILENT MCGG63 Overcurrent Relay Logic Diagram [19]

The MCGG relay logic diagram above indicates the definite time and instantaneous elements that are available in the relay i.e. Logic Tdel RelLogic and Logic Inst RelLogic blocks respectively. [19, 51]

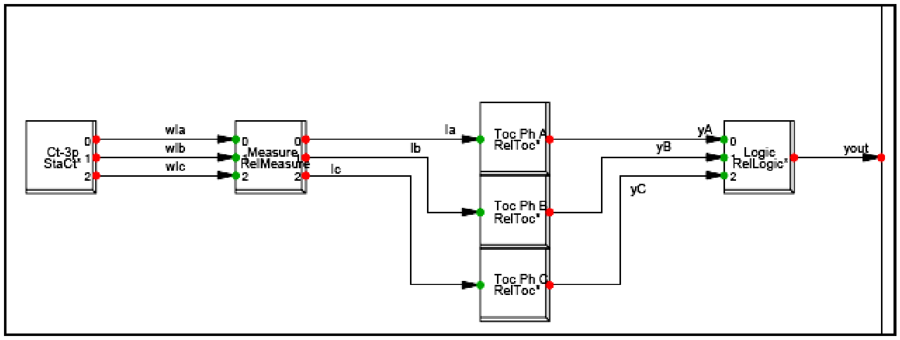


Figure 4-2. DigSILENT CAG Overcurrent Relay Logic Diagram [19]

The CAG relay logic diagram indicates it has an instantaneous element and as such, the DigSILENT relay model has no time delay setting. [19, 51]

The characteristic curves indicate that the CAG relay model has only an instantaneous setting as per manufacturer's manual [19, 43]. The DigSILENT CAG relay model therefore does not have an associated time delay setting [19].

The DigSILENT MCGG relay model has an instantaneous and a definite time setting, also as per manufacturer's manual [19, 23]. However, the definite time delay can only be set up to a maximum of 100ms [56].

It is also noted, from the CAG and MCGG relay logic diagrams, that these models employ the same RelMeasure block to measure the input current. This measurement block does not contain any digital filtering functions. [51]

The output from the RelMeasure block is shown in the figure below.

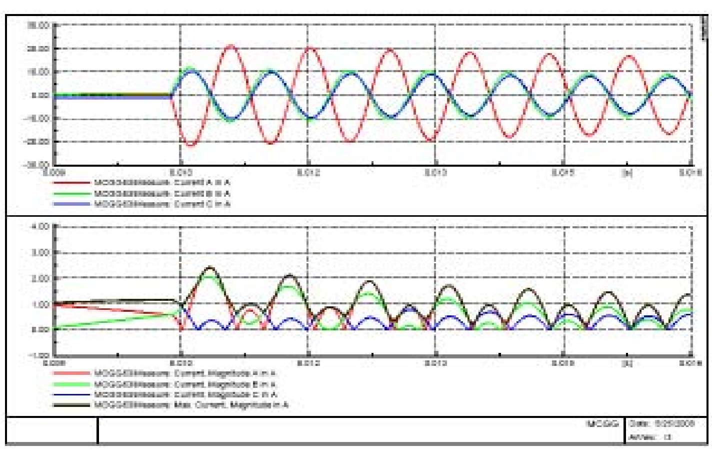


Figure 4-3. MCGG RelMeasure output [19]

This output of the RelMeasure block is identical for both the CAG and MCGG overcurrent relay models. This suggests that in DigSILENT simulations these relays would measure the input current in an identical manner. [51, 56]

Therefore, in DigSILENT EMT studies, these relays should operate identically and any difference in the operation is as a consequence of the definite time delay setting. This is confirmed below in Figure 4-4 where there is no time delay setting on the MCGG relay model. This was done so as to compare the MCGG relay model to the instantaneous CAG relay model.

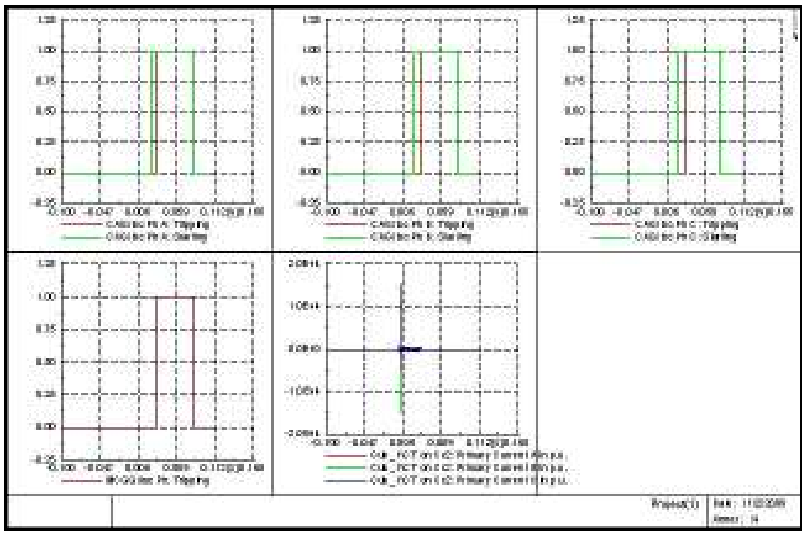


Figure 4-4. DigSILENT CAG and MCGG relay output indications [19]

Figure 4-4 indicates that the CAG and MCGG overcurrent relays trip approximately at the same time for a 3P fault on the Eltro feeder i.e. 30ms and 35ms respectively. This confirms that the DigSILENT MCGG and CAG relay models operate identically. [56]

As the DigSILENT relay models could not be set as they were in the Westgate SCB application, further testing of the DigSILENT relay models was discontinued. The reasons for this were as follows:

- the DigSILENT CAG relay was modelled as an instantaneous relay as opposed to the definite time application (with an external timer) at Westgate;
- MCGG relay models has a maximum definite time delay of 100ms, as opposed to the 200ms definite time application at Westgate substation;
- amending the standard DigSILENT relay models, for the detailed analysis of relay operations and to reflect all differences more precisely, was outside the scope of this research.

4.2. DigSILENT simulations

RMS waveforms obtained from the DigSILENT EMT fault simulations were analysed to determine if a definite time overcurrent trip operation is likely. This will also be compared to the RMS waveforms obtained from MatLAB.

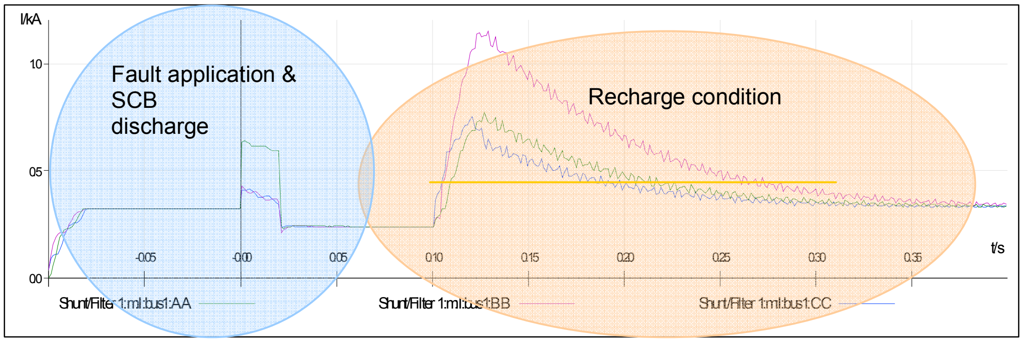


Figure 4-5. 3P fault at 1% from Westgate 132kV Busbar (100ms fault duration)

The figure above shows that during a fault application, the SCB discharges itself into the fault. After this discharge condition, the SCB current stabilises at a lower current level due to the depressed voltage created by the fault. Once the fault is cleared, the voltage increases to the nominal busbar voltage and the SCB would recharge back to this voltage.

The above simulation establishes that the fault itself was not the only phenomenon to be considered when identifying the possibility of an overcurrent relay protection operation in the SCB environment.

A protection operation could occur in the recharge condition of the SCB. The current can be seen rising above the 472A pick-up value of the overcurrent relay after the feeder fault has cleared i.e. in the recharge condition of the SCB.

The fault portion of this simulation, indicated in blue area on the diagram above, can be compared to the MatLAB simulation indicated in Figure 3-4. The MatLAB simulation, however, does not indicate the recharge condition of the SCB.

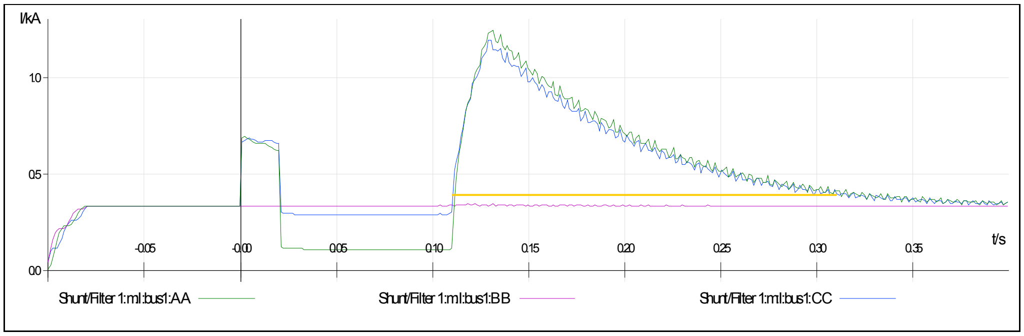


Figure 4-6. L-L fault at 1% from Westgate 132kV busbar

Figure 4-6 above indicates the RMS phase currents for a L-L fault. Again, a protection operation is very likely as the current exceeds the 472A pick-up setting, in the discharge condition of the SCB, for the required 200ms definite time delay setting.

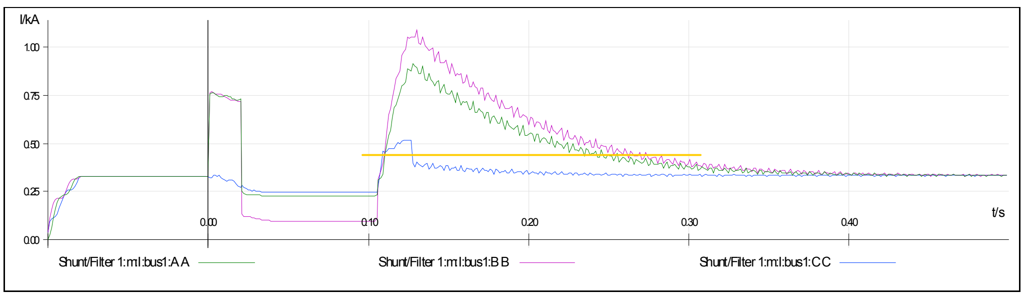


Figure 4-7. DLG fault at 1% from Westgate 132kV busbar

Figure 4-7 above indicates that the overcurrent relay would detect the DLG fault. However, a trip operation is unlikely as the current does not exceed the 472A pick-up current for the required 200ms definite time delay setting.

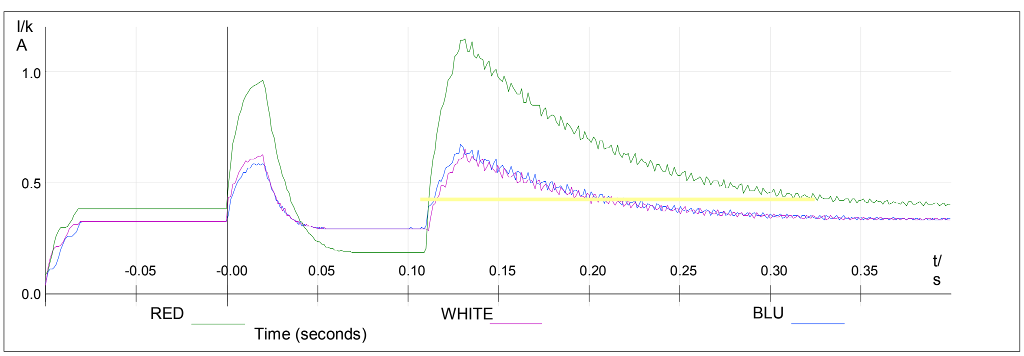


Figure 4-8. SLG fault, 100ms fault duration, 1% from Westgate

Figure 4-8 above indicates that the overcurrent relay would detect the SLG fault. A trip operation is possible as the current exceeds the 472A pick-up setting for the required 200ms definite time delay setting.

The DigSILENT simulations provide an indication that a close-in fault condition (either SLG, L-L and 3P) can lead to an overcurrent relay operation. This is based on pure RMS current, with no filtering techniques applied.

4.3. Correlation of MatLAB and DigSILENT results

MatLAB and DigSILENT simulation packages indicated that an overcurrent relay operation was possible for a close-in 3P fault condition.

Further MatLAB simulations indicated that no other fault condition would result in an overcurrent relay protection operation. This may be due to the difference between the MatLab and DigSILENT simulations i.e. MatLab simulations did not indicate the recharge condition of the SCB.

The DigSILENT simulations, however, did not exclude this possibility in the recharge condition of the SCB following a SLG, L-L and 3P fault condition.

These finding were deduced from the RMS current, as seen by the phase CT's, when compared to the overcurrent relay definite time settings at Westgate substation.

4.4. Summary

This chapter presented the DigSILENT simulations of the 2007 Westgate incident.

As the DigSILENT relay models could not be set as the actual overcurrent relays applied at Westgate substation, the results obtained from the DigSILENT relay models could not replicate the actual overcurrent relay's performance. Adjustments to the standard overcurrent relay models would be required for the detailed analysis of relay operation, to reflect all differences in operation more precisely. The DigSILENT overcurrent relay models were therefore disabled for the external fault simulations.

When compared to the definite time overcurrent relay settings, these DigSILENT simulations indicated that a relay operation was possible for a close-in 3P fault condition. This would correlate with the 2007 Westgate incident.

Further DigSILENT simulations indicated that additional overcurrent relay operations were possible, in the recharge condition of the SCB, following a SLG, L-L and 3P fault condition.

To observe the performance of the actual overcurrent relays, DigSILENT fault simulations were conducted for external fault conditions i.e. various fault types and locations on the Westgate substation model. The CT inputs to the overcurrent relays, as obtained from these simulations, were injected into the overcurrent relays applied in ESKOM SCB protection schemes.

The practical injection test findings are presented in Chapter 5.

5. PRACTICAL TEST RESULTS

DigSILENT simulations were conducted on the Westgate substation model as available on the ESKOM Transmission case file [19]. This was repeated on the most common SCB configurations in the ESKOM transmission network, to determine any difference this could have as suggested in [58].

These simulations were then injected into the three technologies of overcurrent relays commonly applied in the ESKOM SCB environment. The injection tests identified protection operations of the overcurrent relays due to a definite time overcurrent protection settings. This chapter presents these results from the practical laboratory injection tests.

5.1. ESKOM SCB configurations

The ESKOM transmission network has SCB configurations as indicated in Figure 5-1.

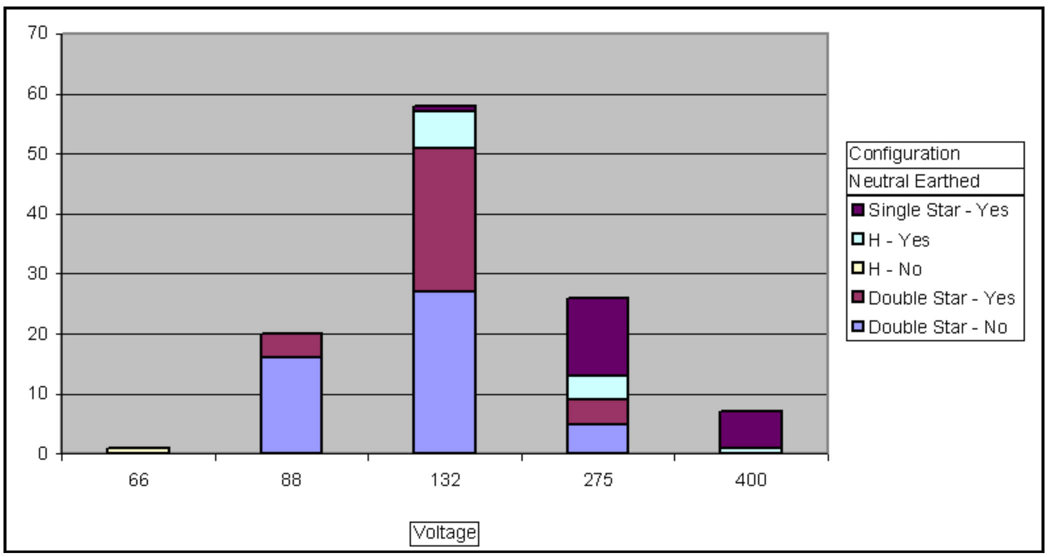


Figure 5-1. ESKOM SCB configurations [44]

It is noted that the most prevalent 132kV SCB configurations are of the earthed and unearthed double star configuration. The simulations produced in DigSILENT were therefore repeated on these two SCB configurations in the ESKOM environment.

5.2. DigSilent simulation description

5.2.1. Fault type and location detail

Simulations were conducted using DigSilent EMT software. These were injected into overcurrent relays to assess their performance for external faults and system disturbances in the SCB environment.

The diagram below illustrates the Westgate Substation and indicates the various locations where the external fault simulations were conducted.

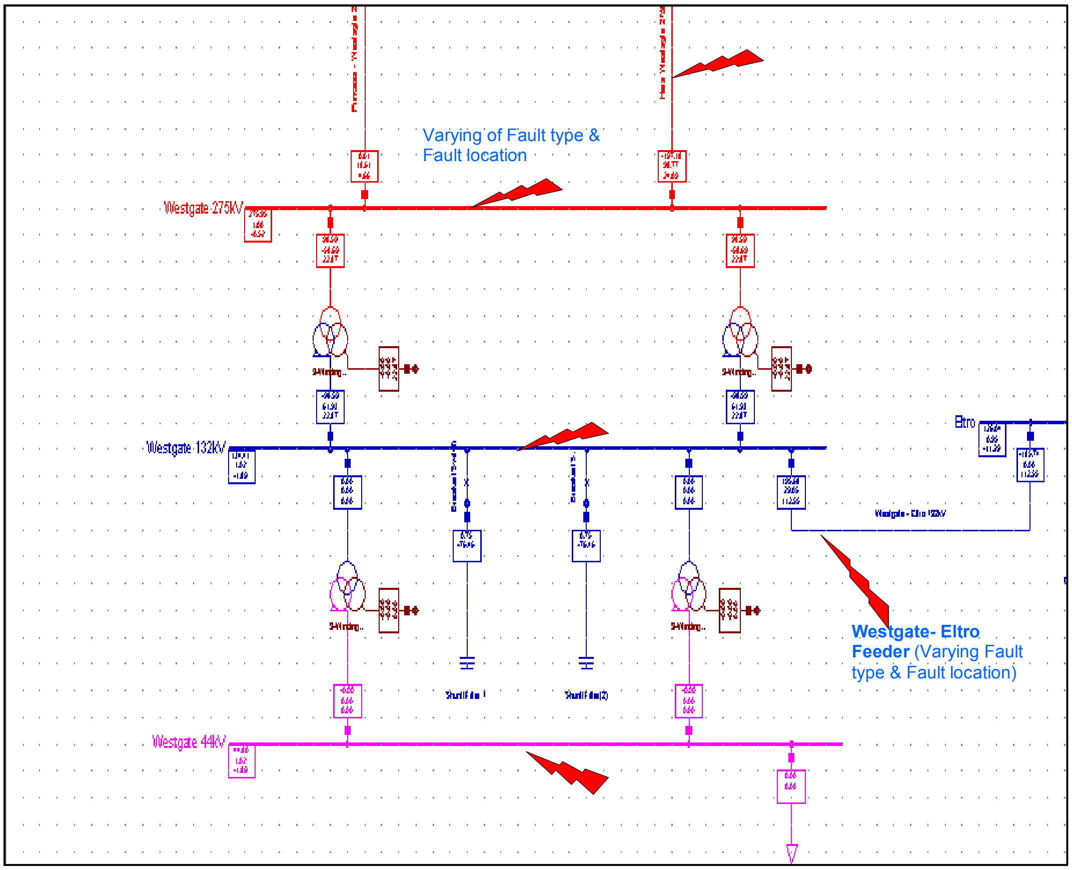


Figure 5-2. Indication of fault locations on earthed SCB simulations [19]

The simulations entailed varying the following:

- fault type i.e. SLG, L-L, DLG and 3P faults;
- fault location on the Eltro feeder, as a percentage of feeder length; and
- faults on the adjacent 275kV, 132kV and 44kV busbars.

Prior to any simulation injections, each relay used was tested to confirm it’s correct operation and is discussed further in Section 5.3.1.
All of the simulations were repeated for earthed and unearthed SCB configurations.

An Omicron Test Universe set was used to inject the DigSILENT simulations into the electromechanical, electronic and digital overcurrent relays. This was to determine if all generations of relays are equally suitable for SCB overcurrent protection.

Each simulation has a pre-fault condition, with the fault occurring at 100ms from the start of the simulation. The fault is cleared after a further 100ms.

It should also be noted that in the Westgate SCB No.1. overcurrent application, the CAG instantaneous relay is used together with an external timer providing a 200ms time delay. For the purposes of the experiment, if the CAG relay 'pick-up' output signal was evident for less than 200ms, it was concluded that the external timer would prevent any trip signal to the SCB No.1 circuit breaker for this switching event. This is a valid deduction, as the CAG39 relay would always be used in a definite time configuration in SCB protection applications.

5.3. Practical injection tests

Below are the connection diagrams for the injection testing of the overcurrent and earth fault relays.

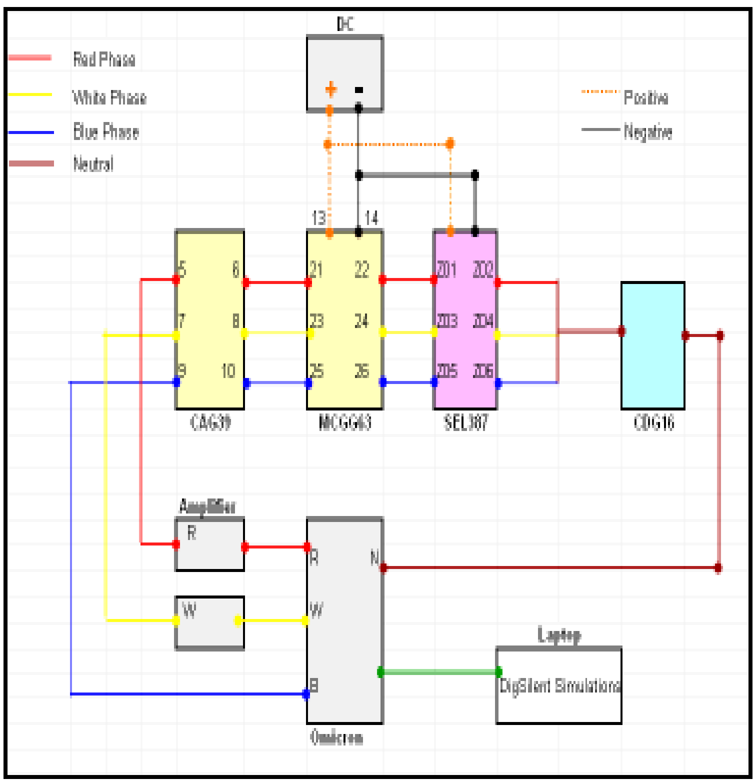


Figure 5-3. Relay input connections for the practical testing

An amplifier was used to accommodate the high SLG and L-L fault currents (on only the red and white phase) as observed in the DigSilent simulations.

Below is the connection diagram for the overcurrent relay output indications. This was used to determine the overcurrent relays' response to the injection testing.

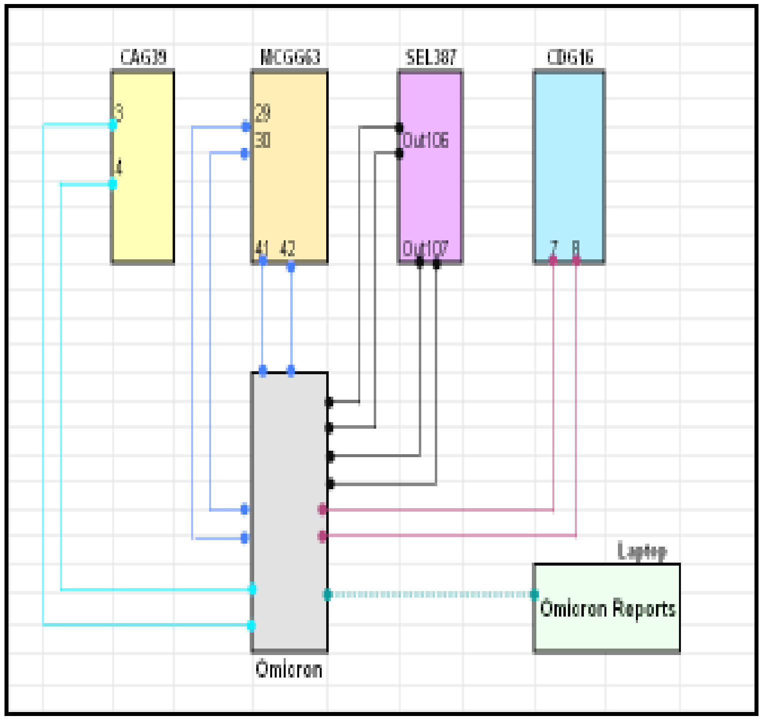


Figure 5-4. Relay output connections for the practical testing

Each simulation injection test has an individual test report and comprises of the current waveform injected and the associated relay output indications. This was saved into a report format using Omicron Test Universe. Each simulation report can be seen in Appendix B.

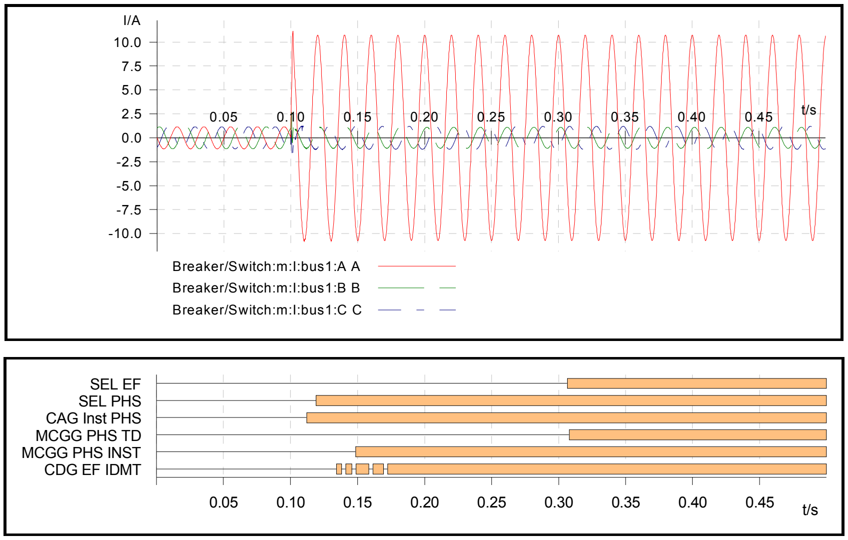
5.3.1. Proof of correct overcurrent relay operation

Prior to any simulation injections, each overcurrent relay used was tested to confirm it's correct operation i.e. the relay issued a protection trip signal at its pick-up setting value, after the definite time delay.

An internal fault on the SCB was simulated to test for correct relay operation. The results for earthed and unearthed SCB configurations are presented in below.

5.3.1.1. Unearthed SCB

The overcurrent relay output indications for an internal fault condition on an unearthed SCB is shown below in Figure 5-5.



Key	Relay Element Description
SEL EF	SEL Earth Fault element
SEL PHS	SEL Phase element
CAG Inst PHS	CAG Instantaneous Phase element
MCGG PHS TD	MCGG Phase Time Delay element
MCGG PHS INST	MCGG Phase Instantaneous element
CDG E/F IDMT	CDG Earth Fault Inverse Definite Mean Time element

Figure 5-5. Unearthed SCB: Internal fault overcurrent relay output indications

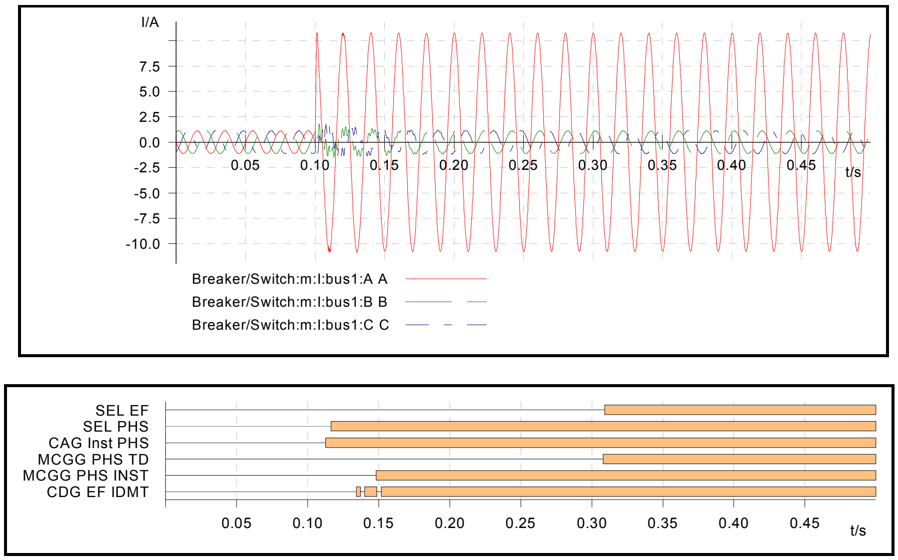
For this simulation, the fault occurs at 100ms (0.1s on Figure 5-5). The SEL earth fault element, the CAG phase instantaneous element (with 200ms external definite time delay) and the MCGG phase element would issue a correct protection trip signal to the circuit breaker after the 200ms time delay. This corresponds to their definite time setting.

The SEL phase element, MCGG instantaneous phase element and CDG earth fault element each issued a correct protection trip indication within 50ms of the fault occurrence.

Figure 5-5. therefore indicates that all overcurrent relays operate as expected, for an internal fault condition on an unearthed SCB.

5.3.1.2. Earthed SCB

The configuration of the bank was changed to an earthed bank and the internal fault simulation was repeated to confirm the correct operation of the relays. The results are shown in Figure 5-6.



Key	Relay Element Description
SEL EF	SEL Earth Fault element
SEL PHS	SEL Phase element
CAG Inst PHS	CAG Instantaneous Phase element
MCGG PHS TD	MCGG Phase Time Delay element
MCGG PHS INST	MCGG Phase Instantaneous element
CDG E/F IDMT	CDG Earth Fault Inverse Definite Mean Time element

Figure 5-6. Earthed SCB: Internal fault overcurrent relay output indications

For this simulation, the fault occurs at 100ms. The SEL earth fault element, the CAG phase instantaneous element (with 200ms external definite time delay) and the MCGG phase element issued a correct protection trip signal to the circuit breaker after the 200ms time delay. This also corresponds to their definite time setting.

The SEL phase element, the MCGG phase instantaneous and the CDG earth fault element issued a trip indication within 50ms of the fault occurrence. The overcurrent relay output indications illustrate that all relays operate as expected.

5.4. Unearthed SCB Omicron injection results

The external fault simulations for the unearthed SCB configuration included the following fault scenarios:

- SLG, L-L, DLG and 3P faults;
- varying the fault location on the Eltro feeder, as a percentage of feeder length;
- placing faults on the adjacent 275kV, 132kV and 44kV Westgate busbars; and
- switching in of a second SCB.

The simulation findings were analysed and are presented below.

5.4.1. Faults on the Eltro Feeder

The table below indicates the overcurrent relay operations for external faults, repeated at various lengths of the Eltro feeder. The fault location is indicated as a percentage of the feeder length.

Table 5-1. Unearthed SCB: Relay operation for faults on the Eltro feeder

Unearthed SCB					
Fault type with duration of fault					
		SLG 100ms	L-L 100ms	DLG 100ms	3P 100ms
Fault location (% of feeder)	1%	D	D	-	D
	10%	-	D	D	D
	20%	-	-	-	D
	50%	-	-	-	-
	98%	-	-	-	-

Key:	Description
D	MCGG Phase (Time Delay)
-	No relay operation

For the SCB No.2 overcurrent relay scheme application at Westgate, the MCGG relay operates for various fault occurrences in the unearthed SCB environment. This relay would issue a trip signal to its associated circuit breaker for the external faults on feeder as indicated in Table 5-1.

The most onerous fault conditions for the electronic MCGG relay were the close-in 3P fault simulations. The MCGG relay operates for the 3P external feeder faults up to 20% of the feeder length away from the Westgate busbar.

The MCGG relay operation in the practical injection tests confirms the 2007 Westgate incident where this relay tripped for the external 3P fault on the Eltro feeder. The operation of this relay can be explained due to its sensitivity to the transient current of an external fault in the SCB vicinity. This discharge current and its frequency were calculated in Section 2.7. and Chapter 2 indicated that the electronic relay would not filter the input current adequately.

5.4.2 Faults on the adjacent busbars

The table below indicates the overcurrent relay operations for external fault occurrences on the adjacent busbars at Westgate Substation.

Table 5-2. Unearthed SCB: Relay operation for faults on adjacent busbars

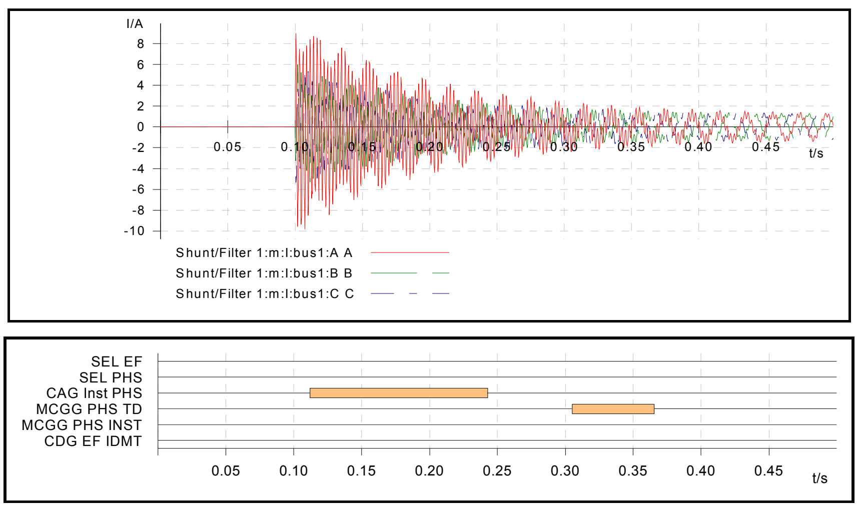
Unearthed SCB				
Fault type with duration of fault				
	SLG 100ms	L-L 100ms	DLG 100ms	3P 100ms
On 275kV BB	-	-	-	-
On 132kV BB	-	-	-	-
On 44kV BB	-	-	-	-

Key:	Description
-	No relay operation

No definite time overcurrent protection operations occurred due to faults simulated on the adjacent busbars.

5.4.3. Back-to-back switching of unearthed SCB

The relay output indications in Figure 5-7 below are for the second SCB being switched onto the Westgate 132kV busbar. The CAG instantaneous and the MCGG time delay phase element trip output indications are shown.



Key	Relay Element Description
SEL EF	SEL Earth Fault element
SEL PHS	SEL Phase element
CAG Inst PHS	CAG Instantaneous Phase element
MCGG PHS TD	MCGG Phase Time Delay element
MCGG PHS INST	MCGG Phase Instantaneous element
CDG E/F IDMT	CDG Earth Fault Inverse Definite Mean Time element

Figure 5-7. Back-to-back switching of an unearthed SCB

It can be concluded that only the electronic MCGG overcurrent relay could issue a trip signal to its associated SCB circuit breaker. The operation of this relay can be explained due to sensitivity to the transient current of a back-to-back switching event, for its definite time overcurrent protection settings. The operation of the CAG relay is prevented by its external timer.

5.4.4 Result analysis of unearthed SCBs

Protection operations were observed from the MCGG electronic relay in the unearthed SCB environment including a protection operation that corresponds to the 2007 Westgate incident. This electronic overcurrent relay could provide incorrect tripping output signals for both feeder faults and for the normal switching event of a second SCB energisation.

The most onerous fault for the unearth SCB is a 3P fault, which can occur up to 20% of the feeder length away from the SCB.

5.5. Earthed SCB Omicron injection results

The external fault simulations for the earthed SCB configuration include the following fault scenarios:

- SLG, L-L, DLG and 3P faults;
- varying the fault location on the Eltro feeder, as a percentage of feeder length;
- placing faults on the adjacent 275kV, 132kV and 44kV Westgate busbars; and
- switching in of a second SCB.

The results from these simulations were analysed and are presented below.

5.5.1 Faults on the Eltro Feeder

The table below is a summary of the overcurrent relay operations for fault simulations in the external fault environment of earthed SCBs.

Table 5-3. Earthed SCB: Relay operation for faults on the Eltro feeder

Earthed SCB					
Feeder Faults (Fault type with duration of fault)					
		SLG 100ms	L-L 100ms	DLG 100ms	3P 100ms
Fault location (% of feeder)	1%	-	-	-	-
	10%	-	-	-	-
	20%	-	-	-	-
	50%	-	-	-	-
	98%	-	-	-	-

Key	Description
-	No relay operation

There were no definite time overcurrent protection operations due to external Eltro feeder faults, on the earthed SCB configuration.

5.5.2 Faults on the adjacent busbars

The table below is a summary of the overcurrent relay protection operations for fault occurrences on the adjacent busbars at Westgate Substation.

Table 5-4. Earthed SCB: Relay operation for faults on adjacent busbars

Fault type with duration of fault				
	SLG 100ms	L-L 100ms	DLG 100ms	3P 100ms
On 275kV BB	-	-	D	-
On 132kV BB	-	-	-	-
On 44kV BB	-	-	-	-

Key	Description
D	MCGG Phase (Definite Time)
-	No relay operation

The above indicates that the definite time element of the MCGG relay would operate for external fault occurrences on adjacent busbars in the earthed SCB environment, for external DLG fault on the 275kV busbar at Westgate Substation. This result indicates that the MCGG63 overcurrent relay would be unreliable in the earthed SCB environment for this fault occurrence.

5.5.3 Back-to-back switching of earthed SCB

The back-to-back switching simulation output (shown using Omicron TransView) could not be injected into the relays due to the high peak value (>20kA) of the transient current as shown in the figure below.

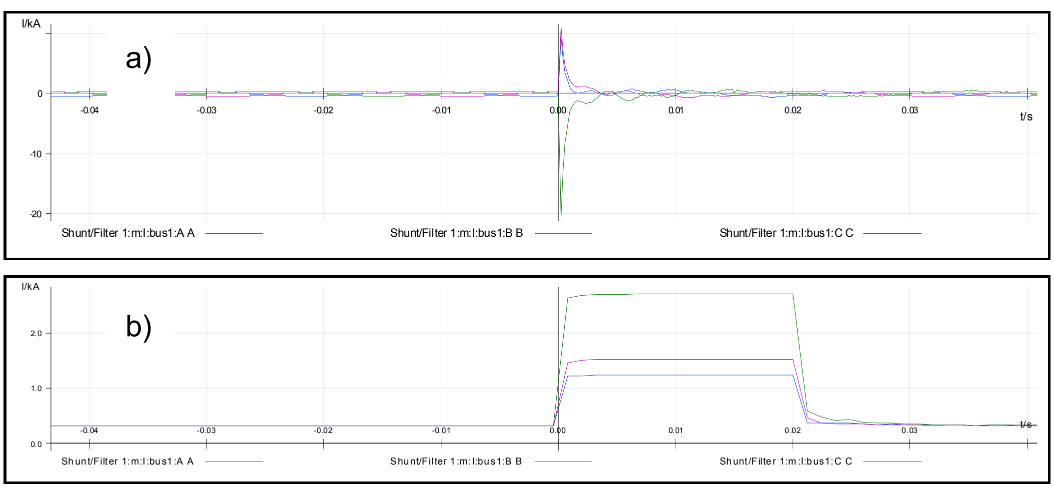


Figure 5-8. Back-to-back switching of earthed SCB a) Instantaneous currents b) RMS currents

It can be deduced from the RMS current waveforms that the possibility of a definite time overcurrent relay element issuing a protection operation is low. This is due to the current values not exceeding 472A for the 200ms required. This setting value was calculated in Section 3.2.1.

5.5.4 Result analysis of earthed SCBs

Protection operations were observed from the electronic MCGG overcurrent relay in the earthed SCB environment. Most alarming is the indication that this overcurrent relay would operate for a busbar fault on an adjacent 275kV busbar.

5.6. Summary

The injection test results indicated that electronic overcurrent relays operate incorrectly in the SCB environment for faults on an adjoining feeder and on adjacent busbars.

These practical injection test results also correlated with the 2007 Westgate substation incident.

This incorrect operation of electronic overcurrent relay is seen on the two most common SCB configurations used in ESKOM i.e. double star unearthed and double star earthed SCBs. However, the electronic MCGG relay operates for significantly less fault scenarios in the earthed SCB configuration than for the unearthed SCB configuration.

The CAG relay was also seen to operate for certain fault conditions but it is assumed that no trip indication would be sent to the associated circuit breaker. This could be attributed to the external timer and/ or the increased operating time due to harmonics, as suggested in the literature review. The phenomenon of harmonic susceptibly is investigated further in Chapter 6, to determine a root cause.

6. RELAY FREQUENCY RESPONSE

This chapter presents the frequency response of the relays tested in the practical injection investigations.

A possible finding of harmonic susceptibility was introduced in the literature review presented in Section 2.4. Due to incorrect and unexpected relay operation in the practical studies, and the literature review findings, all the relays were injected to establish their frequency response.

6.1. Relay settings

To produce the frequency harmonic response curves, the relays were tested independently.

The instantaneous pick-up current setting for a single SCB application is 3A. Due the CAG relay being an instantaneous relay [43], this relay's settings were changed from its 1.2A definite time setting to a 3A instantaneous setting. This was done to show a comparison of an electromechanical instantaneous relay to the electronic relay's instantaneous element.

Table 6-1: Overcurrent Protection settings

Relay type	Protection Description	Relay Type	Pick-up Setting	Time Setting
Electromechanical	Overcurrent Instantaneous	GEC CAG39	3A	Instantaneous
Electronic	Overcurrent Instantaneous	GEC MCGG63	3A	Instantaneous
Electronic	Overcurrent Definite Time	GEC MCGG63	1.2A	0.2 Sec
Digital	Overcurrent Definite Time	SEL	1.2A	0.2 Sec
Electromechanical	Earth fault	GEC CDG16	0.2A	0.2 Sec
Digital	Earth fault	SEL	0.2A	0.2 Sec

6.2. Relay pick-up current

To produce the graph below, the current injected into the overcurrent relays was increased from 0.1A to the overcurrent relay pick-up setting value. This was done in 0.1A increments in get the overcurrent relay to issue a protection trip indication. This was repeated at various frequencies of the injected current.

The maximum current required for the relays to issue a trip was recorded from the Omicron test Universe and plotted against the frequency of the injected current.

As this test is independent of the Westgate substation model, Figure 6-1 is purely an indication of the relay's frequency response i.e. response of the relay to the harmonics at which current is being injected.

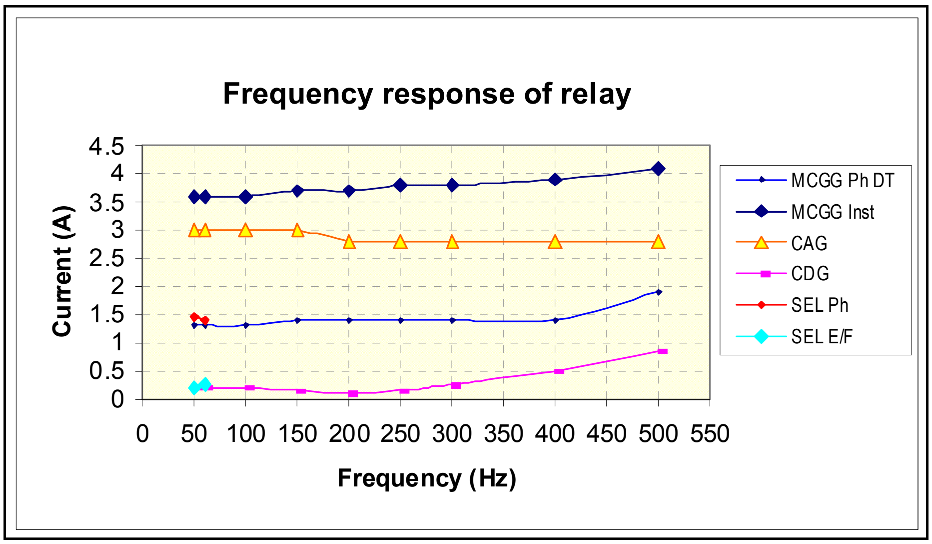


Figure 6-1: Frequency response of overcurrent relays

The CDG electromechanical relay and the MCGG electronic relay (both phase and earth fault elements) indicate a general trend of increased pick-up current, as the frequency increases. The other electromechanical relay, the CAG relay, shows a small decrease in pick-up current for the increase in frequency.

The results suggest that for input currents that contain harmonics, the CDG and MCGG relay would trip at a higher current value than its predetermined pick-up current, and the CAG relay (used as an instantaneous overcurrent relay) would trip for a lower predetermined pick-up current setting. Both these responses indicate these electronic and electromechanical relays would be unreliable in a harmonic environment.

As the pick-up setting is calculated and should be fixed for each application, this is an undesirable effect.

The digital SEL overcurrent and earth fault elements both operate only for the 50Hz and 60Hz current injections. This would be due to the relays dual frequency application around the world. This relay exhibits no vulnerability to harmonic content of the injected current. This is due to the anti-aliasing filtering circuits and advanced relay algorithms as described in Section 2.6.

6.3. Relay operation time

To produce the Figure 6-2, the injected current was increased from 0.1A to the overcurrent relay pick-up setting. This was done in 0.1A increments in so as to get the overcurrent relay to issue a protection trip indication. This was repeated at various frequencies.

The time for the relay to issue a trip indication was recorded from Omicron test Universe and plotted against the frequency of the current injected.

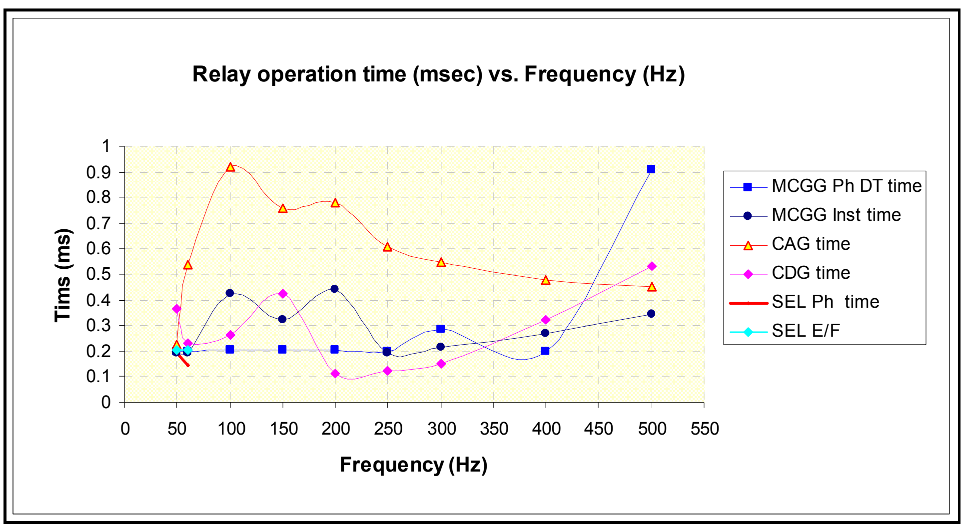


Figure 6-2. Relay operation trip time vs. Frequency of injected current

Figure 6-2 is an indication of the influence harmonic content of the injected current has on the relay operation time i.e. time taken for the relay to issue a trip indication.

The digital SEL relay (both overcurrent and earth fault elements) only issues a trip indication for the 50Hz and 60Hz current injection simulations. The operation times for the SEL relay to trip are fairly consistent and therefore this relay exhibits no vulnerability in this harmonic environment.

As the frequency increases, the electromechanical relays (both CDG16 and CAG39) and the MCGG63 electronic relay all indicate erratic changes in the time taken to issue a protection trip indication. The general trend seen in Figure 6-2 is that the operation time for these relays increases.

An increase in operation time indicates the relay would be slow to issue a trip output indication. This would cause the high frequency fault current to flow for a longer time than necessary and could cause harm to the relay itself and the SCB it protects.

This further indicates that the electromechanical and electronic relays would be unsuitable in the SCB external fault environment due their susceptibility to harmonics of the input current.

6.4. Possible application in ESKOM's transmission network

The composition of electronic, electromechanical and digital relays as applied to the ESKOM transmission network is extracted from [37] and indicated in Figure 6-3 below.

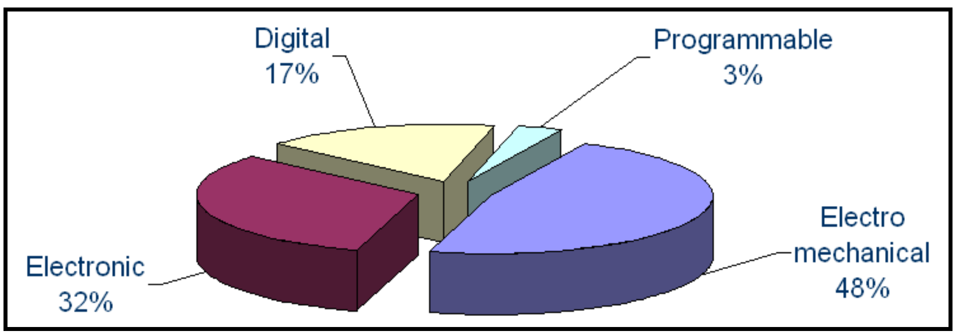


Figure 6-3: Relay technologies applied in ESKOM Transmission [37]

The MCGG63 electronic relay and electromechanical relays (CAG39 and CDG16) were found to be susceptible to harmonics. The technology of these relays is widely applied in the ESKOM transmission network. [37]

Previous incidents where these protection relays have operated incorrectly might be due to the phenomenon of harmonic susceptibility.

6.5. Summary

The frequency response tests indicate that the electronic and electromechanical relays are susceptible to harmonics of the injected current.

Harmonic frequencies impact both the pick-up current and relay operating time of electronic and electromechanical overcurrent relays. This indicates that these relays would operate regardless of the predetermined settings for which these relays have been set. This effect makes the electronic and electromechanical relays unreliable in a harmonic environment.

It is therefore concluded that the CAG relay did not issue a trip signal to the SCB No.1 circuit breaker due to the application of the external timer. This would explain its non-operation and correlates with actual 2007 Westgate incident.

The digital SEL relay (both phase overcurrent and earth fault elements) did not trip for frequencies outside its dual frequency operation range of 50-60 Hz. This is attributed to it being insensitive to harmonics with the assistance of advanced filtering circuits.

The SEL digital relay would therefore be the most suitable preference in a SCB harmonic environment for overcurrent protection purposes.

7. RECOMMENDATIONS

The Westgate electronic MCGG relay operated correctly due to its definite time overcurrent settings i.e. the operation is correct according to its calculated and implemented settings.

However, an overcurrent relay applied in the SCB protection scheme should operate only for an internal fault [10]. Therefore the setting, and possibly the application, of this electronic overcurrent relay is not appropriate in the SCB environment.

7.1. Recommendations to address MCGG operation

Recommendations to address the incorrect operation of the electronic MGCC overcurrent for the Westgate SCB application are presented below.

7.1.1. Do nothing option

As the ESKOM transmission network is designed for N-1 contingencies, the tripping of a single SCB should not be detrimental to system integrity. Moreover, after such trip event, ESKOM's National Control personnel can re-energise the SCB, via supervisory control, once the fault has been removed from the system and the SCB has sufficiently discharged. The risk, therefore, may be accepted until refurbishment of protection scheme can be prioritised. [59]

For this option, the Westgate electronic MCGG relay would continue to operate in the external fault environment of the SCB. Therefore this substation and SCB would need to be included in ESKOM's System Operation Guideline (SOG). The SOG identifies known protection issues and highlights the possibility of sympathy trips to ESKOM personnel. However, this would apply only if the relay settings can not be adjusted appropriately. [59]

7.1.2. Pick-up current setting

SCBs are designed to carry 130-135% rated load current, at 100% system voltage [12, 55]. When a maximum system voltage of 110% is considered, this SCB rated current would increase to 143%-148%. [2, 55]

According to [6], the total RMS current of the SCB (including fundamental and harmonic overvoltage up to and including the maximum system voltage) shall not exceed 180%. Moreover, IEC 60871-1 indicates that thermal and electrodynamics stresses occur in SCB transient conditions [55].

The Westgate MCGG relay had a pick-up setting of 150% of the rated load, which would meet the above recommendation [19]. Due to the many factor affecting transients currents, shown in Section 2.9, the 150% setting should not be increased to prevent unwanted damage to the SCB.

7.1.3. Definite time setting

A 200ms definite time setting is usually applied to overcurrent relays in the SCB application to prevent relay operation during transient conditions [6, 10].

The simulations and injection tests indicated that this existing 200ms definite time delay would not prevent the operation of the Westgate electronic MCGG relay. The operation of the relay is due to the 472A pick-up value being present for the 200ms definite time delay, in the SCB recharge condition, which occurs after an external fault is removed.

Most alarming was the operation of this relay for a feeder fault, with a fault duration of 100ms. This would indicate that the relay would operate even though the feeder protection scheme operates correctly and removes this fault within its allotted timeframe.

These findings indicate that if this electronic overcurrent relay is to be applied correctly in the SCB environment, the definite time of this relay would have to be increased. This could prevent this relay operation for external fault occurrences, and the transients of the SCB recharge condition when these faults are removed. These fault occurrences were identified in Chapter 4 and Chapter 5.

From the simulations conducted, the minimum definite time delay required to prevent the Westgate MCGG relay operation was identified as 300ms. This was seen for a SLG fault occurrence in Section 4.2, Figure 4-8. However, this would need to be confirmed by injection testing for this fault simulation. Also, any definite time setting change should also take into account the SCB manufacturers' recommendations regarding their thermal withstand limits.

7.1.4. Replacement of the MCGG relay

If the settings of the Westgate electronic MCGG relay remain as is, this relay could continue to operate in the external fault environment of the SCB, especially for close-in 3P and short duration fault occurrences.

If the relay settings cannot be appropriately amended for the SCB environment, this relay should be replaced with a digital overcurrent relay, as is currently implemented in the ESKOM transmission network [58].

7.1.5. IDMT curve application

ESKOM philosophy for SCB overcurrent protection has historically applied the overcurrent relay with a definite time setting [6, 10].

However, overcurrent settings for SCB applications in Australian utilities use a standard IDMT curve with a 1.5 PS and a 0.1-0.2 TM, which prevents the operation of the overcurrent relay for transient conditions [60].

As the MCGG63 relay has IDMT functionality, [23], this could be explored to determine if this could prevent the incorrect operation of this relay. However, this would need to be confirmed in practical injection tests of the Westgate MCGG relay.

7.2. Summary

The Westgate electronic MCGG relay operated incorrectly for an external fault in the SCB environment, due to its definite time overcurrent settings. Therefore the setting, and possibly the application, of this electronic overcurrent relay are not appropriate in the SCB environment.

Recommendations to address the incorrect operation of the Westgate electronic MGCC overcurrent relay were presented, including amending the definite time setting of the relay. However this would need to be confirmed in practical studies, and take into account the SCB manufacturers' recommendations regarding its thermal withstand limits.

If the Westgate electronic MCGG overcurrent relay settings cannot be appropriately amended for the SCB environment, this relay should be replaced with a digital overcurrent relay, as is currently implemented in the ESKOM transmission network.

8. CONCLUSIONS

8.1. Westgate incident findings

MatLAB simulations for the 2007 incident indicated that all technologies of overcurrent relays could operate for a close-in 3P fault on the Eltro feeder. Further MatLAB simulations conducted indicated that no other overcurrent relay operations were possible, when compared to the overcurrent relay definite time settings.

The DigSILENT simulation for a close-in 3P fault condition also indicated that an overcurrent relay operation was possible. Further simulations, however, indicated that overcurrent relay operations were possible in the recharge condition of the SCB following a SLG, L-L and 3P fault condition.

A further difference between the MatLAB and DigSILENT simulations were that the MatLAB simulation results did not indicate the recharge condition of the SCB when faults were cleared.

The use of the DigSILENT relay models to predict, or repeat, the Westgate relay operation was not successful. This is because the DigSILENT relay models could not be set as the actual overcurrent relays applied at Westgate substation. The standard DigSILENT relay models would have to be amended in detail to replicate the actual overcurrent relay's performance.

Practical injection tests confirmed the 2007 Westgate incident on SCB No.2, which was due to the MCGG electronic relay operation for the 3P external fault on the Eltro feeder. It also indicated that the MCGG relay operates for 3P external feeder faults up to 20% of the feeder length away from the Westgate busbar. These tests also indicated that electronic MCGG overcurrent relays operate incorrectly in the SCB environment for short duration external faults.

These incorrect operations were observed on the two most common SCB configurations, though these are significantly less in the earthed SCB configuration.

The operation of this MCGG electronic relay, under the external fault conditions tested, makes the MCGG electronic relay unsuitable for application in the SCB environment.

An increase in the definite time settings could prevent the operation of this relay, but requires confirmation from injection tests. If the setting change does not prevent the incorrect operation for external and short duration faults, these relays should be replaced, preferably with digital relays.

The electromechanical CAG relay did not send a trip signal to the SCB No.1 circuit breaker due to the definite time application of an external timer. This would explain its non-operation and correlates with the actual 2007 Westgate incident.

The digital SEL and electromechanical CAG overcurrent relays did not operate incorrectly in the practical injection tests and therefore indicate they are reliable in the SCB environment.

8.2. Discussion of possible problem areas

Due to the literature review findings, frequency response tests were conducted. These demonstrated that the electronic GEC MCGG63 and electromechanical GEC CAG39 overcurrent relays were susceptible to harmonics.

Harmonic frequencies impact both the pick-up current and relay operating time of electronic and electromechanical overcurrent relays. This indicates that these relays would operate, regardless of the predetermined settings for which these relays have been set. Therefore the application of simple electronic and electromechanical overcurrent relays in a harmonic environment is problematic due to frequency susceptibility.

The digital SEL relay (phase overcurrent and earth fault elements) did not trip for frequencies outside its dual frequency operation range of 50-60 Hz. This is attributed to it being insensitive to harmonics with the assistance of advanced filtering circuits.

It is concluded that the solution to prevent mal-operations due to harmonics in the SCB environment, and possibly the larger ESKOM power system network, is to apply overcurrent relays that have suitable filtering to remove the transient harmonics from the input waveform.

Therefore digital relays would be the most suitable in the SCB environment for overcurrent protection applications.

8.3. Philosophy and guidelines for overcurrent relays on SCBs

The application of advanced, harmonic restrained digital overcurrent relays would be the most appropriate for ESKOM’s transmission SCB environment.

Newly commissioned overcurrent protection schemes on SCBs should be immune to the fault scenarios highlighted in this report, due to digital technology presently being applied in ESKOM. It would be the older SCB overcurrent protection schemes, with electronic overcurrent relays, that could be at risk of incorrect operations.

Recommendations were made in order to prevent the operation of the electronic MCGG relay operation for external faults in the SCB environment. The setting changes recommended for the MCGG relay would have to be confirmed in practical tests, and take into consideration the SCB and relay thermal withstand levels. This relay could also be replaced with a digital relay to prevent incorrect operation.

8.4. Summary of report findings

The report findings can be summarised as follows:

- DigSilent EMT studies would be the most appropriate to determine transient behaviour;
- The practical injection tests confirmed the electronic MCGG relay operation for the 2007 Westgate incident;
- The CAG relay (with the external timer providing a definite time setting) and the digital SEL relay proved to be reliable in the SCB environment;
- DigSILENT relay models for the electronic MCGG and electromechanical CAG relay could not be set as they were applied at Westgate substation;
- Modern digital relays have advanced sampling and filtering circuits while electronic relays have simple filter circuits. Electromechanical relays have no special filtering circuits. It is therefore concluded that the technology of the overcurrent relay determines its vulnerability to harmonics.
- The switching events of a single SCB, back-to-back switching events and external faults in the SCB vicinity gives rise to harmonics. These switching and fault events could cause incorrect protection operations in harmonic susceptible overcurrent relays applied in SCB applications;
- Electronic and electromechanical overcurrent relays in harmonic environments could operate incorrectly due to frequency susceptibility; and
- The MCGG relay could be replaced with a digital relay, or an appropriate overcurrent setting could be determined in practical testing.

8.5. Further research study prospect

A further research prospect would be to verify the harmonic response of all electronic overcurrent protection relays currently employed in the ESKOM transmission SCB environment.

This further research could include an investigation into the various overcurrent relay manufacturers and the year of manufacture. This is to determine if the manufacturer, or the age of the relay, plays any role in the operation of these overcurrent relays. The harmonic sensitive relays identified in this further research should be earmarked for replacement, preferably with digital relays.

REFERENCES

[1] Horowitz SH and Phadke AG: "Power System Relaying", 2nd Edition, Research Studies Press Ltd., England, 1995

[2] Brunello G, Kasztenny B and Wester C: "Shunt Capacitor Bank Fundamentals and Protection", 2003 Conference for Protection Relay Engineers, Texas, April 2003

[3] "Protective Relays Application Guide", 3rd Edition, ALSTOM T&D Protection and Control, 1987

[4] "Network Protection & Automation Guide", Chapter 3, ALSTOM T&D Protection and Control, 2003

[5] Mason CR: "The Art & Science of Protective Relaying", Chapter 1, obtained via http://www.gedigitalenergy.com/multilin/notes/artsci/index.htm

[6] "Protection Philosophy: Shunt Capacitor Banks", ESKOM Distribution Standard, February 1998

[7] 'Technology Reference for Power Capacitor Applications and Protection", ESKOM Transmission Guideline, September 1994

[8] Gopakumar G, et al: "Shunt Capacitor Bank Switching Transients: A Tutorial and Case Study", Michigan Technological University, USA

[9] Dalci KB, Yumurtaci R, Bozkurt A: "Harmonic Effects on Electromechanical Overcurrent Relays" Yildiz Technical University, Turkey, 2005

[10] "Protection Settings Philosophy for Transmission and Sub-Transmission Grids", ESKOM Transmission Operation Philosophy, February 2006

[11] "EPRI Power System Dynamics Tutorial", 1001983, EPRI, Palo Alto, CA, 2002

[12] "IEEE Guide for Application of Shunt Power Capacitors", IEEE, USA, 1993

[13] Blackburn JL, Domin TJ: "Protective Relaying Principles and Application", 3rd Edition, CRC Press, 2006

[14] "Network Protection & Automation Guide", Chapter 7, ALSTOM T&D Protection and Control, 2003

[15] IEC 871-3 'Shunt Capacitors for AC Power Systems having a rated voltage above 1000V, Part 3: Protection of Shunt capacitors and Shunt capacitor banks"; 1996

[16] "Network Protection & Automation Guide", Chapter 9, ALSTOM T&D Protection and Control, 2003

[17] Hewitson LG, Brown M and Balakrishnan R: "Practical Power System Protection", Chapter 9, Newnes, 2004

[18] Greenwood A: "Electrical Transients in Power Systems", 2nd Edition, Chapter 3 & 4; John Wiley & Sons, New York, 1991

[19] ESKOM Transmission DigSILENT file: TX Master Project 2008_10_20.dz (Available using DigSILENT software)

[20] Mason CR: "The Art and Science of Protective relaying", Chapter 2, obtained via http://www.gedigitalenergy.com/multilin/notes/artsci/index.htm

[21] CIGRE 305: "Guide For Application of IEC 62271-100 and IEC 62271-1", Part 2, Page 79-117, October 2006

[22] Anderson, PM: "Power System Protection", Chapter 3 and 4, IEEE Press, New York, 1999

[23] MCGG Relay manual

[24] IEEE WGI10 Power System Relaying Committee: "Understanding Microprocessor-based Technology Applied to Relaying", IEEE, 2004

[25] http://www.selinc.com/SEL-387/ accessed October 2008

[26] Schweitzer EO, Kumm JJ, Feltis MW: "Negative Sequence Overcurrent Element Application and Coordination in Distribution Protection", IEEE, 1992

[27] Yumurtaci R, Gulez K, Bozkurt A, Kocatepe C & Uzunoglu M: "Analysis of Harmonic Effects on Electromechanical Instantaneous Overcurrent Relays with Different Neural Network Models" Yildiz Technical University, Turkey, 2005

[28] Srivastava D: "Switching Studies for the Islington Substation Capacitor Bank with Surge Arrestors', New Zealand, 2006

[29] http://www.shreemcapacitors.com accessed November 2008

[30] http://www.ece.mtu.edu.com accessed November 2008

[31] Irizarry MF, Vélez TE: "Mitigation of Back-to-Back Capacitor Switching Transients on Distribution Circuits", PREPA, Puerto Rico

[32] "Harmonic Testing of Protective Relays", Wichita State University Power Quality Lab, USA, 1994

[33] "Fundamental Relay Operating Principles and Characteristics", Chapter 2,

[34] Horowitz SH and Phadke AG: "Power System Relaying", 3rd Edition, Chapter 2, Research Studies Press Ltd., England, 2008

[35] ESKOM's Power System Operations Protection Settings database

[36] SEL Relay manual

[37] Bartylak A: "Evaluation of Weak Infeed Tripping Technique on the ESKOM Transmission Network"; CIGRE Committee B5 Colloquium, September 2005

[38] Rostron J: Outrush Reactors of Capacitor Banks, Georgia USA

[39] Peelo DF: "Current Interrupting Capability of Air Break Disconnect Switches", IEEE Transactions on Power Delivery, vol. PWRD-1, No. 1, January 1986.

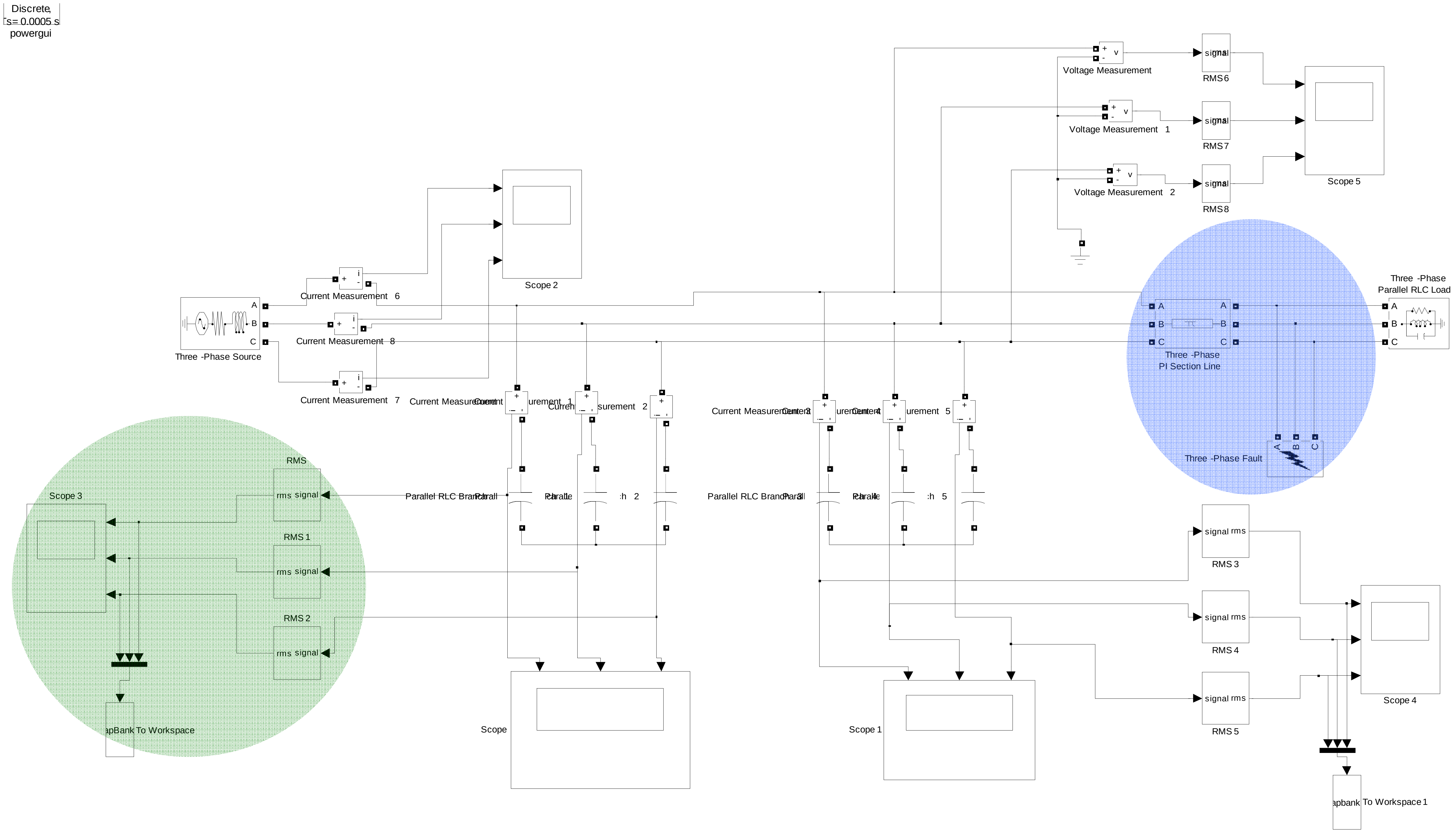
[40] www.abb.com accessed May 2009

[41] ESKOM's Transmission Incident Protection Performance System (TIPPS) database, November 2008
[42] CDG Relay manual
[43] CAG Relay manual
[44] Personal email from Neels van Staden (ESKOM Capacitor Technology Consultant) containing SCB (shunt capacitor bank) information regarding configurations applied in ESKOM, Transmission, October 2008
[45] MatLab software
[46] www.cooperpower.com accessed January 2009
[47] www.nepsi.com accessed January 2009
[48] Kulas SJ: "Capacitor Switching Techniques", ICREPQ, Spain, 2009
[49] "Improved Reliability of Switched Capacitor Banks and Capacitor Technology", EPRI Technical Report, Palo Alto, CA, 2004, 1002154
[50] Declaration as per "Essential requirements for the preparations of Dissertations and Theses", November 2009
[51] "Digital measurement block", DigSILENT Technical Documentation, Germany, 2009
[52] "Measurement block", DigSILENT Technical Documentation, Germany, 2009
[54] "Power Quality and Utilisation Guide - Voltage Disturbances", Clause 6, Leonardo ENERGY, June 2007
[55] IEC 60871-1 "Shunt Capacitors for AC Power Systems having a rated voltage of above 1000V", Third edition, 2005
[56] Personal email from Alberto Borgnino (DigSILENT protection specialist) regarding the operation of DigSILENT relay models, November 2009
[57] Grebe TE: "Application of Distribution System Capacitor Banks and Their Impact on Power Quality", IEEE Transactions on Industry Applications, Vol 32, No.3, May/June 1996
[58] Constable RM, van Staden N: "Improvements in the Performance of HV Shunt Capacitor Banks", 2008/9
[59] Personal email from Adam Bartylak, ESKOM Corporate Protection Consultant, regarding the recommendations made, November 2009
[60] Moor B: "Fundamental Principles of Power System Protection", September 2009

APPENDIX

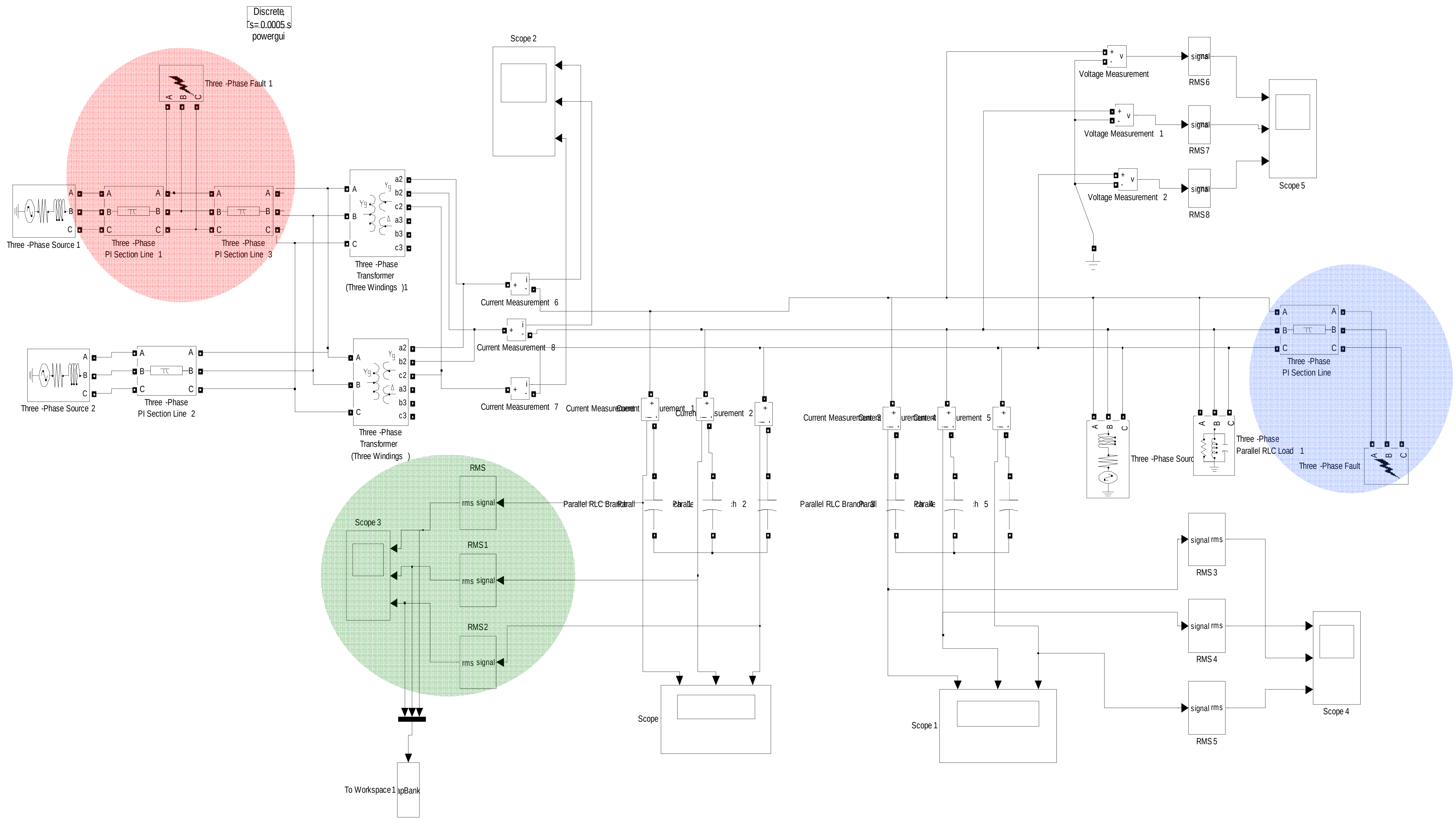
Westgate Models used for Simulations on MatLAB

Model includes unearthed capacitor banks with a source and oscilloscopes to view RMS and instantaneous current waveforms.



Blue Oval (Top right): Fault on Eltro feeder (10 October 2007 Incident);
Green Oval (Bottom left): RMS values of currents seen by CTs of all 3 phases

Simulations on MatLAB: Model of Westgate Substation with Hera- Westgate feeder incident



Blue Oval (Top right): Fault on Eltro feeder (10 October 2007 Incident)
Pink Oval (Top left): Fault on Hera-Westgate feeder (13 October 2004 Incident)
Green Oval (Bottom left): RMS values of currents seen by CTs of all 3 phases

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Westgate Capacitor Bank No. 1

Station: Westgate
Busbar voltage: 132
Bay: Cap 1

MVA rating 72 MVar
VT RATIO :- 132 /110
Trfr VCR Voltage Setting 132

Capacitor unit type :- Westing Corp Externally Fused
Cap. elements in // P= 1 Arrangement in Can
Cap. element rows r =1 Arrangement in Can
Num. of Cap. units in // per stack c = 9
Num. of stacks in series 4
Capacitor unit ratings:
In = 17.48
Cn = 3.06
Un = 19.053
Qn = 333
Dr = 1.9
Ce =

Maximum Fault Current = 20584.5

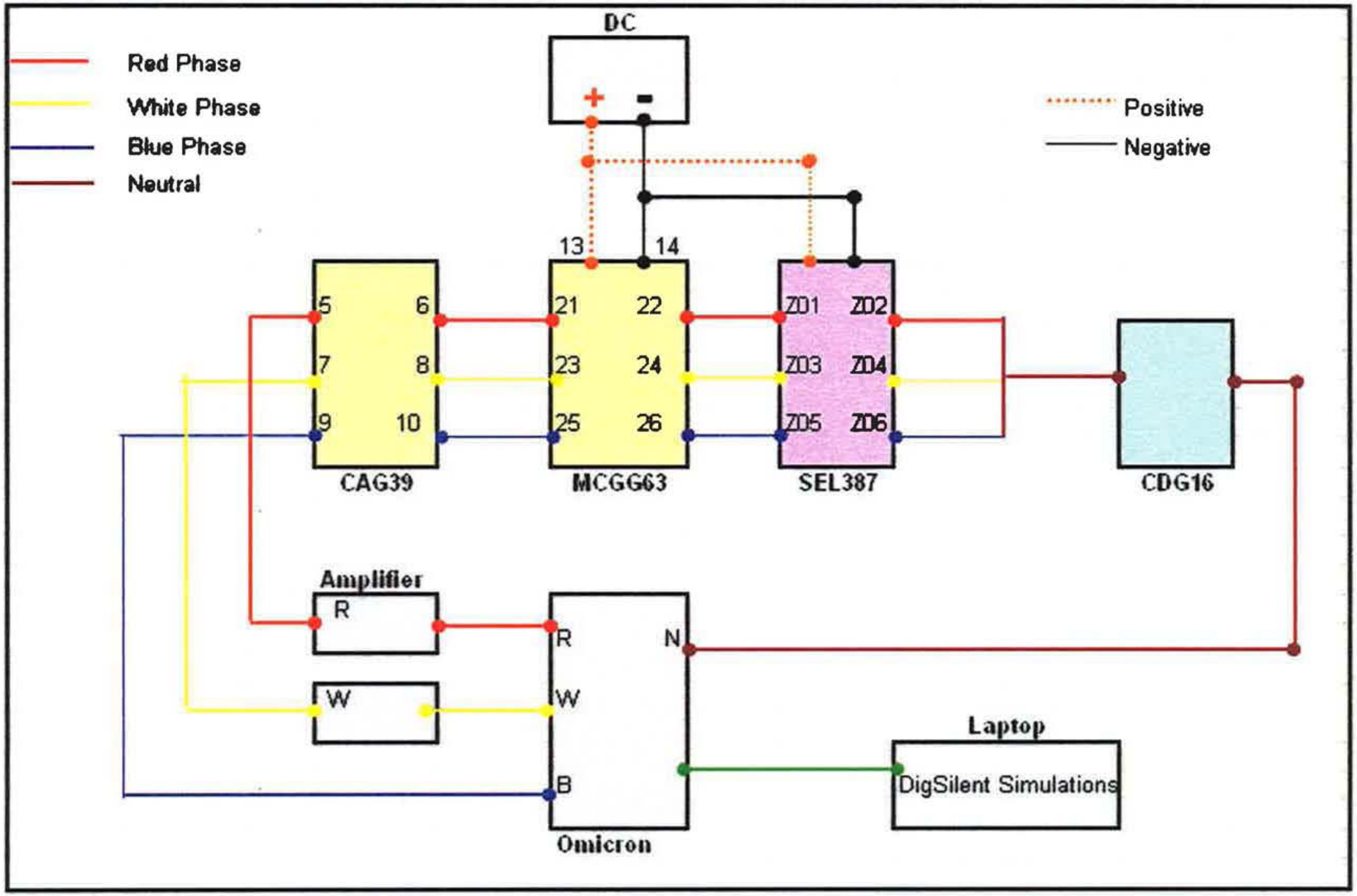
Westgate Capacitor Bank No. 2

Station: Westgate Scheme No: 2CB0200
Busbar voltage: 132 kV Drawing No: 0.18/17276

Bay: Capacitor Bank 2 Double Star

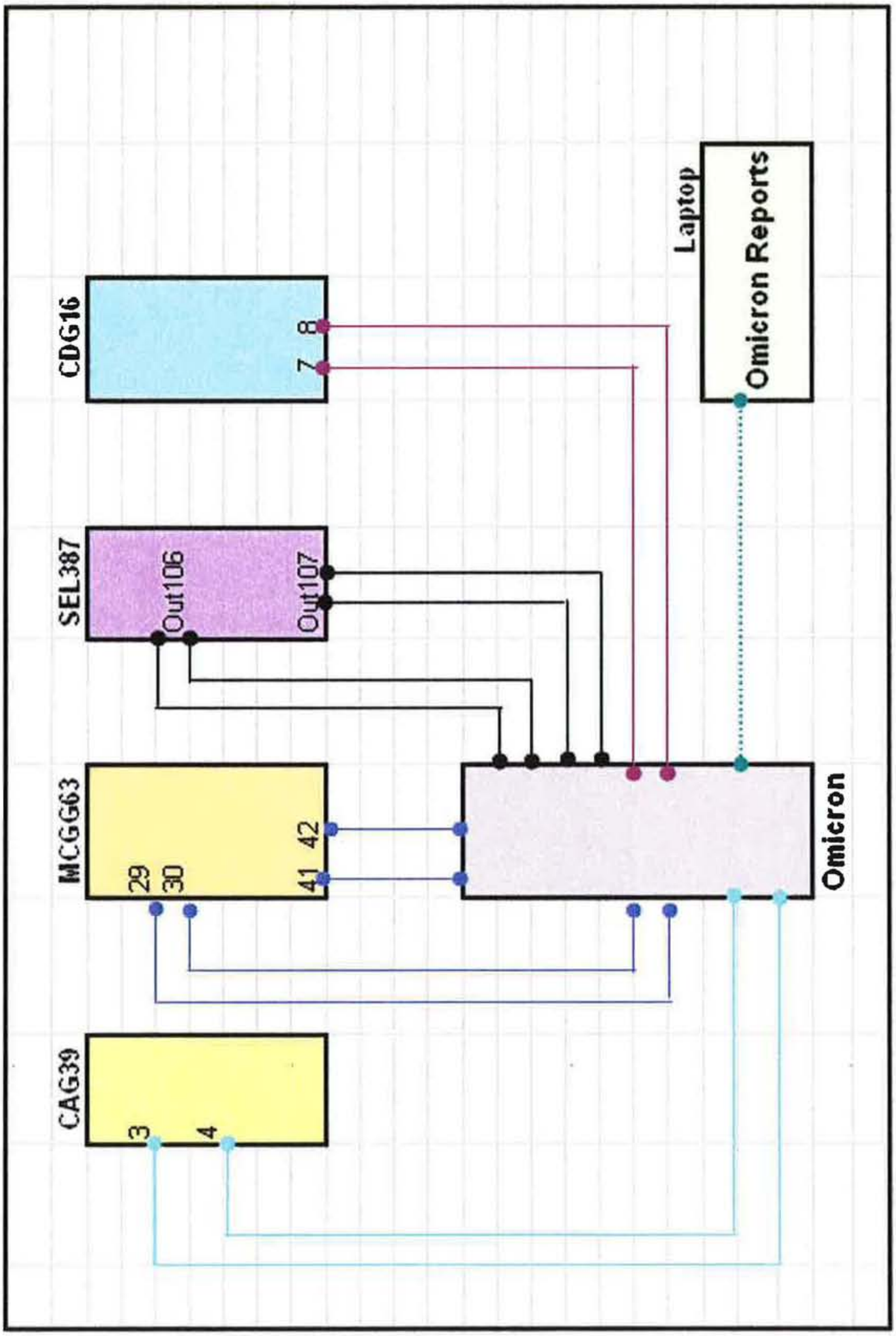
MVar rating 72 MVar
VT RATIO :- 132000 / 110
VTR = 1200
Trfr VCR Voltage Setting 134 kV
Capacitor unit type :- Westing Corp Externally Fused
Cap. elements in // P= 1
Cap. element rows r =1
Num. of Cap. units in // per stack c = 9
Num. of stacks in series 4
Capacitor unit ratings :
In = 17.42 Amp.
Cn = 2.9 micro farad
Un = 19.053
Qn = 333 KVAr
Dr = 1.9 Meg. ohm
Ce =

Maximum Fault Current: 15585.0 Amp

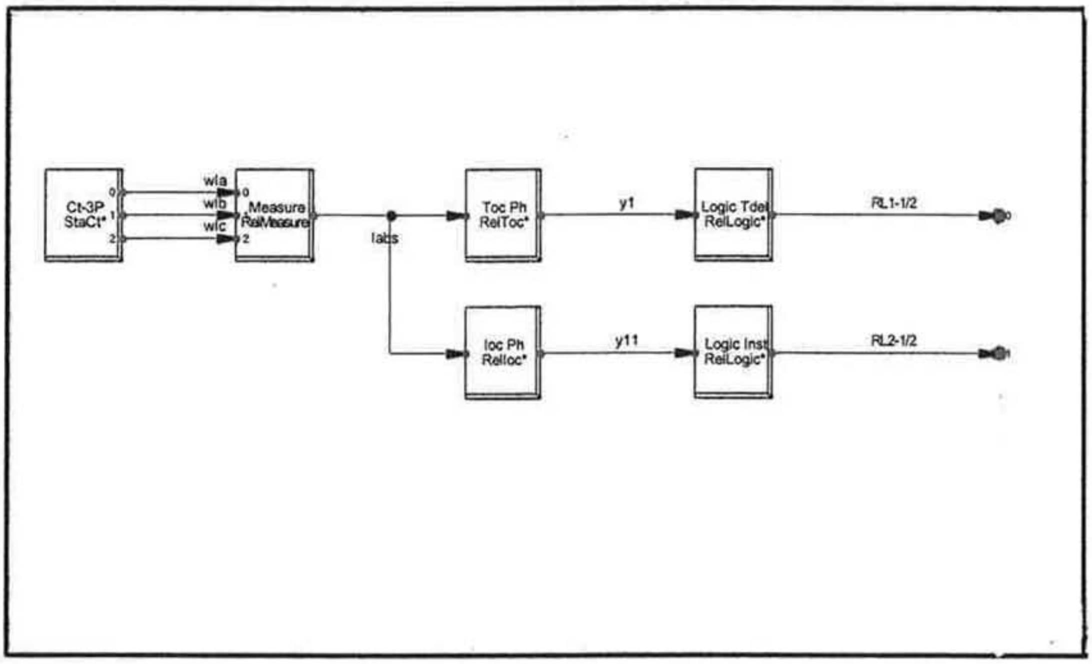


Relay connections diagram for the practical injection testing: Input connections

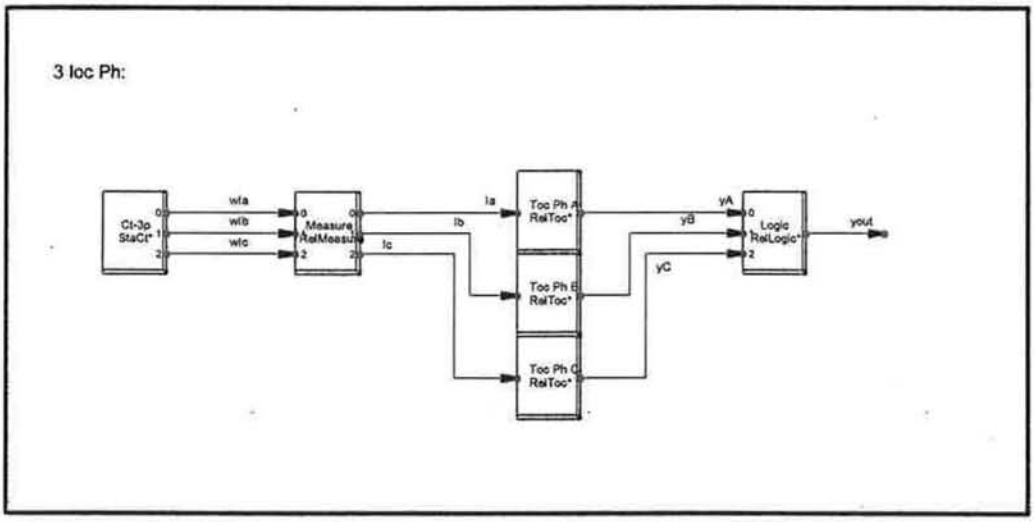
Relay connections diagram for the practical injection testing: Output connections



DigSILENT MCGG63 Overcurrent Relay Logic Diagram
Extracted from [19, 51]



DigSILENT CAG Overcurrent Relay Logic Diagram
Extracted from [19, 51]



Capacitor	Manufacturer	Voltage	Nominal Output	Configuration	Age	Neutral
Apollo Filter 1	ABB/Westingcorp	275	300	Single Star	0	Yes
Apollo Filter 2	ABB/Westingcorp	275	300	Single Star	0	Yes
Apollo 1A	Westingcorp	275	150	Double Star	11	Yes
Apollo 1B	Nokia	275	134	Double Star	33	Yes
Apollo 2A	HTSA	275	150	Double Star	6	Yes
Apollo 2B	Nokia	275	134	Double Star	33	Yes
Acacia 1	ABB	132	72	H	12	Yes
Acacia 2	ABB	132	72	H	12	Yes
Acacia 3	ABB	132	72	H	12	Yes
Ararat 1	ASEA	88	48	Double Star	20	No
Ararat 2	ASEA	88	48	Double Star	18	No
Ararat 11	ASEA	275	144	Double Star	25	No
Ariadne 1	HVT	132	72	Double Star	1	Yes
Ariadne 2	HVT	132	72	Double Star	1	Yes
Athene Filter 1	Westingcorp	132	94	Double Star	13	Yes
Athene Filter 2	Westingcorp	132	94	Double Star	13	Yes
Athene Filter 3	Westingcorp	132	94	Double Star	13	Yes
Athene Filter 11	HVT	400	100	H	0	Yes
Aurora 1	HVT	132	72	Double Star	0	Yes
Bacchus 1	HVY	132	72	Double Star	0	Yes
Bacchus 2	HVY	132	72	Double Star	0	Yes
Aurora 2	HVT	132	72	Double Star	0	Yes
Bernina 1	ASEA	132	72	Double Star	27	No
Beta 11	HVT	400	100	Single Star	1	Yes
Beta 12	HVT	400	100	Single Star	1	Yes
Bighorn 1	Westingcorp	275	142	Single Star	6	Yes
Buffalo 1	ASEA	132	36	Double Star	23	No
Carmel 1	Westingcorp	132	72	Double Star	27	No
Eiger 1	ASEA	88	48	Double Star	25	No
Eiger 2	ASEA	88	48	Double Star	25	No
Esselen 11	HVT	275	150	H	0	Yes
Everest 1	Westingcorp	132	72	Double Star	29	No
Everest 2	Westingcorp	132	72	Double Star	29	No
Foskor 1	ASEA	132	72	Double Star	26	No
Foskor 2	ASEA	132	72	Double Star	26	No
Georgedale 1	ASEA	132	66	Double Star	20	No
Grassridge 1	ASEA	132	36	Double Star	24	No
Grassridge 2	Westingcorp	132	36	Double Star	19	No
Grassridge 3	Westingcorp	132	72	Double Star	11	Yes
Grassridge 4	Westingcorp	132	72	Double Star	11	Yes
Hector 2	Westingcorp	275	150	Single Star	11	Yes
Hector 4	Westingcorp	275	150	Single Star	11	Yes
Hermes 11	Westingcorp	88	48	Double Star	20	No
Hermes 2	Westingcorp	132	72	Double Star	20	No
Hermes 3	Westingcorp	132	72	Double Star	20	No
Hydra 11	HVT	400	100	Single Star	1	Yes
Hydra 12	HVT	400	100	Non-PCB	1	Yes
Illovo 1	ASEA	132	66	Double Star	19	No
Illovo 2	ABB	275	100	H	13	Yes
Impala 1	Westingcorp	132	80	Double Star	13	Yes
Impala 2	Westingcorp	132	80	Double Star	13	Yes
Impala 3	Westingcorp	132	80	Double Star	13	Yes
Impala 4	ABB	275	100	H	13	Yes
Jupiter 1	Westingcorp	88	48	Double Star	20	No
Jupiter 2	Westingcorp	88	48	Double Star	20	No
Jupiter 3	Westingcorp	275	150	Single Star	13	Yes
Jupiter 4	Westingcorp	275	150	Single Star	13	Yes

Komatipoort 1	Westingcorp	132	33	Single Star	23	Yes
Leander 2	ASEA	132	36	Double Star	23	No
Leseding 1	Westingcorp	132	72	Double Star	2	Yes
Leseding 2	Westingcorp	132	72	Double Star	2	Yes
Marang 1	Westingcorp	88	48	Double Star	2	Yes
Marang 2	Westingcorp	88	48	Double Star	2	Yes
Merapi 1	Westingcorp	132	36 (72)	Double Star	16	Yes
Merensky 1	HTSA	132	63	Double Star	7	Yes
Mercury 1	ASEA	132	72	Double Star	17	No
Mercury 2	ASEA	132	72	Double Star	17	No
Mercury 11	HVT	275	150	Single Star	0	Yes
Mercury 12	HVT	275	150	Single Star	0	Yes
Mersey 1	HVT	275	150	Single Star	0	Yes
Mersey 2	HVT	275	150	Single Star	1	Yes
Midas 2	Westingcorp	132	72	Double Star	20	No
Minerva 1A	ASEA	275	131	Double Star	28	No
Minerva 1B	ASEA	275	146	Double Star	28	No
Minerva 2A	Westingcorp	275	150	Single Star	2	Yes
Minerva 2B	Westingcorp	275	150	Single Star	2	Yes
Muldersvlei 1	ABB	132	72	H	12	Yes
Muldersvlei 2	ABB	132	72	H	12	Yes
Muldersvlei 3	ABB	132	72	H	12	Yes
Muldersvlei 4	HVT	132	72	Double Star	0	Yes
Muldersvlei 5	Westingcorp	400	100	Single Star	12	Yes
Normandie 1	HVT	88	48	Double Star	1	Yes
Oranjemond 2	Nokia	66	15	H	33	No
Pembroke 1	ASEA	132	36	Double Star	24	No
Pembroke 2	ASEA	132	36	Double Star	24	No
Perseus 2	HVT	400	100	Single Star	1	Yes
Perseus 4	HVT	400	100	Single Star	1	Yes
Pieterboth 1	ASEA	88	48	Double Star	25	No
Pluto 1A	ASEA	275	144	Double Star	28	No
Pluto 1B	ASEA	275	156	Double Star	28	No
Princess 1	ASEA	88	48	Double Star	25	No
Proteus 1	HVT	132	72	Double Star	0	Yes
Rigi 1	ASEA	88	48	Double Star	23	No
Rigi 2	ASEA	88	48	Double Star	23	No
Stikland 1	Westingcorp	132	72	Double Star	18	Yes
Stikland 2	Westingcorp	132	72	Double Star	18	Yes
Stikland 3	Westingcorp	132	72	Double Star	18	Yes
Spitskop 1	ASEA	88	48	Double Star	27	No
Spitskop 2	ASEA	88	48	Double Star	17	No
Spitskop 3	Westingcorp	132	36	Double Star	17	No
Taunus 1	Westingcorp	132	72	Double Star	20	No
Theseus 1	Westingcorp	132	72	Double Star	18	No
Trident 1	ASEA	88	48	Double Star	25	No
Trident 2	ASEA	88	48	Double Star	17	No
Umfolozi 1	HVT	88	48	Double Star	1	Yes
Venus 1	ABB	275	150	H	0	Yes
Vulcan 1	Westingcorp	132	72	Double Star	18	No
Vulcan 2	ASEA	132	72	Double Star	22	No
Watershed 1	ASEA	88	48	Double Star	21	No
Westgate 1	Westingcorp	132	72	Double Star	21	No
Westgate 2	Westingcorp	132	72	Double Star	19	No
Witkop 1	ASEA	132	36	Double Star	25	No
Witkop 2	HTSA	132	72	Double Star	4	Yes

Simulation reference sheet

Simulations on Y - Y Shunt Capacitor bank

Fault location (% of feeder)	Fault type with duration of fault: ø-E 100ms	ø -ø 100ms	ø-ø-E 100ms	3ø 100ms
1%	B-1	B-2	B-3	B-4
10%	B-5	B-11	B-13	B-15
20%	B-9	B-10	B-11	B-12
50%	B-13	B-14	B-15	B-16
98%	B-17	B-18	B-19	B-20

Location	Busbar fault type with duration of fault: ø-E 100ms	ø -ø 100ms	ø-ø-E 100ms	3ø 100ms
On 275kV BB	B-21	B-22	B-23	B-24
On 132kV BB	B-25	B-26	B-27	B-28
On 44kV BB	B-29	B-30	B-31	B-32

Simulations on Yn - Yn Shunt Capacitor bank

Fault location (% of feeder)	Fault type with duration of fault: ø-E 100ms	ø -ø 100ms	ø-ø-E 100ms	3ø 100ms
1%	B-33	B-34	B-35	B-36
10%	B-37	B-38	B-39	B-40
20%	B-41	B-42	B-43	B-44
50%	B-45	B-46	B-47	B-48
98%	B-49	B-50	B-51	B-52

Location	Busbar fault type with duration of fault: ø-E 100ms	ø -ø 100ms	ø-ø-E 100ms	3ø 100ms
On 275kV BB	B-53	B-54	B-55	B-56
On 132kV BB	B-57	B-58	B-59	B-60
On 44kV BB	B-61	B-62	B-63	B-64

Additional simulations

Switching event	Page
Switching in a SCB	B-65
Internal fault on Y-Y SCB	B-66
Internal fault on Yn-Yn SCB	B-67

Key

SCB = Shunt Capacitor Bank
Y-Y = Star- Star Unearthed Shunt Capacitor Bank
Yn -Yn = Star- Star Earthed Shunt Capacitor Bank

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Data source:

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Info: DIgSILENT PowerFactory

Time Signal:

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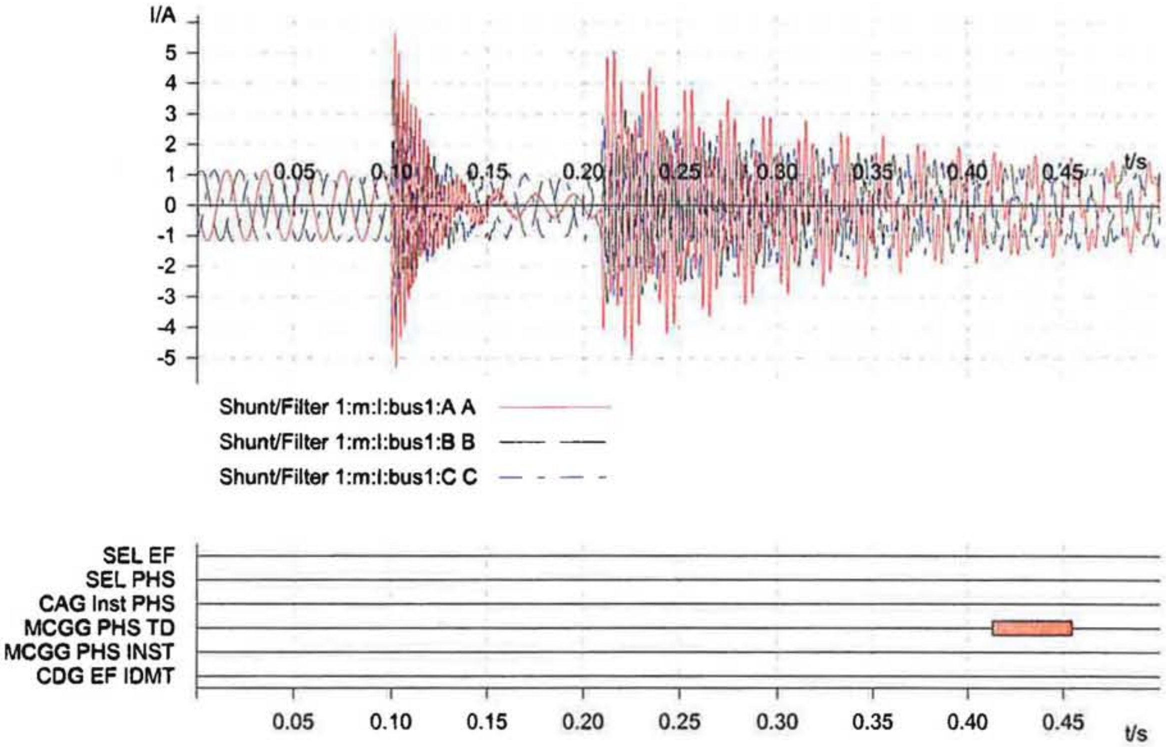

B-1

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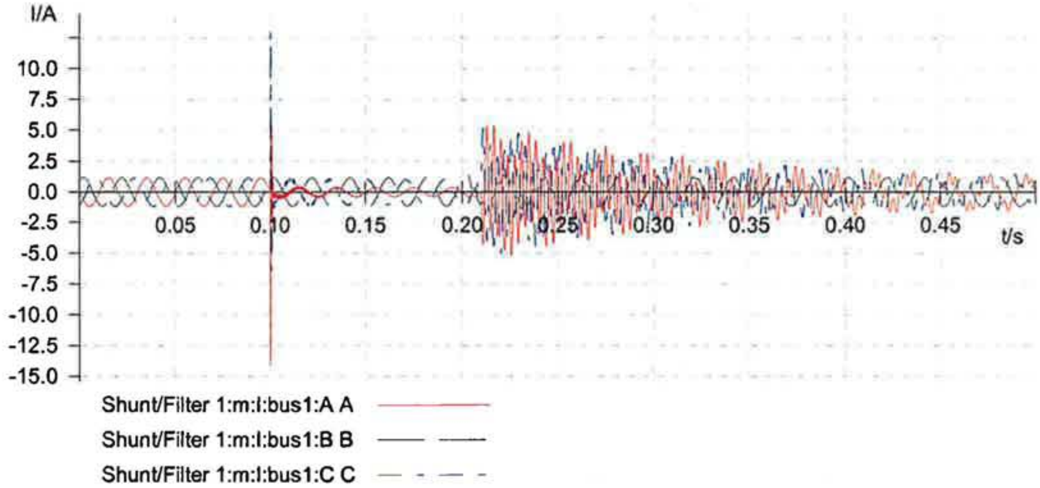

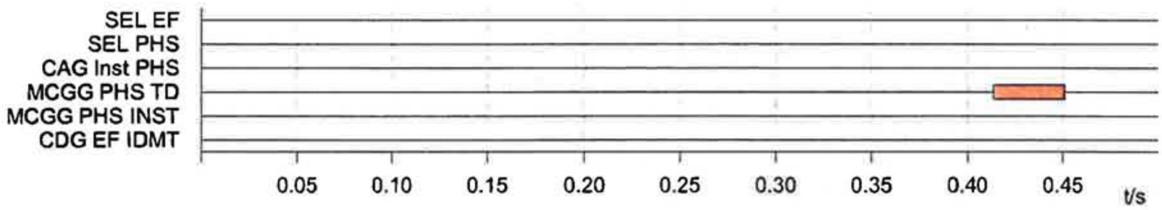

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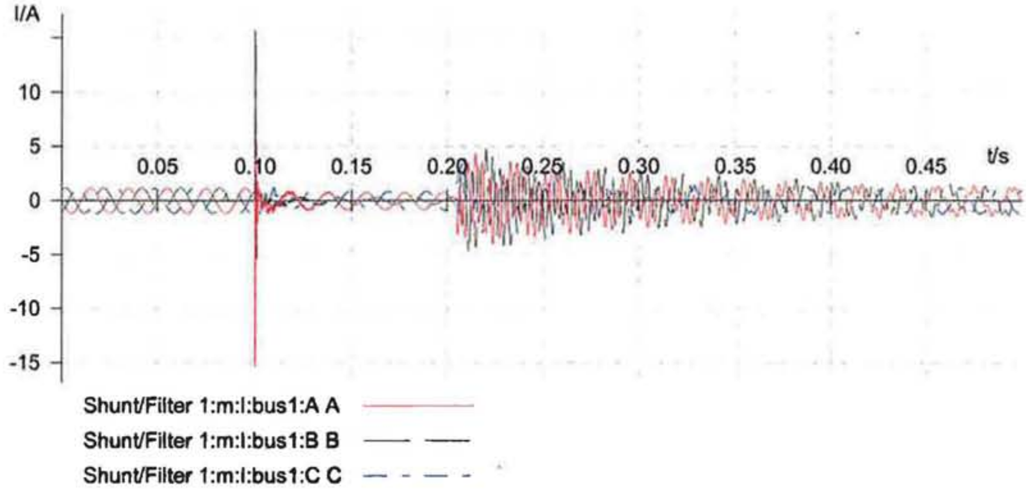

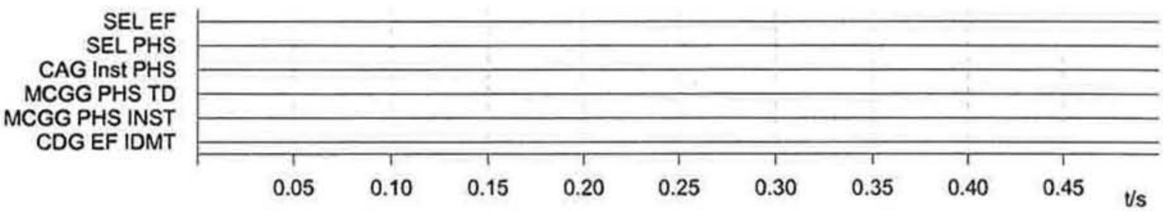

B-3

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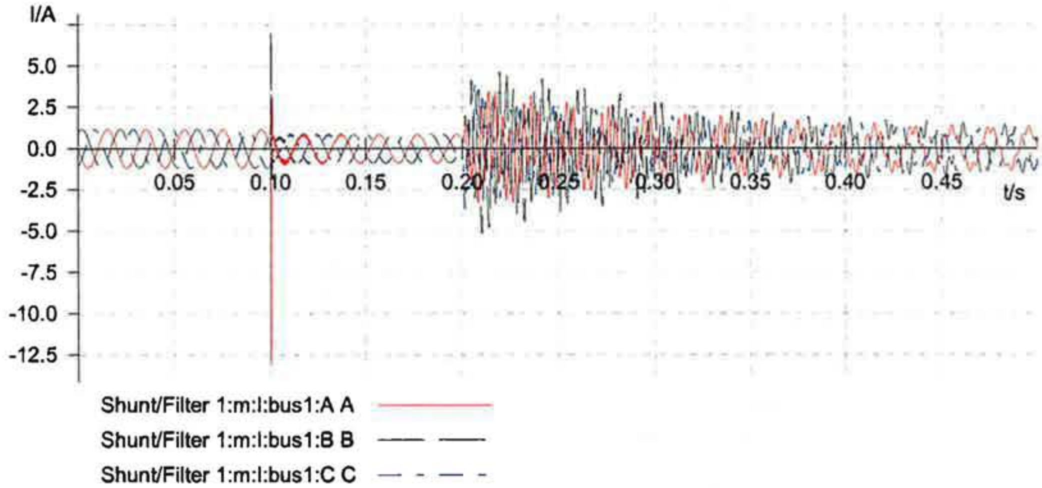

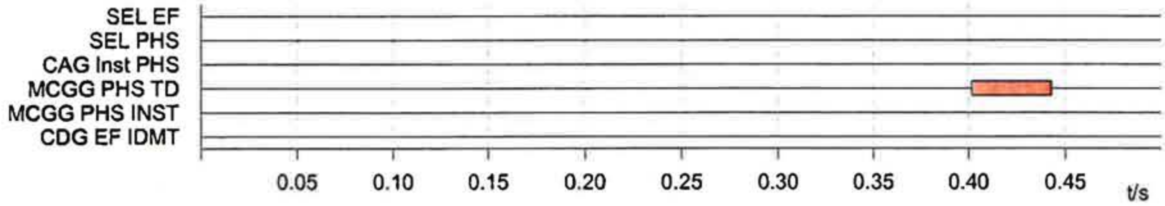

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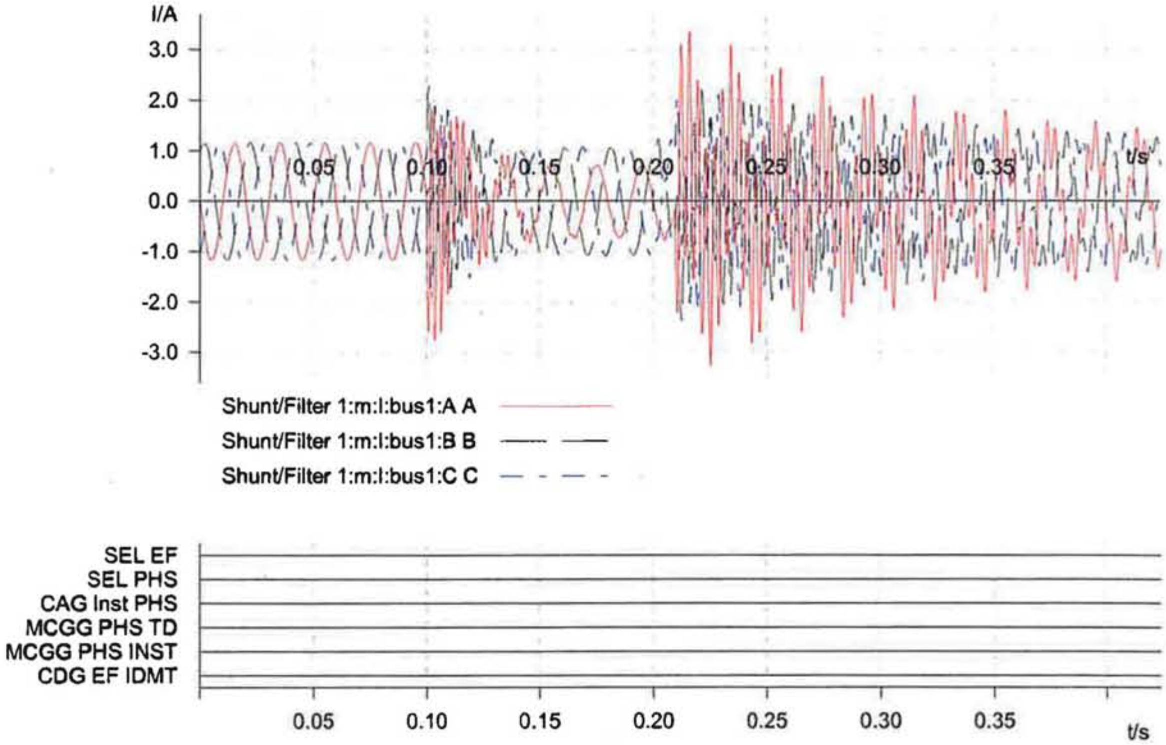

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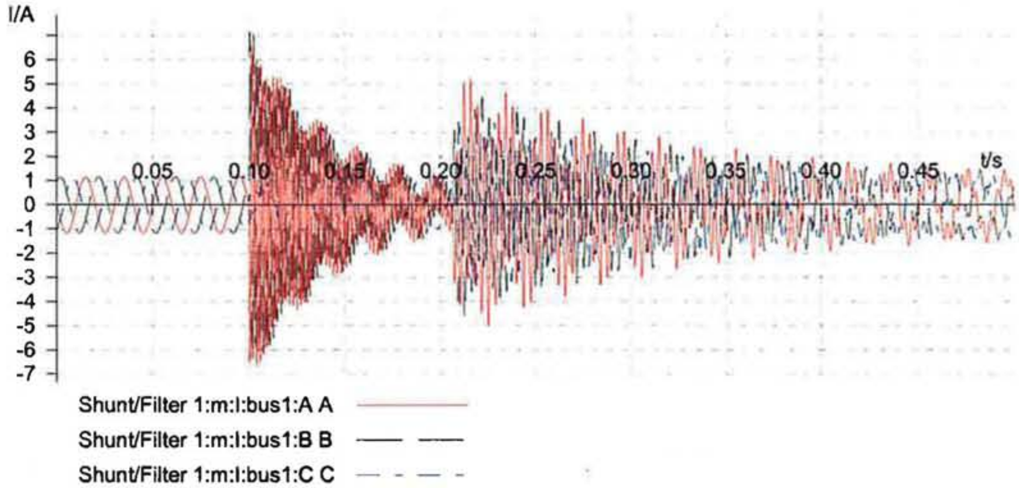

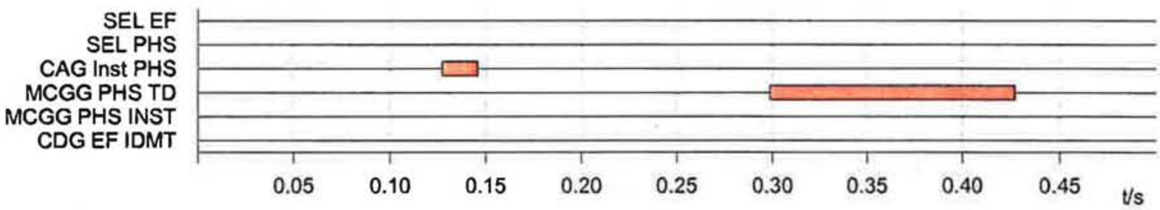

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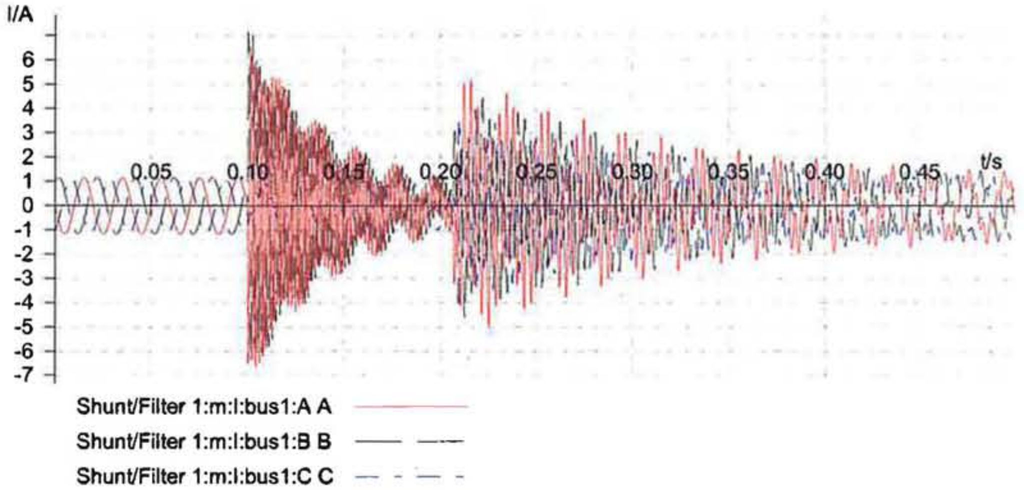

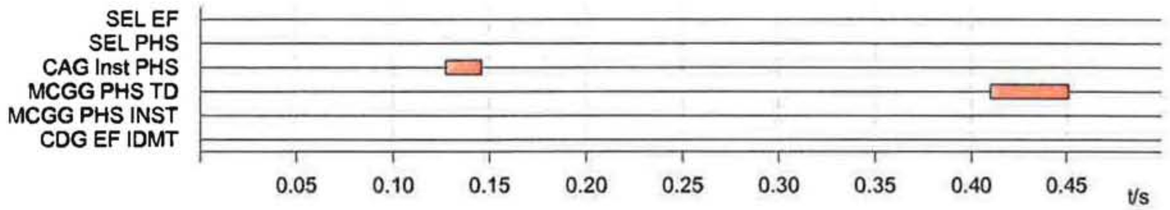

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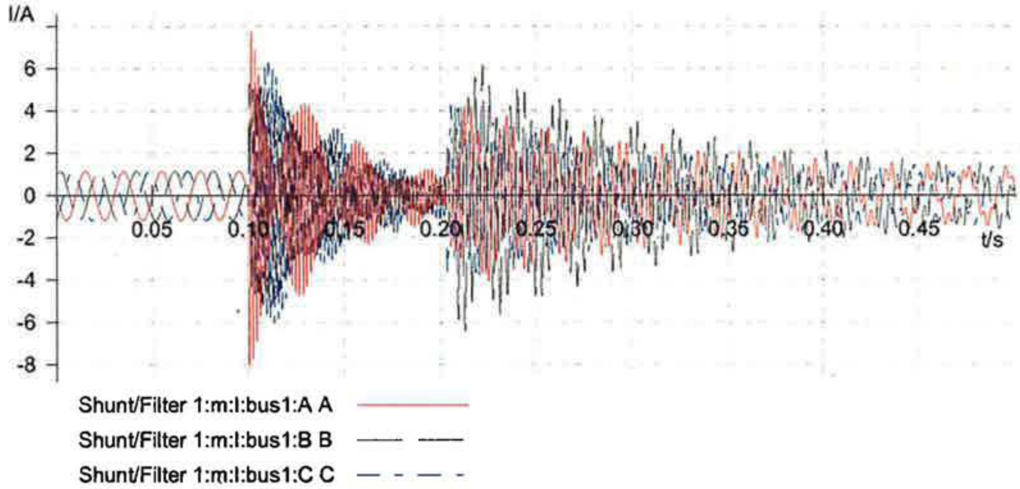

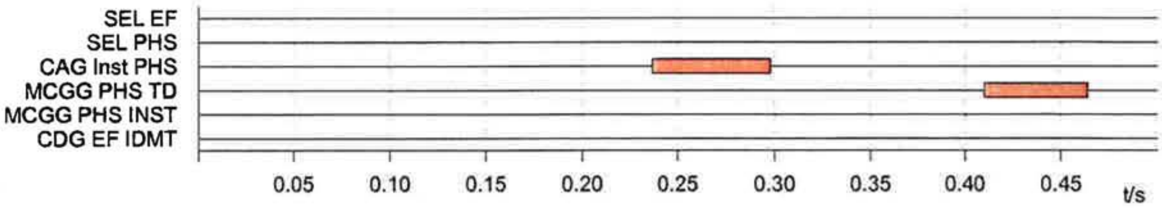

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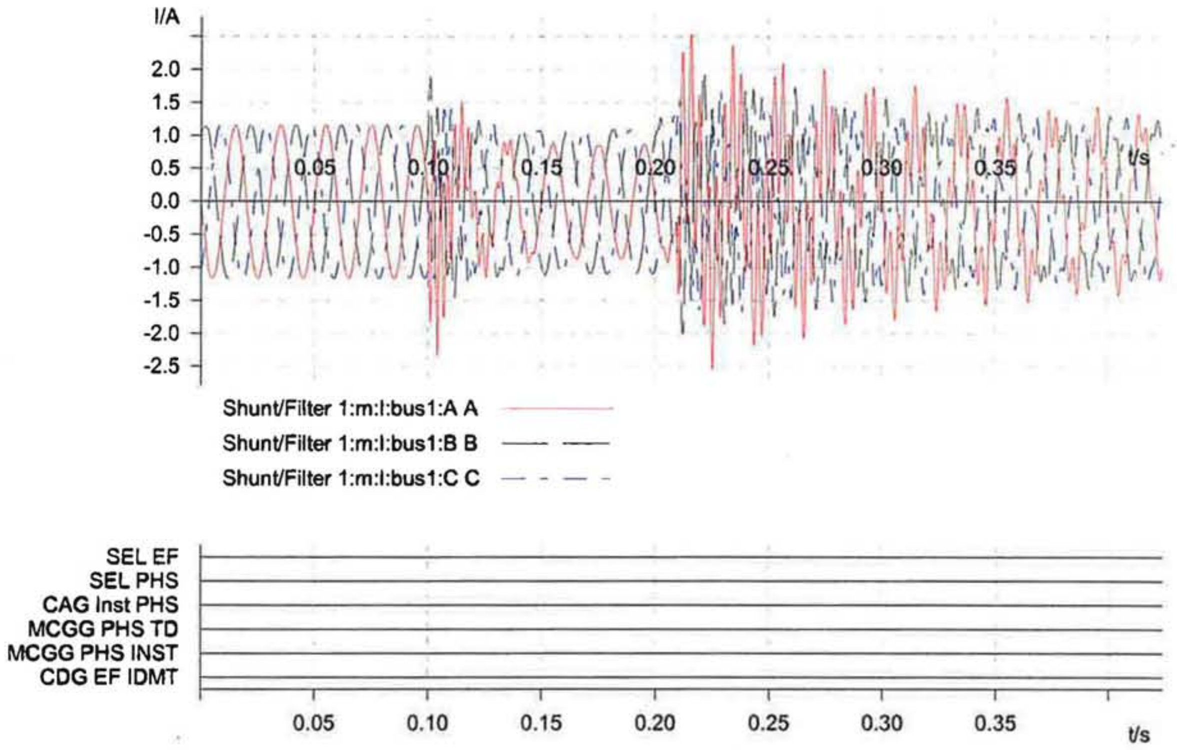

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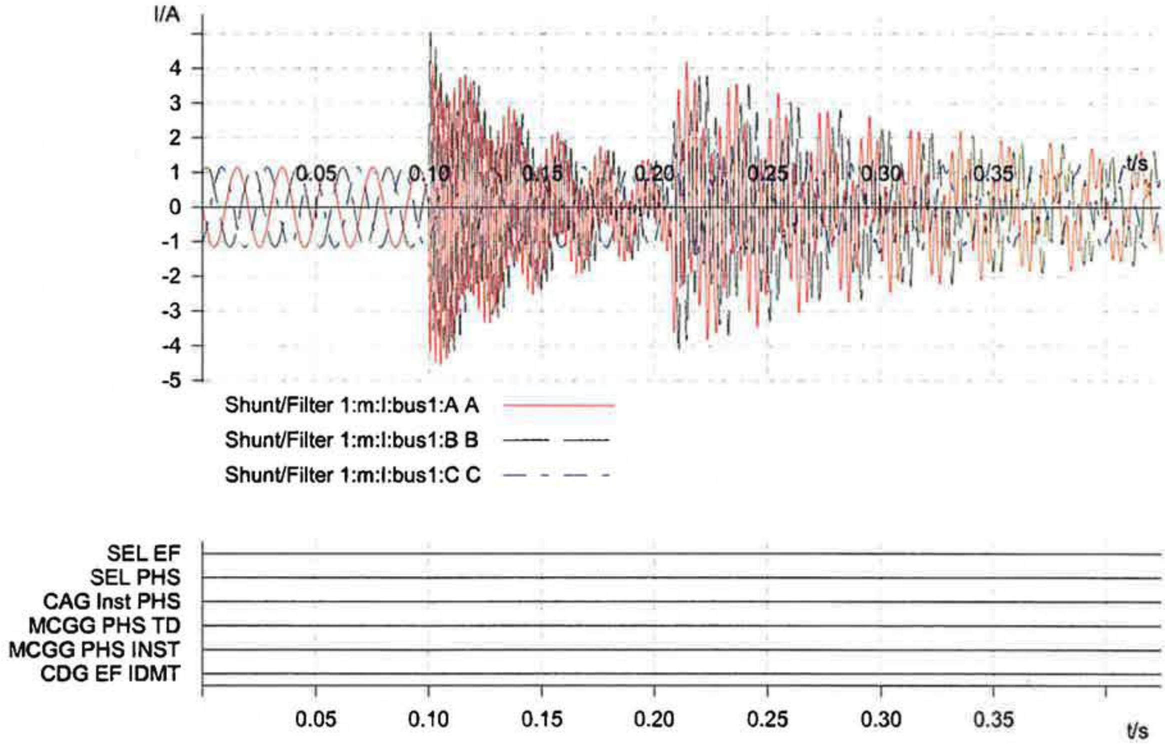

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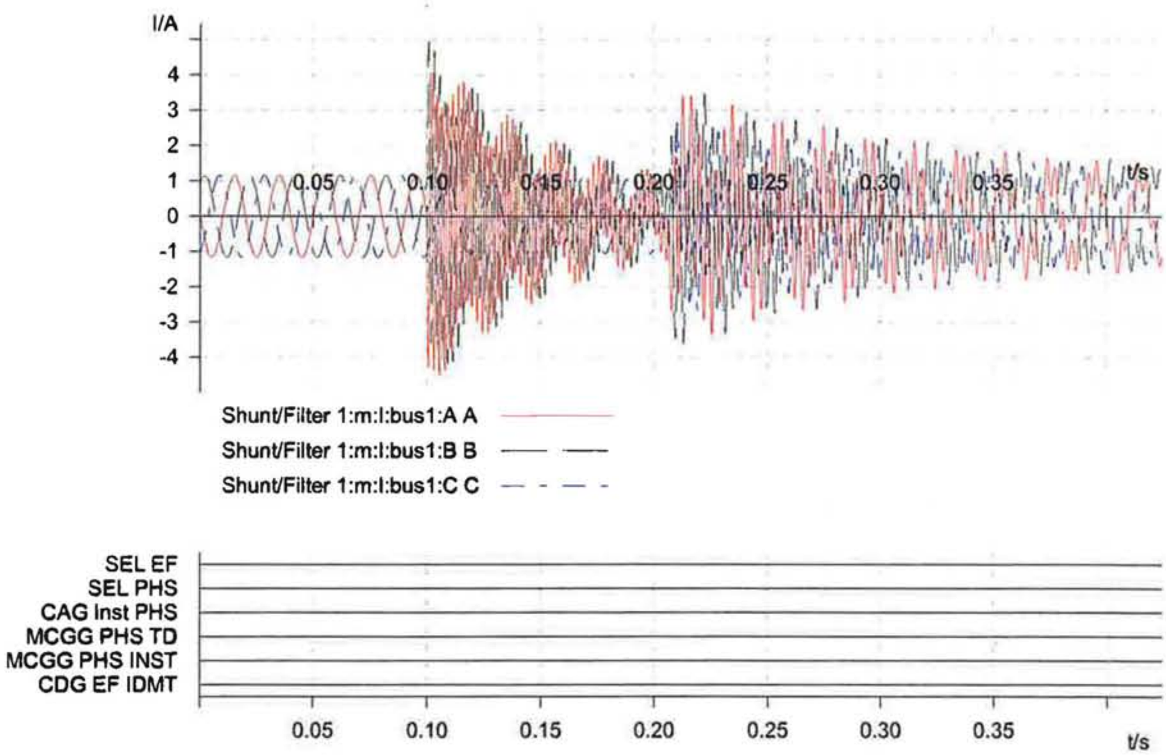

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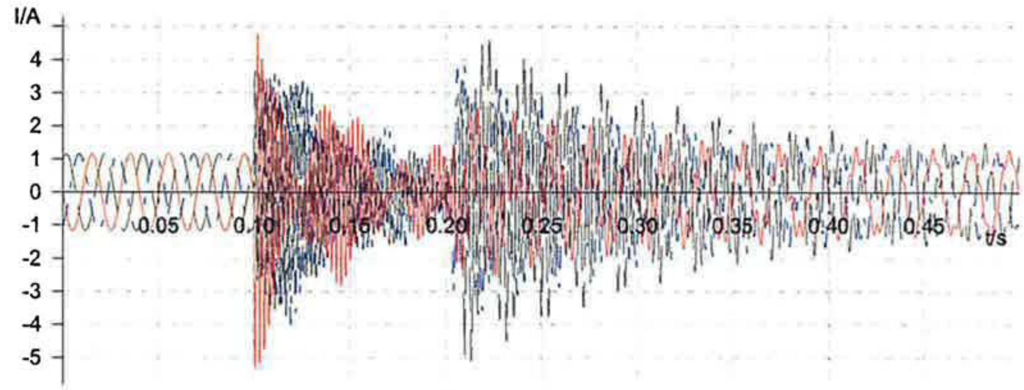

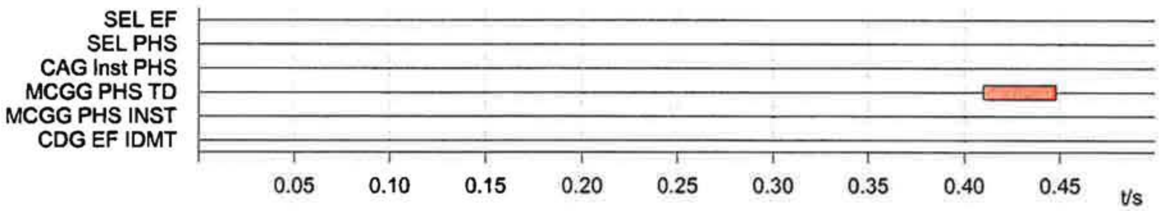

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Info: DIgSILENT PowerFactory

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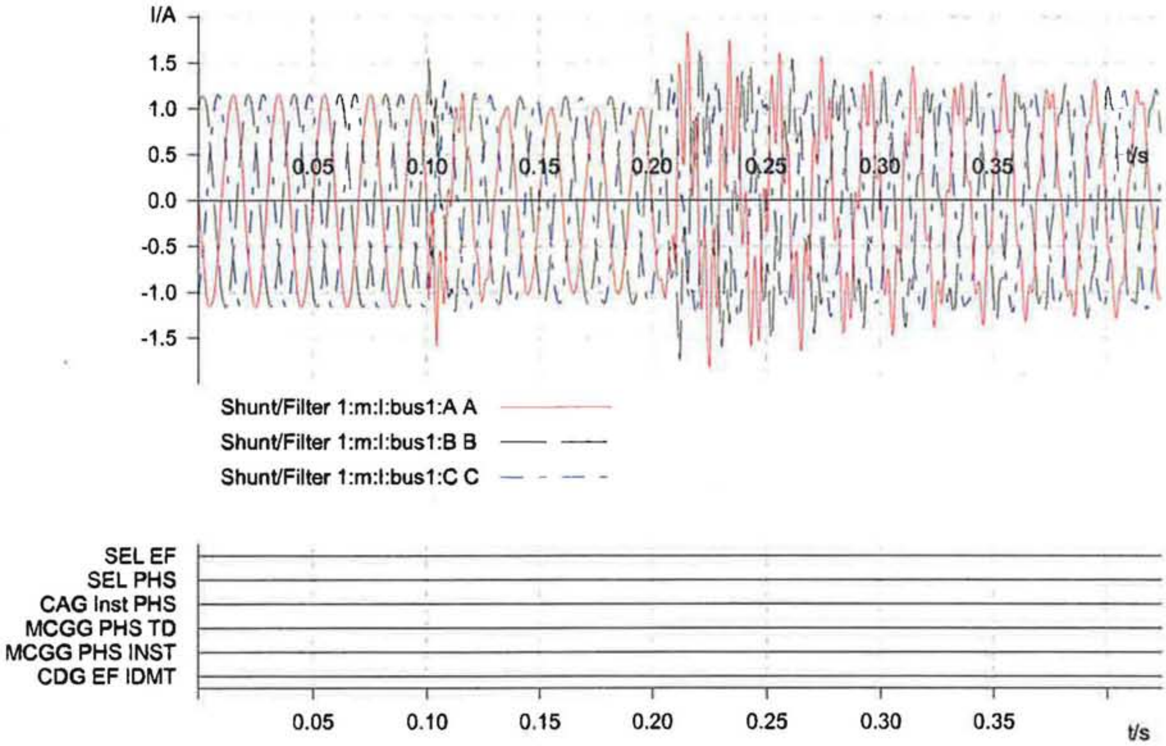

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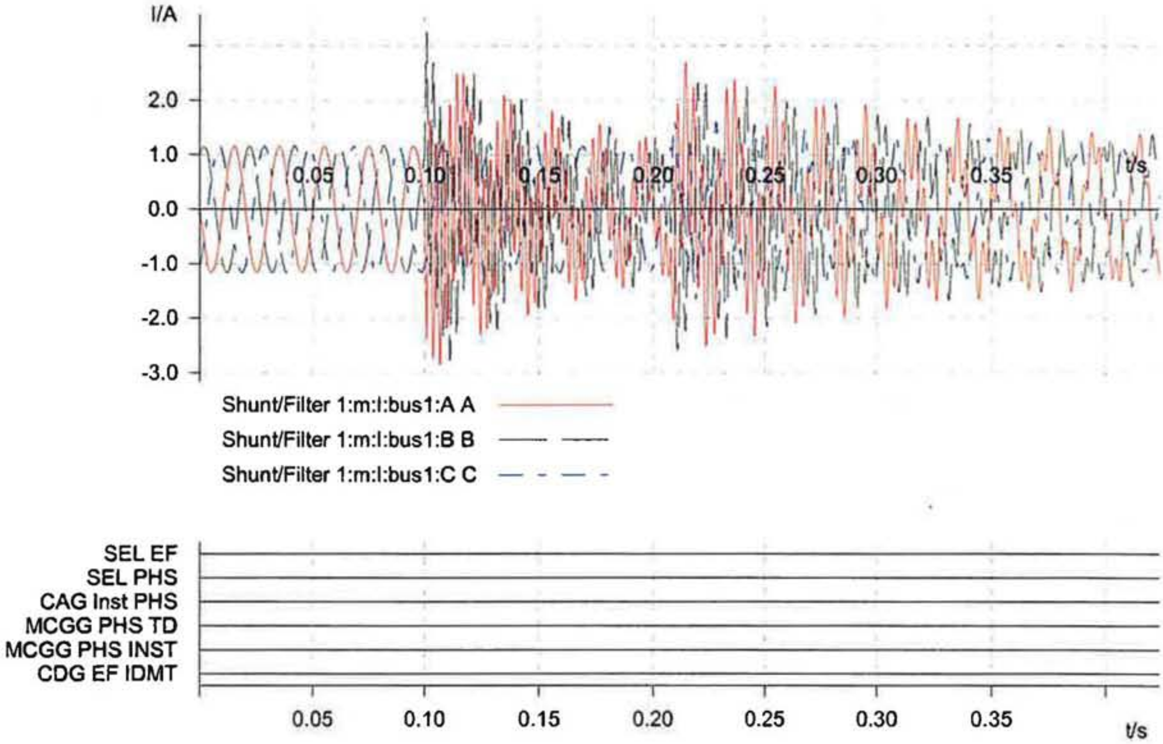

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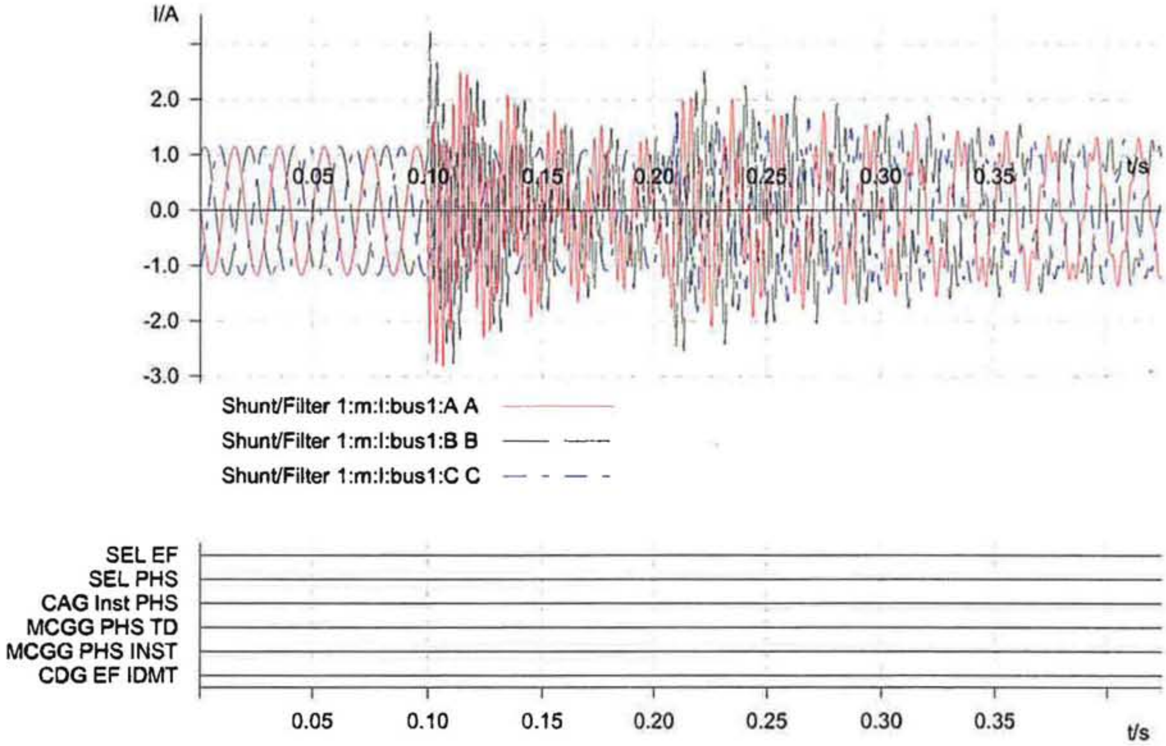

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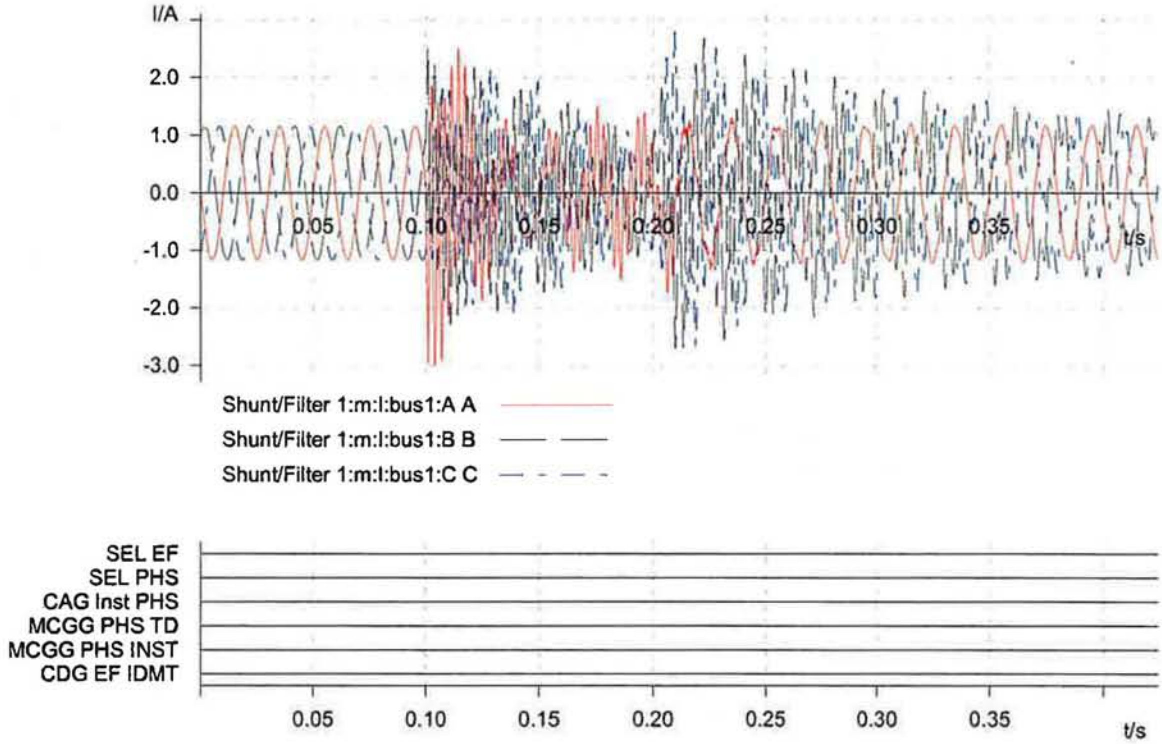

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File: FAULTAT98%OFLINE1P_100MS.CFG

Info: DIgSILENT PowerFactory

Time Signal:

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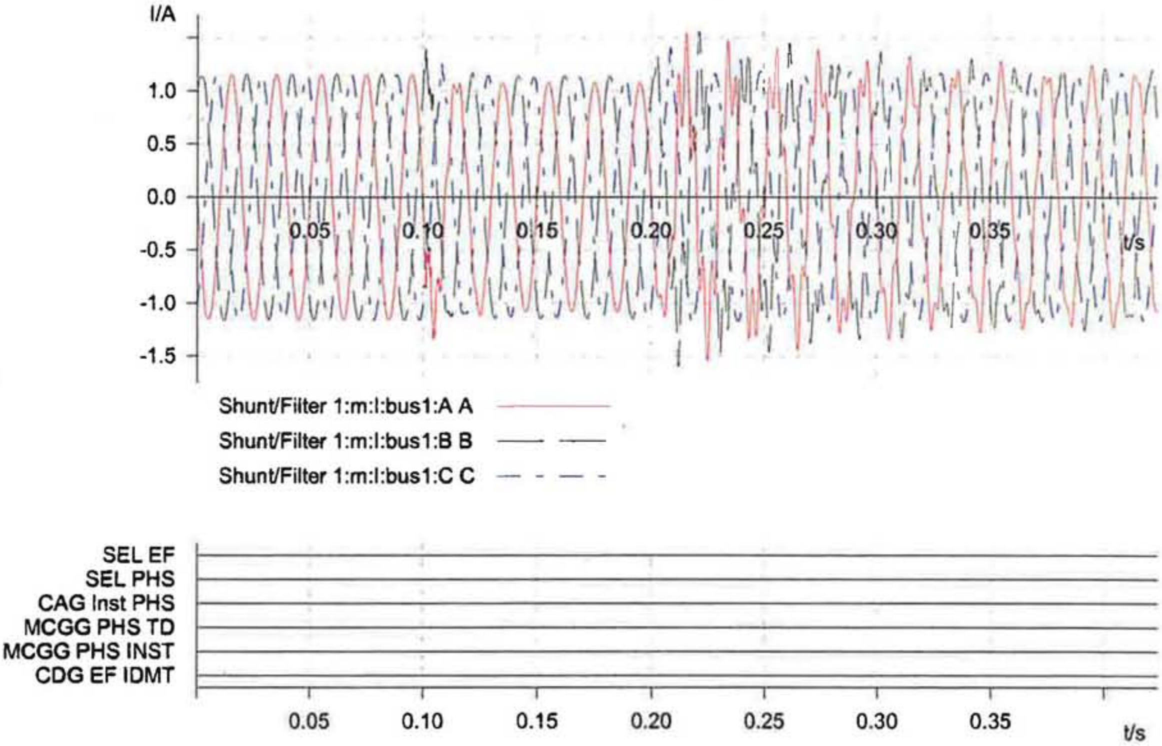

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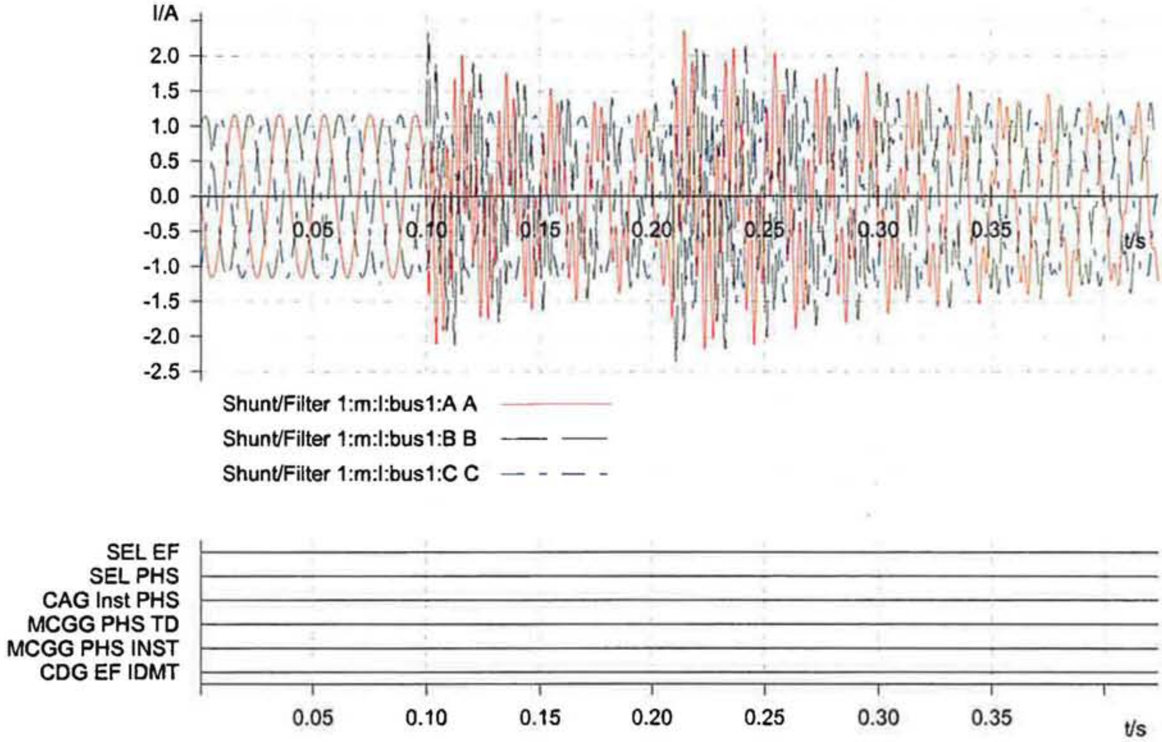

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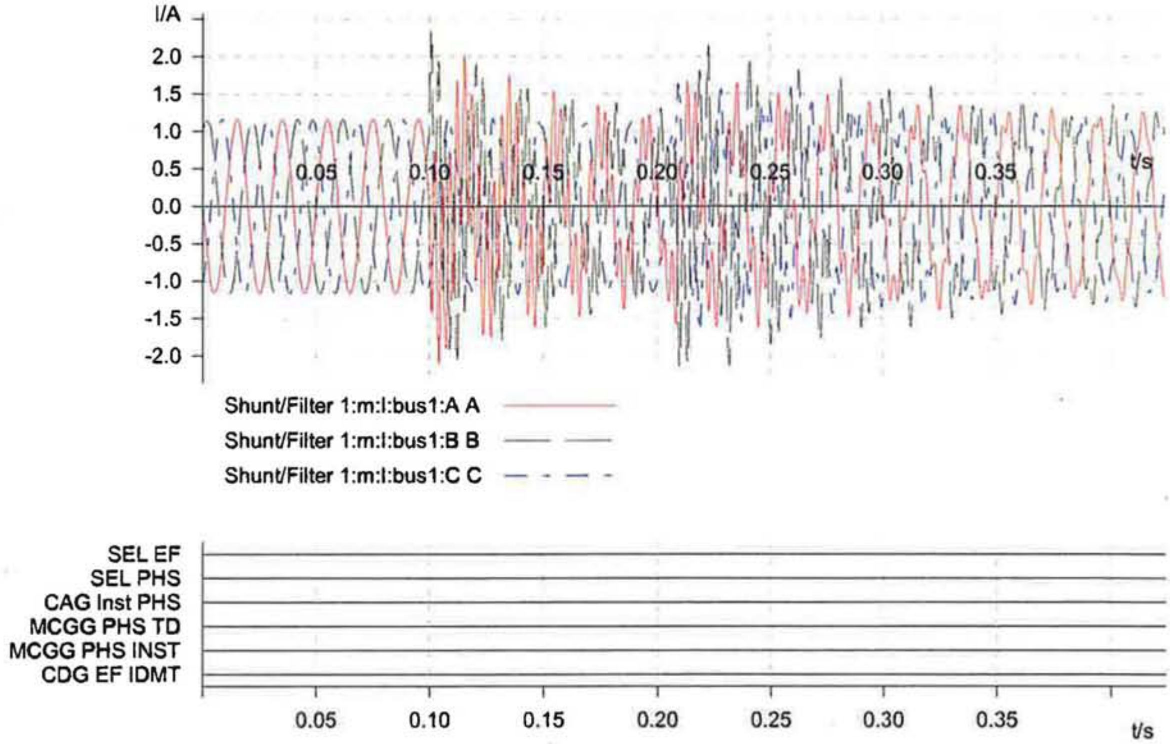

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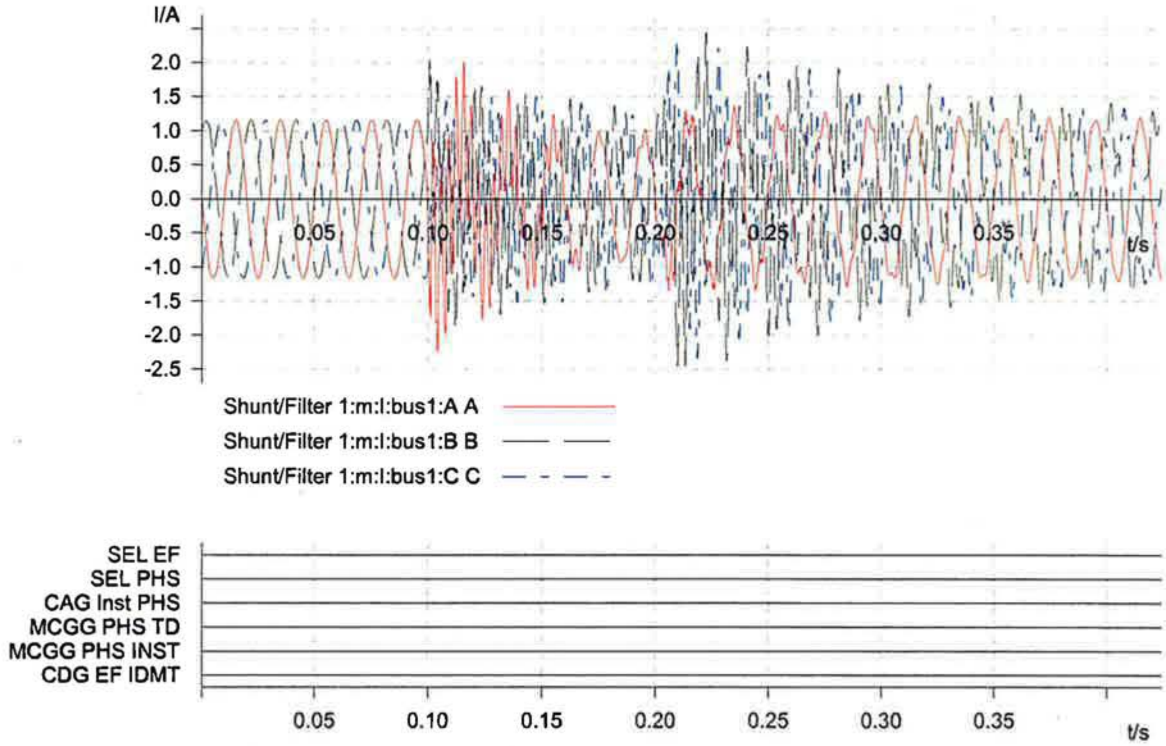

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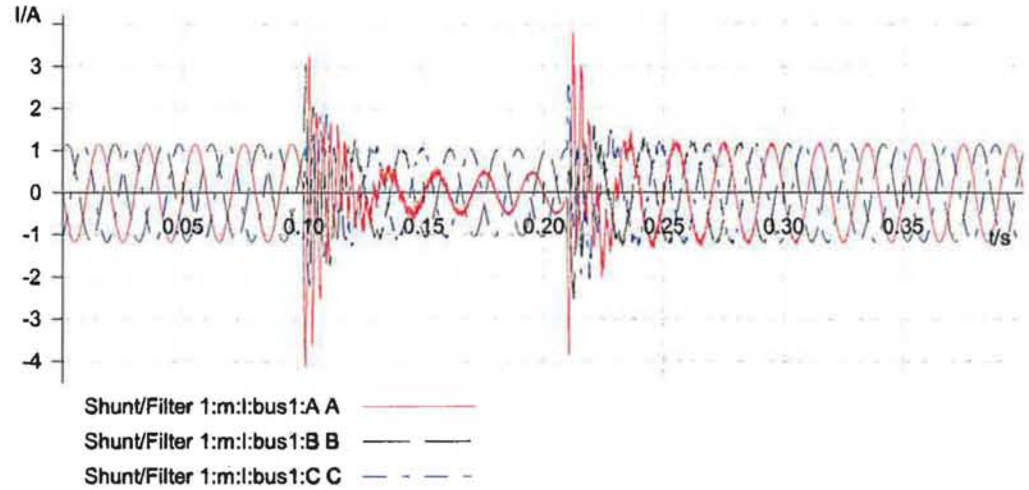
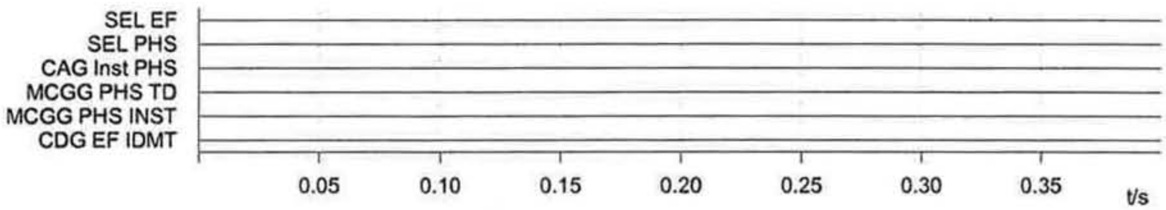
File: FAULTATWG275KVBB1P_100MS.CFG
Info: DIgSILENT PowerFactory

Time Signal:

Measurement no.: 1





revana.tra

Data source:

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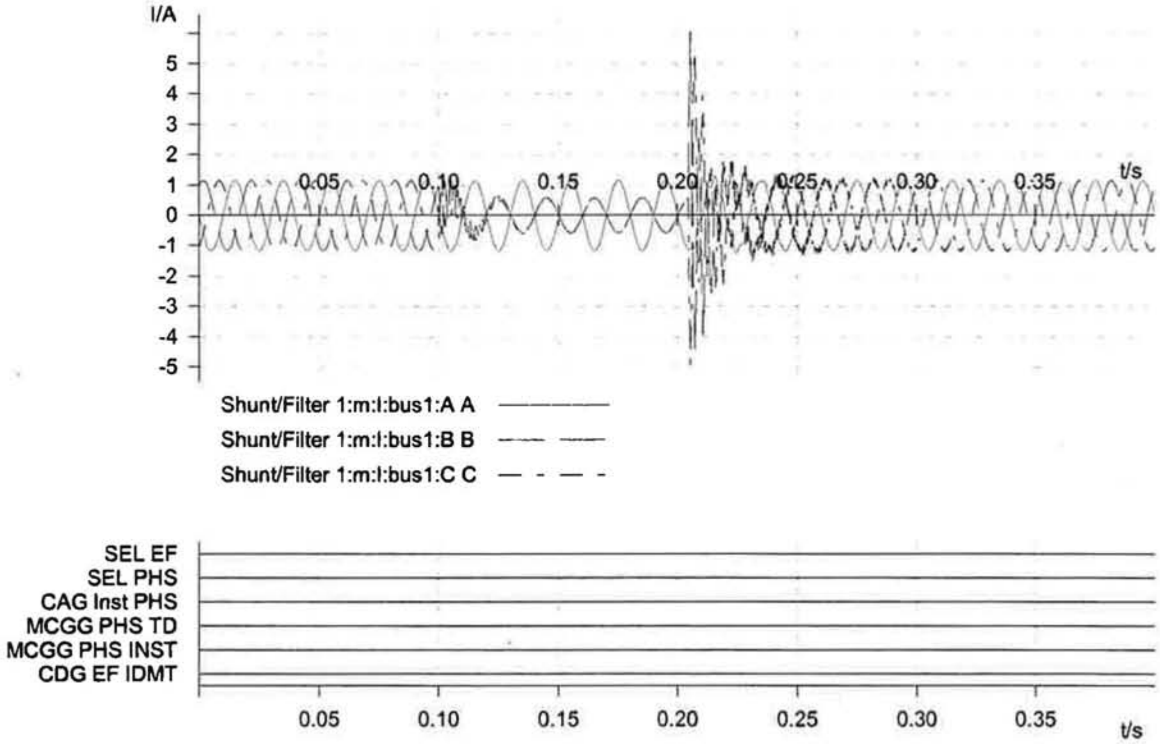
Info: DIgSILENT PowerFactory

Time Signal:

Measurement no.: 1



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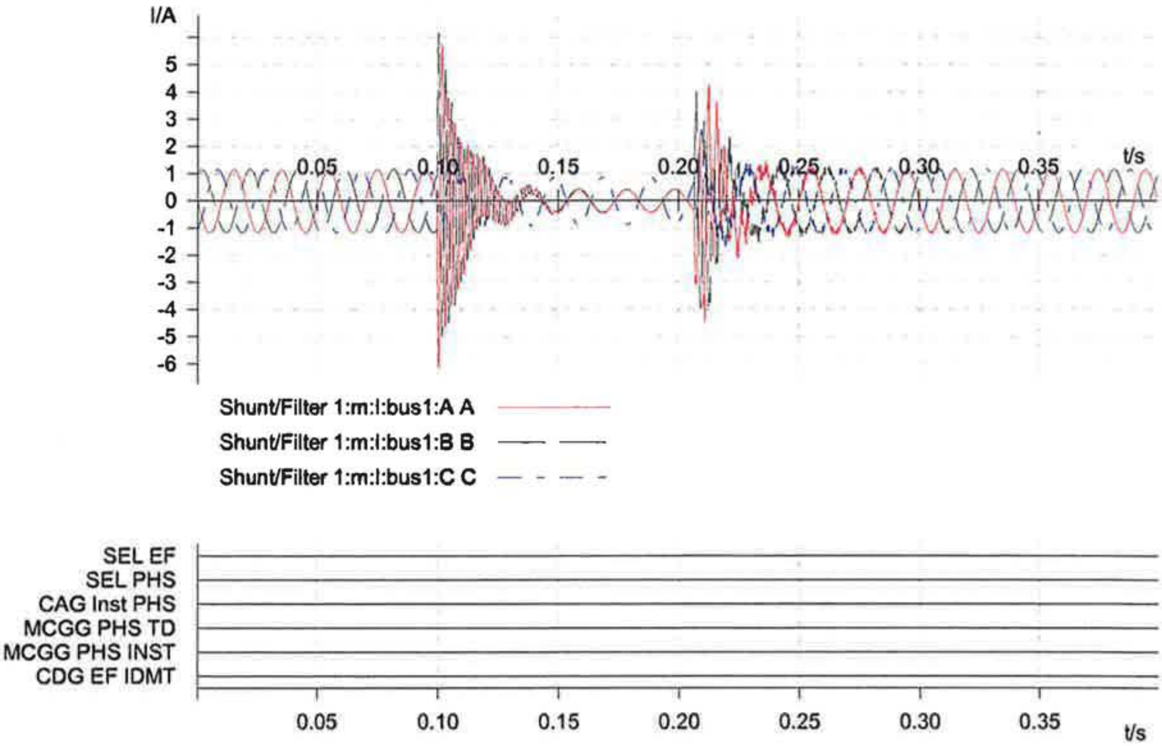
Info:	DigSILENT PowerFactory

Time Signal:

Measurement no.: 1



B-23

revana.tra

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Info: DIgSILENT PowerFactory

Time Signal:

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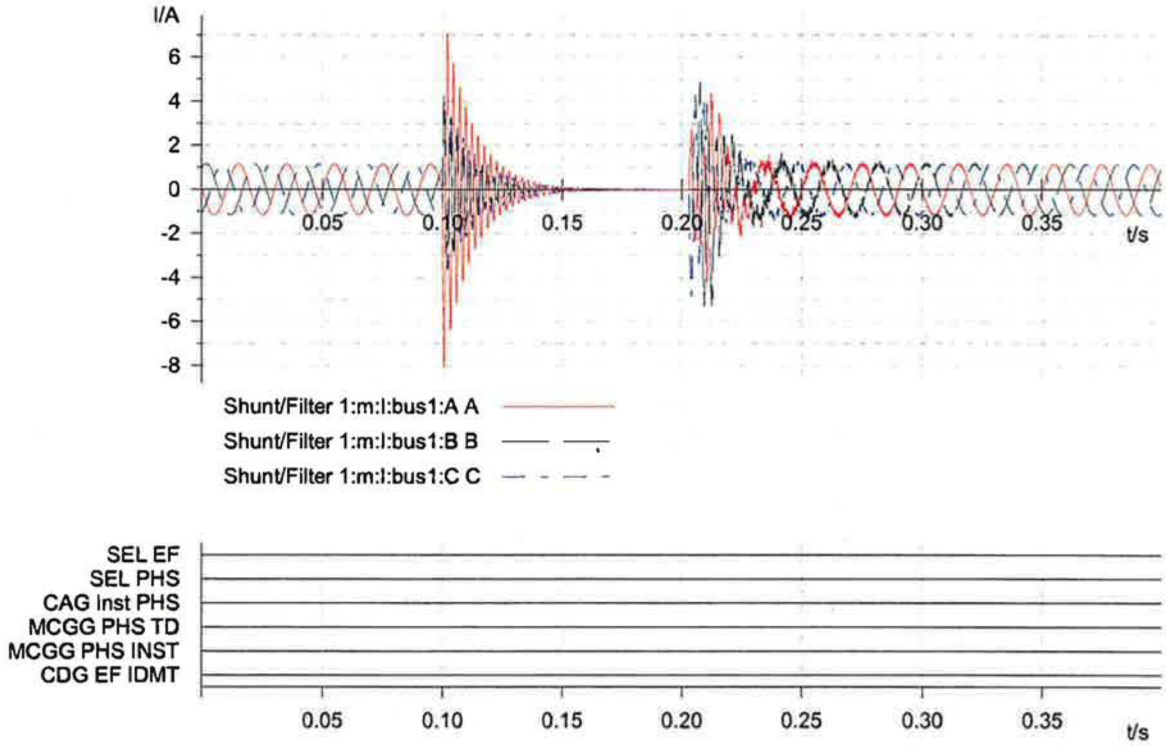

revana.tra

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Info: DIgSILENT PowerFactory

Time Signal:

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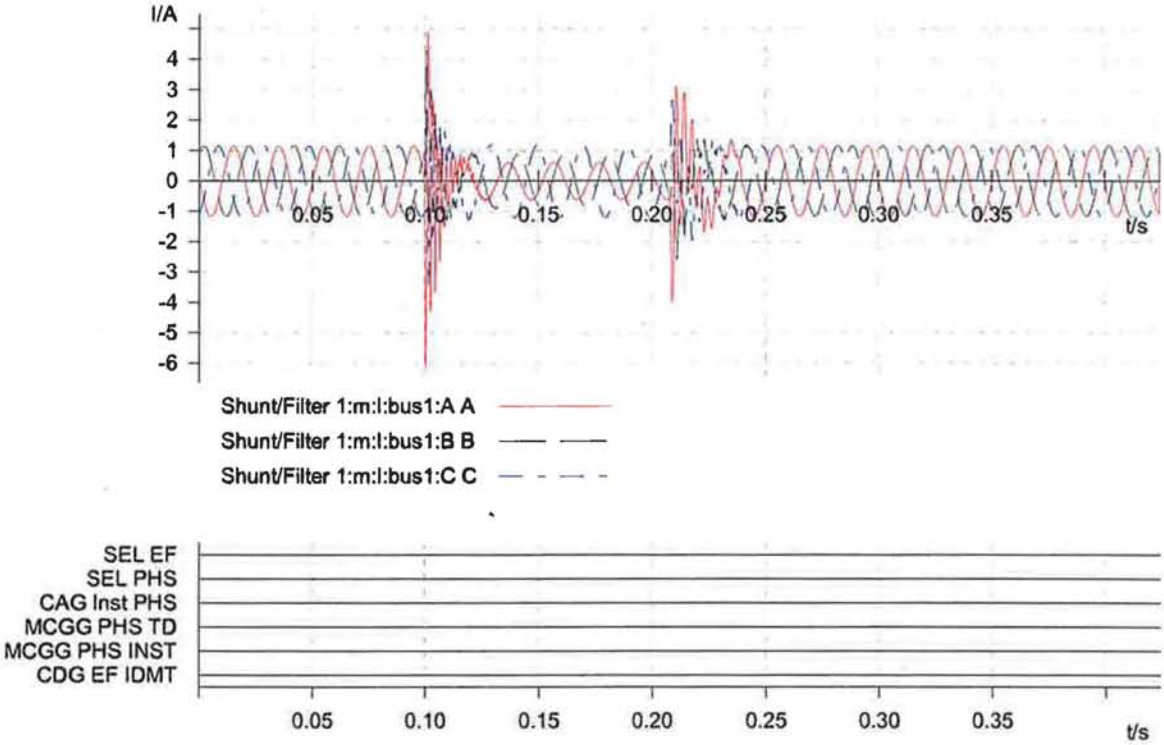

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Time Signal:

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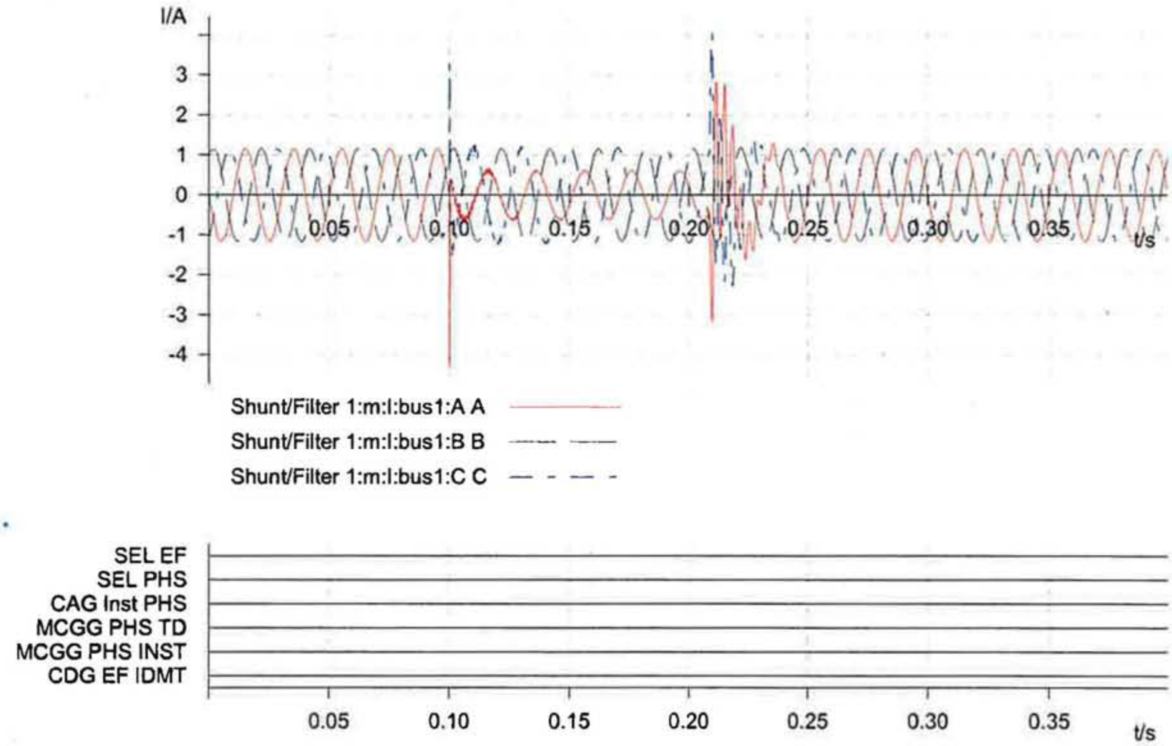

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Time Signal:

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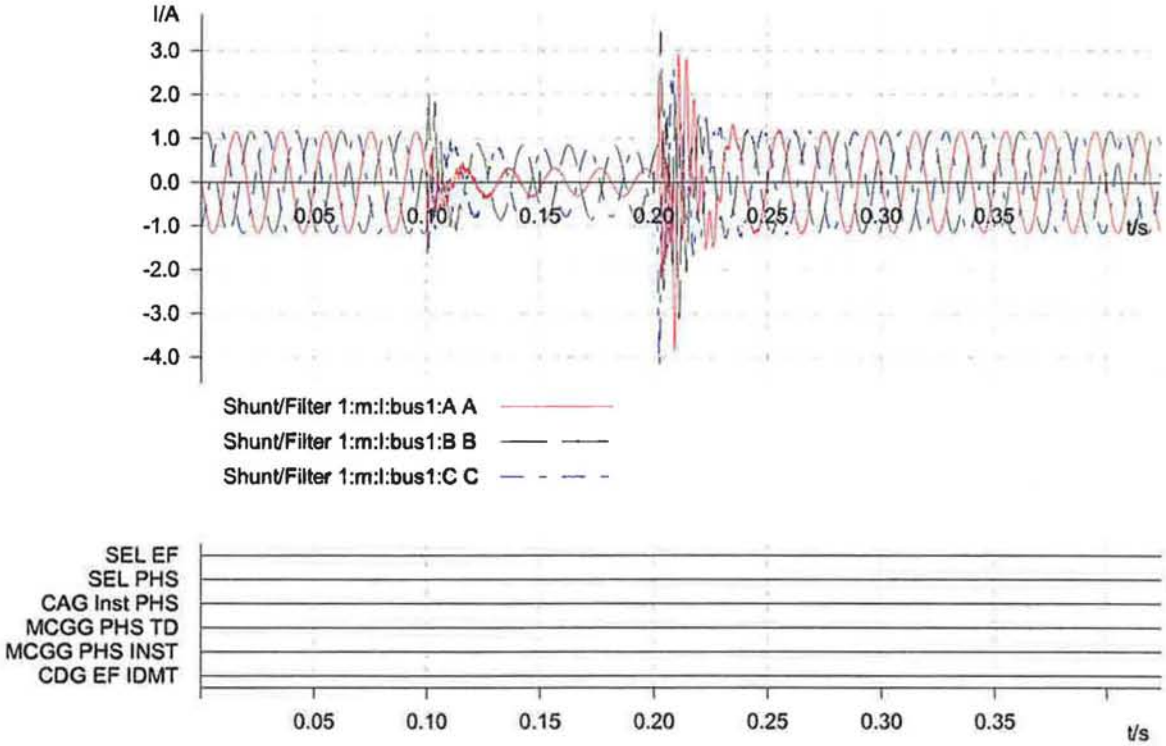

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Info:	DIgSILENT PowerFactory

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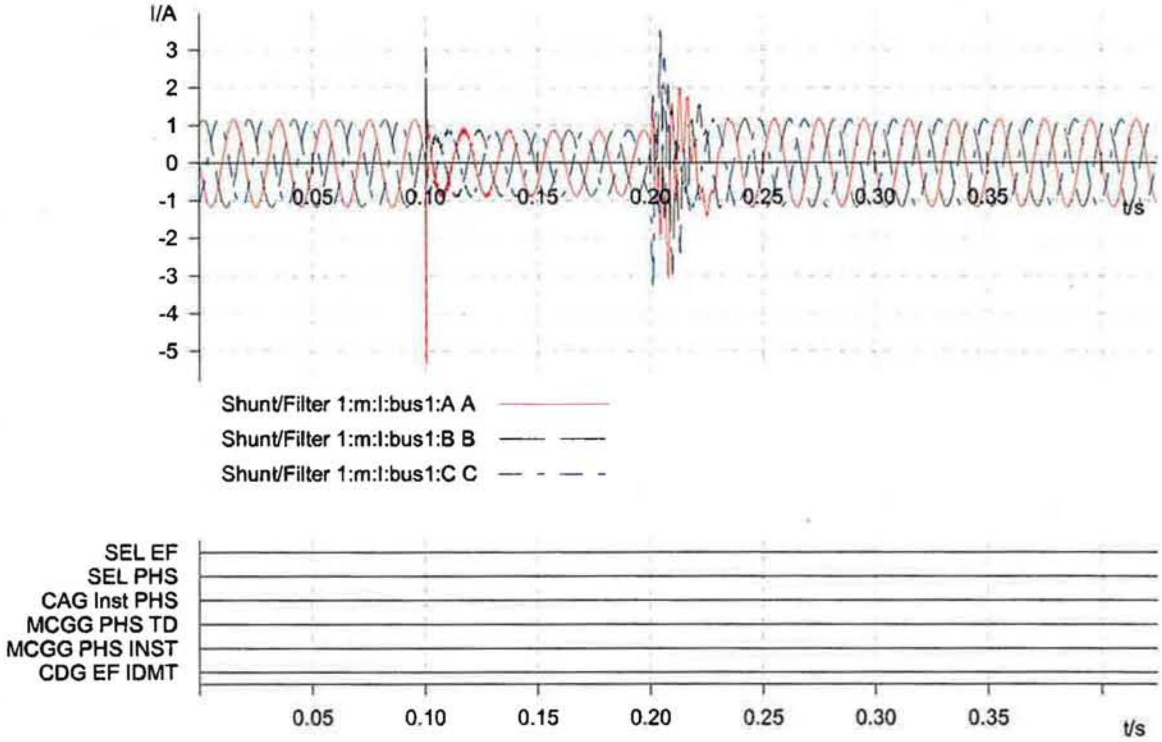

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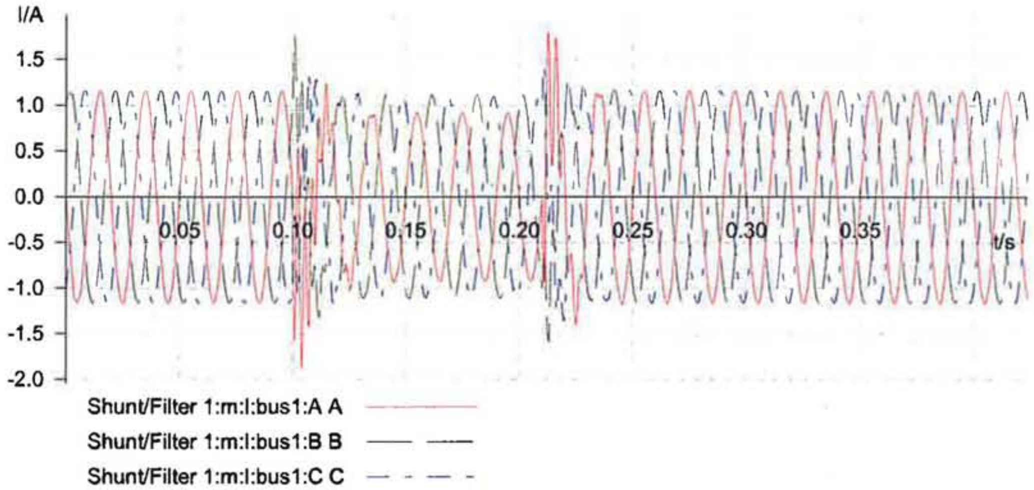
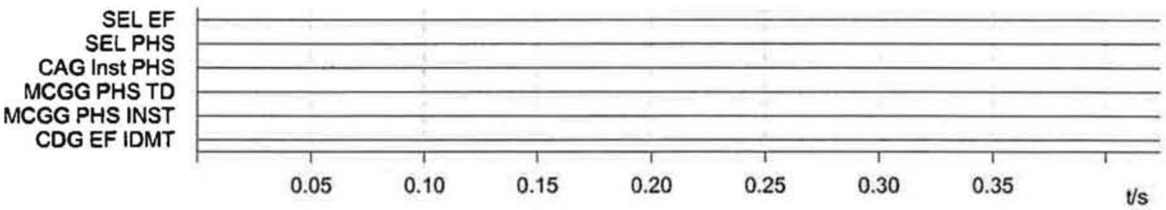
Info:	DIgSILENT PowerFactory

Time Signal:

Measurement no.: 1





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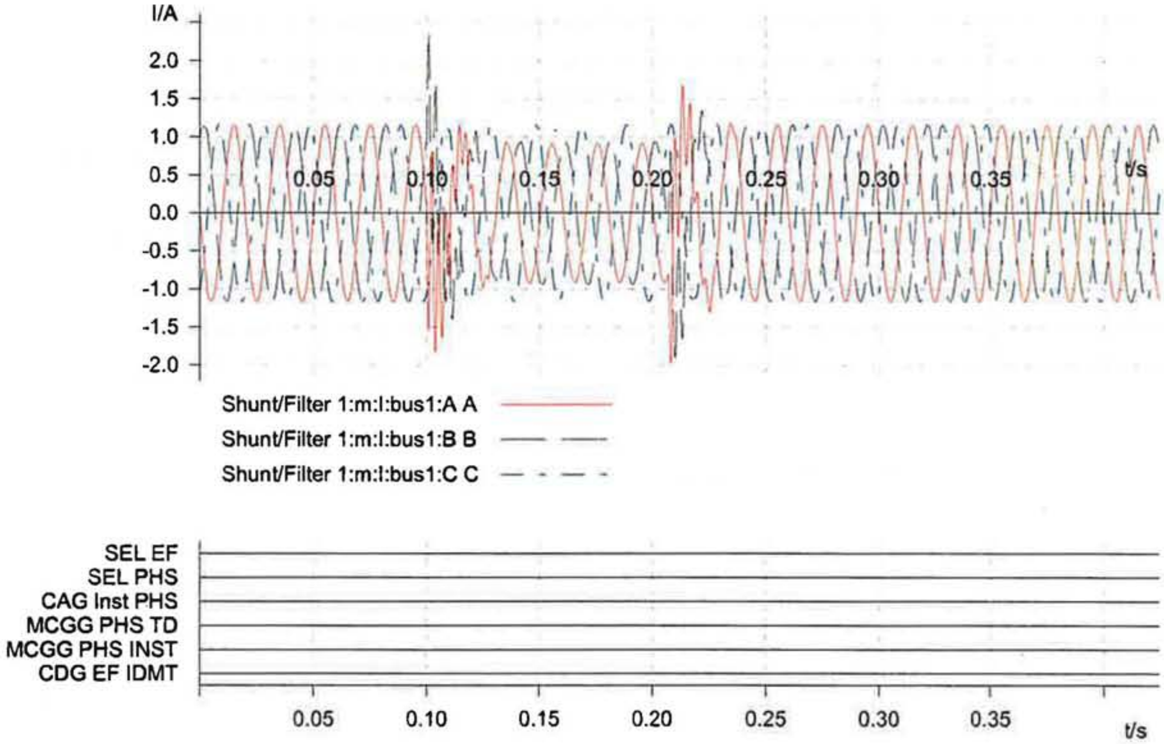
Info: DIgSILENT PowerFactory

Time Signal:

Measurement no.: 1



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File: FAULTAT44KVBB2PE_100MS.CFG

Info: DIgSILENT PowerFactory

Time Signal:

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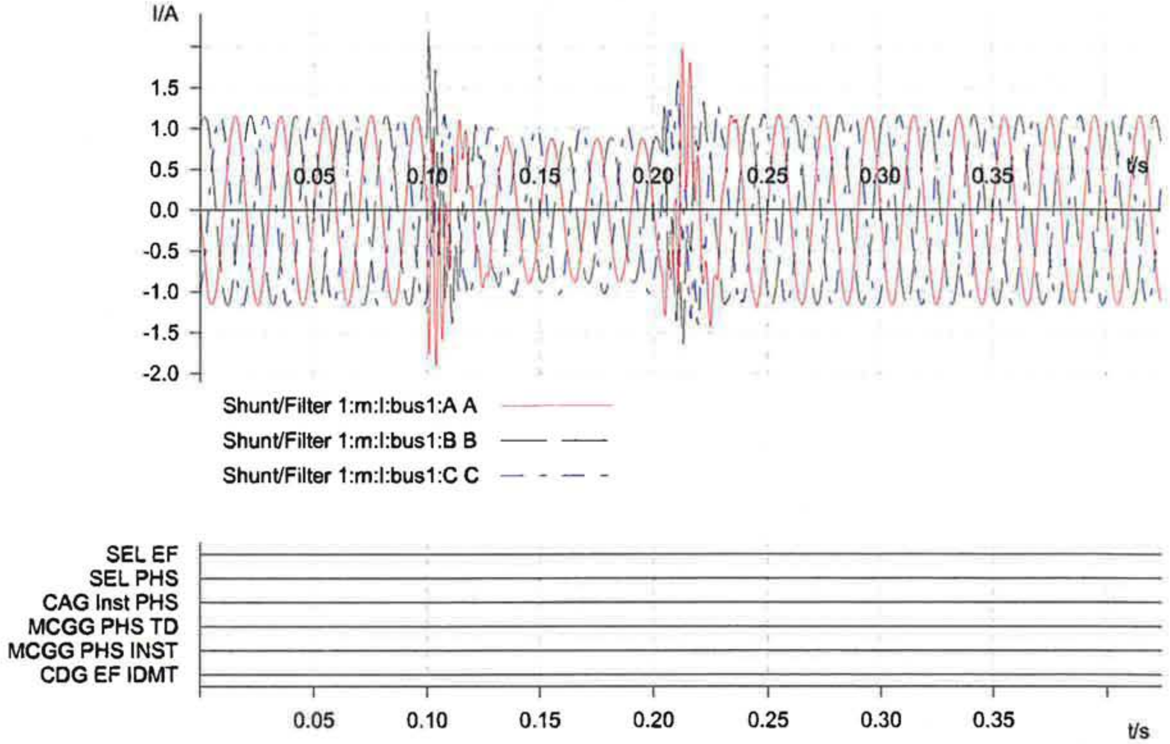

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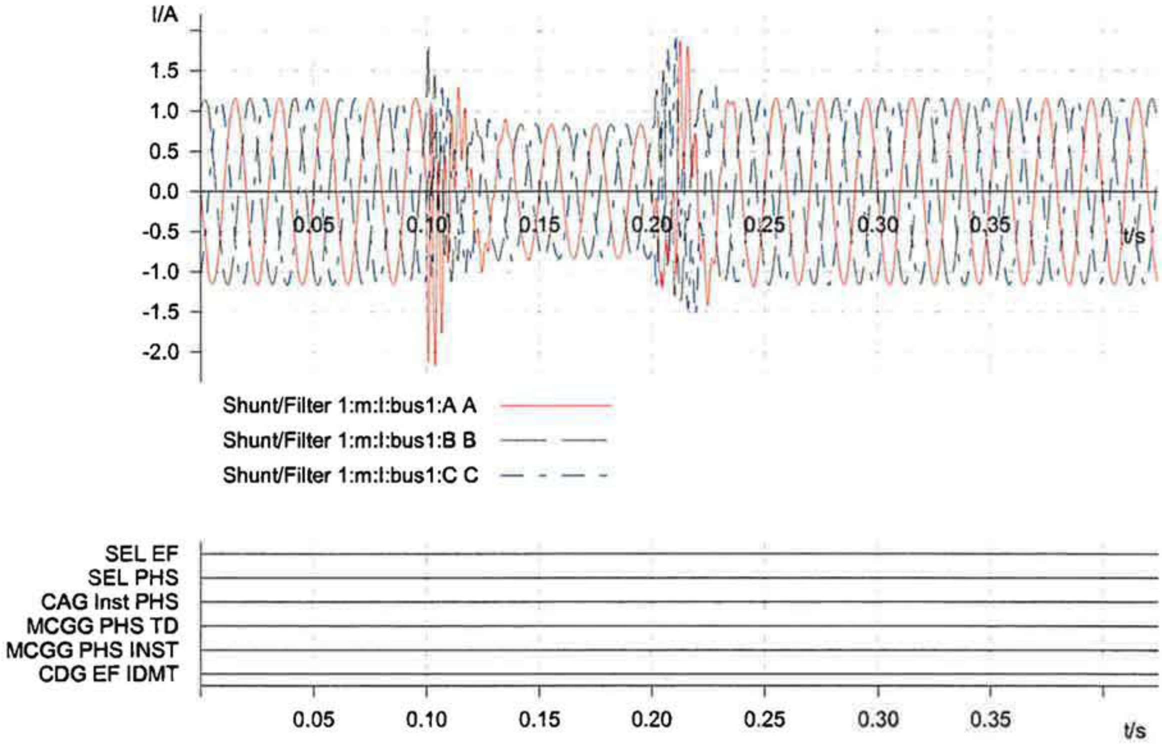
Info: DIgSILENT PowerFactory

Time Signal:

Measurement no.: 1



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File: YN_1%_1P.CFG

Info: DIgSILENT PowerFactory

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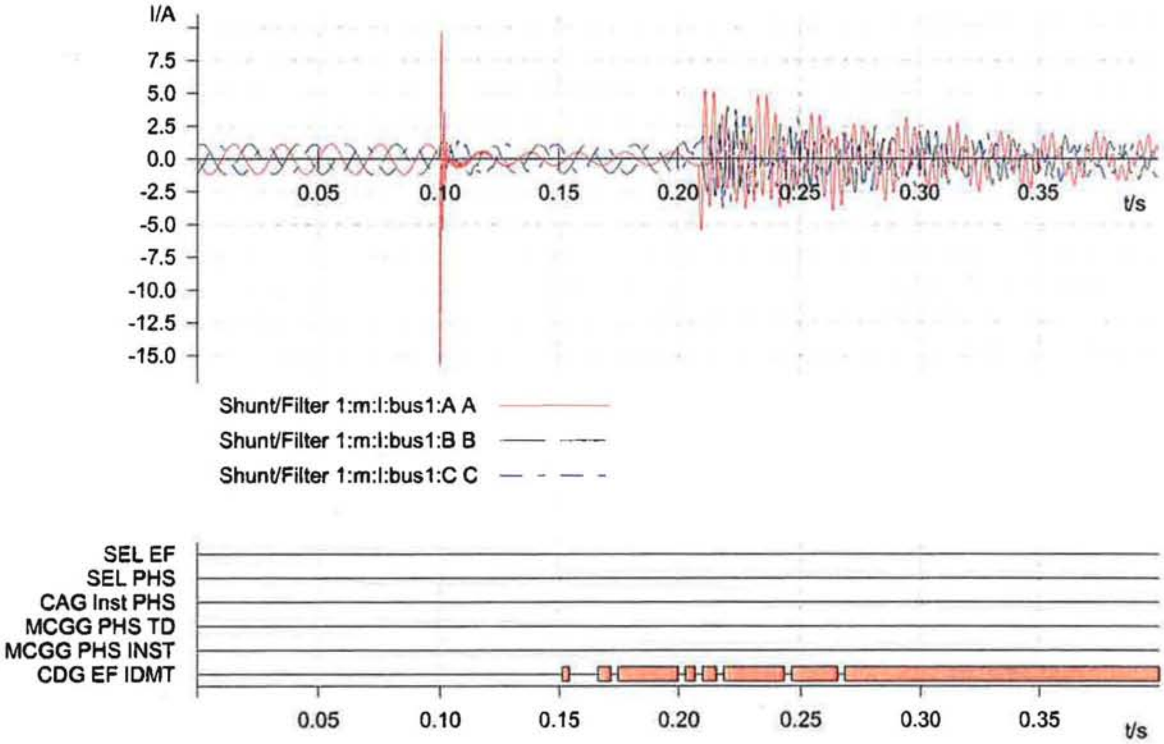
Measurement no.: 1



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Data source:

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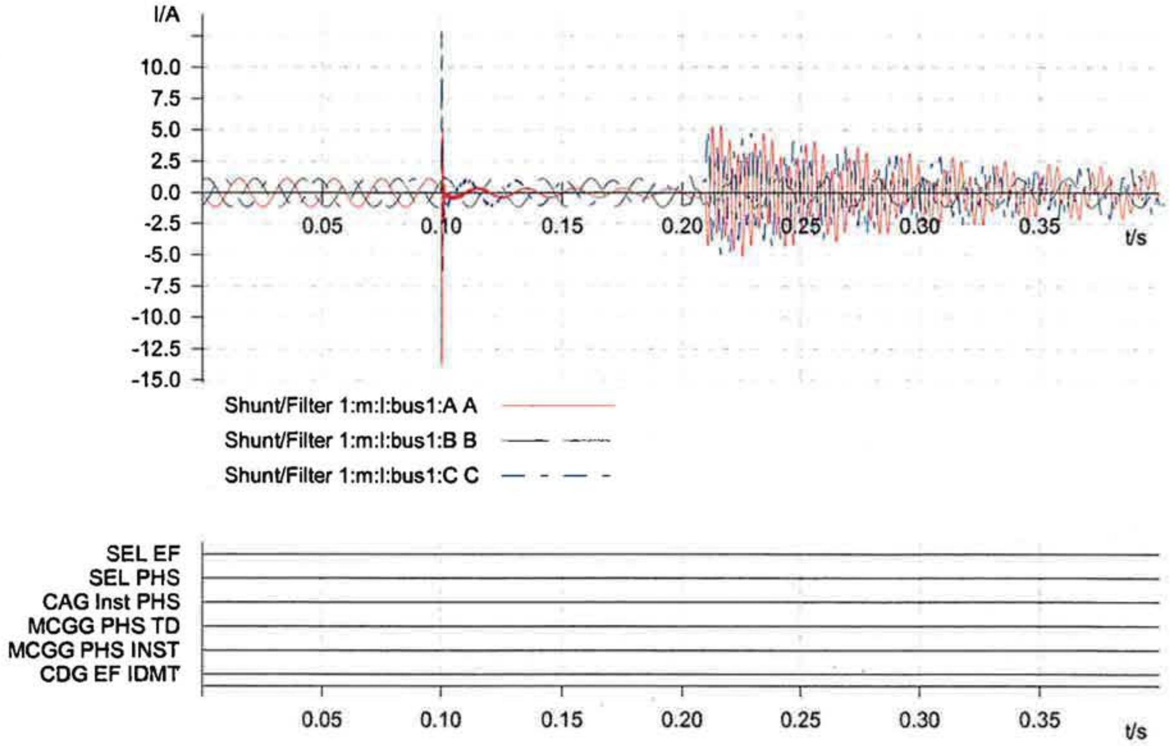
Info:	DIgSILENT PowerFactory

Time Signal:

Measurement no.: 1



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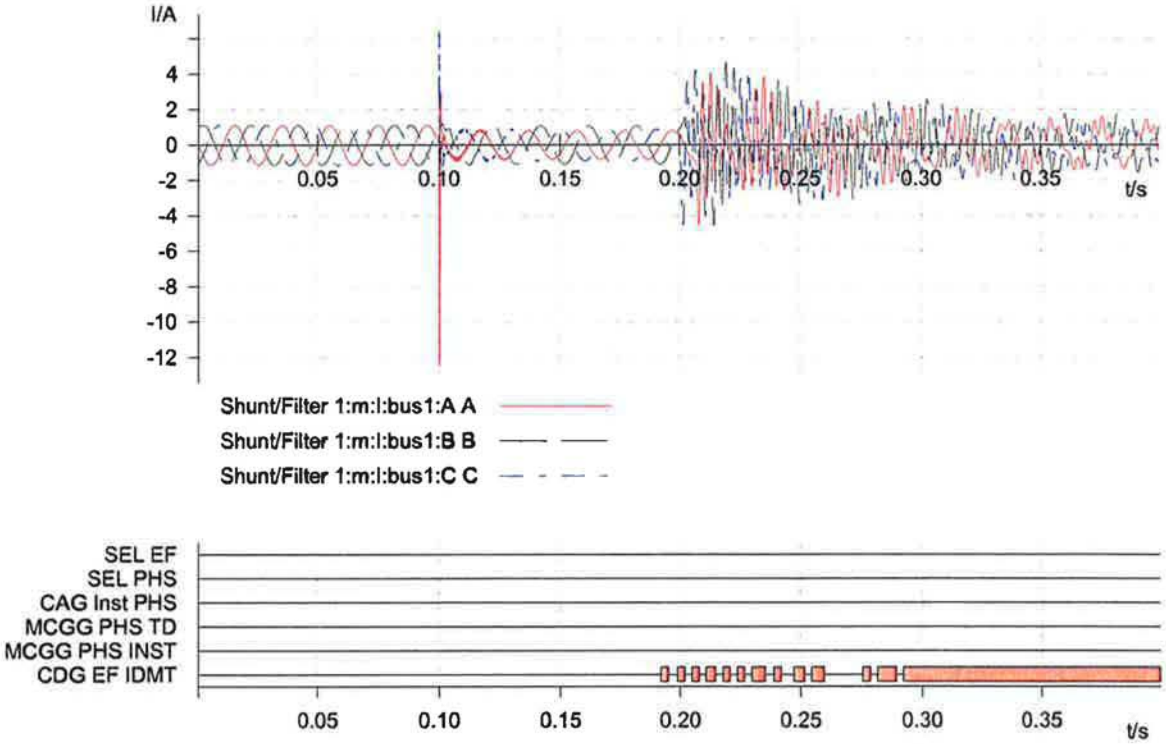

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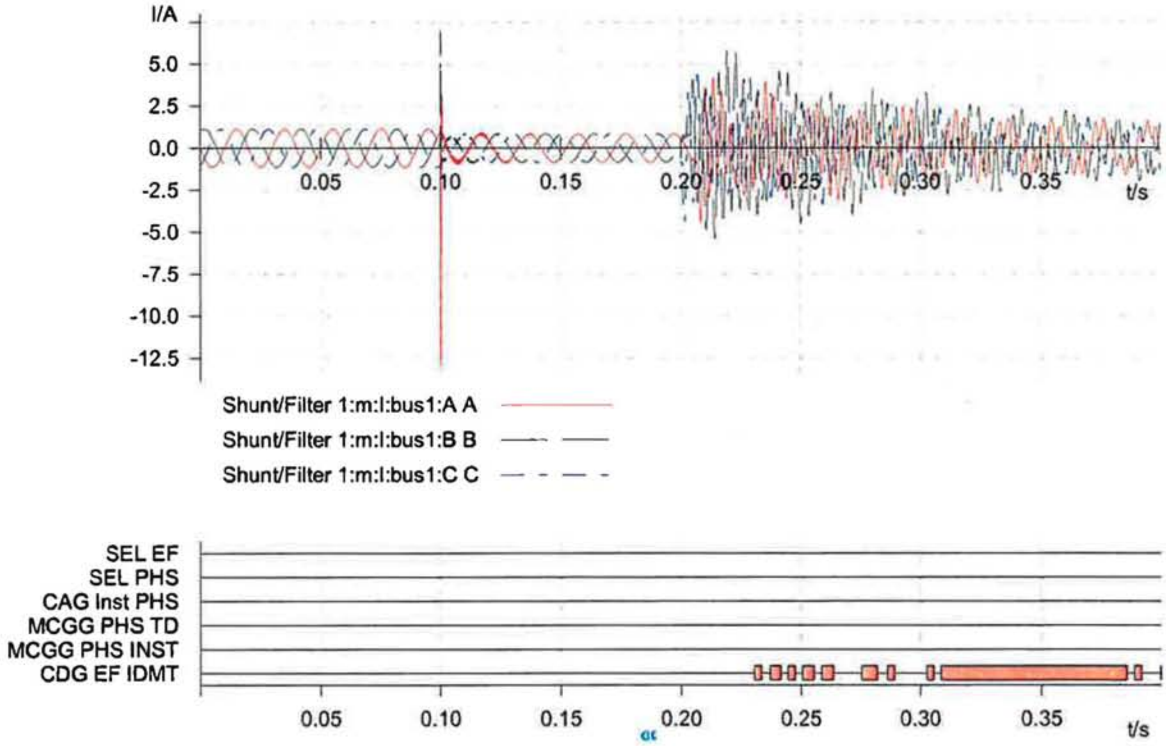
Info: DIgSILENT PowerFactory

Time Signal:

Measurement no.: 1



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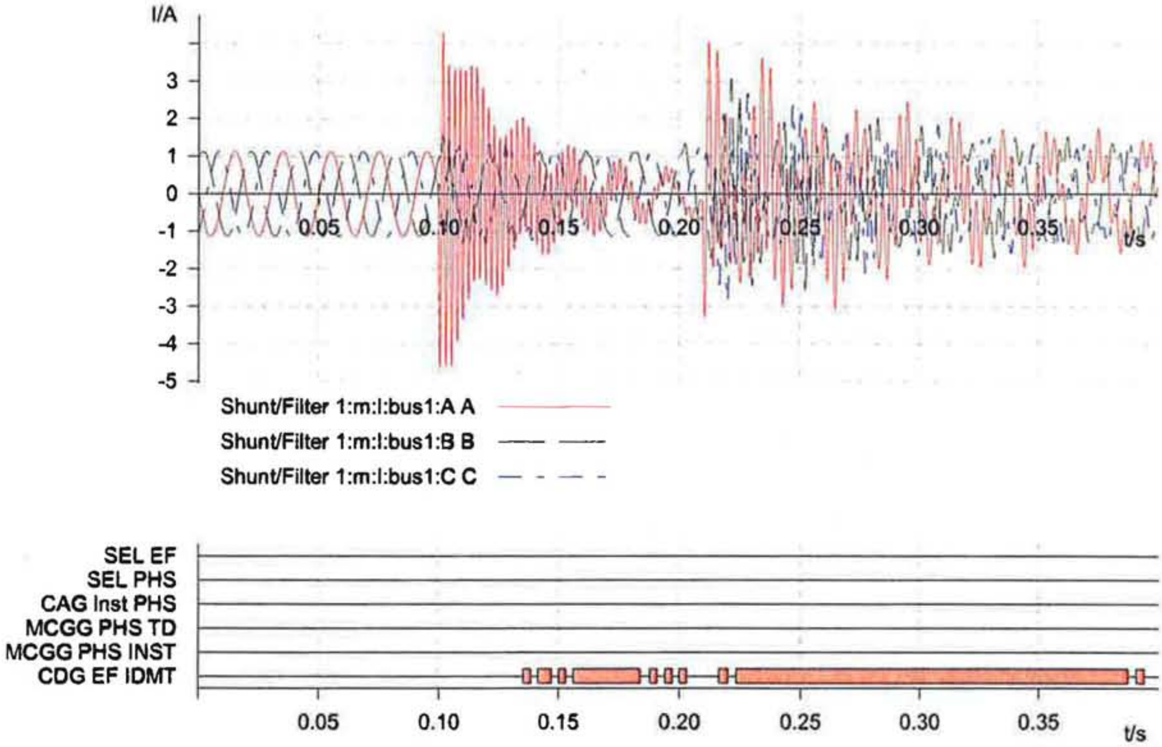
File: YNCAP_FAULTAT10%1P_100MS.CFG

Info: DIgSILENT PowerFactory

Time Signal:

Measurement no.: 1



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Time Signal:

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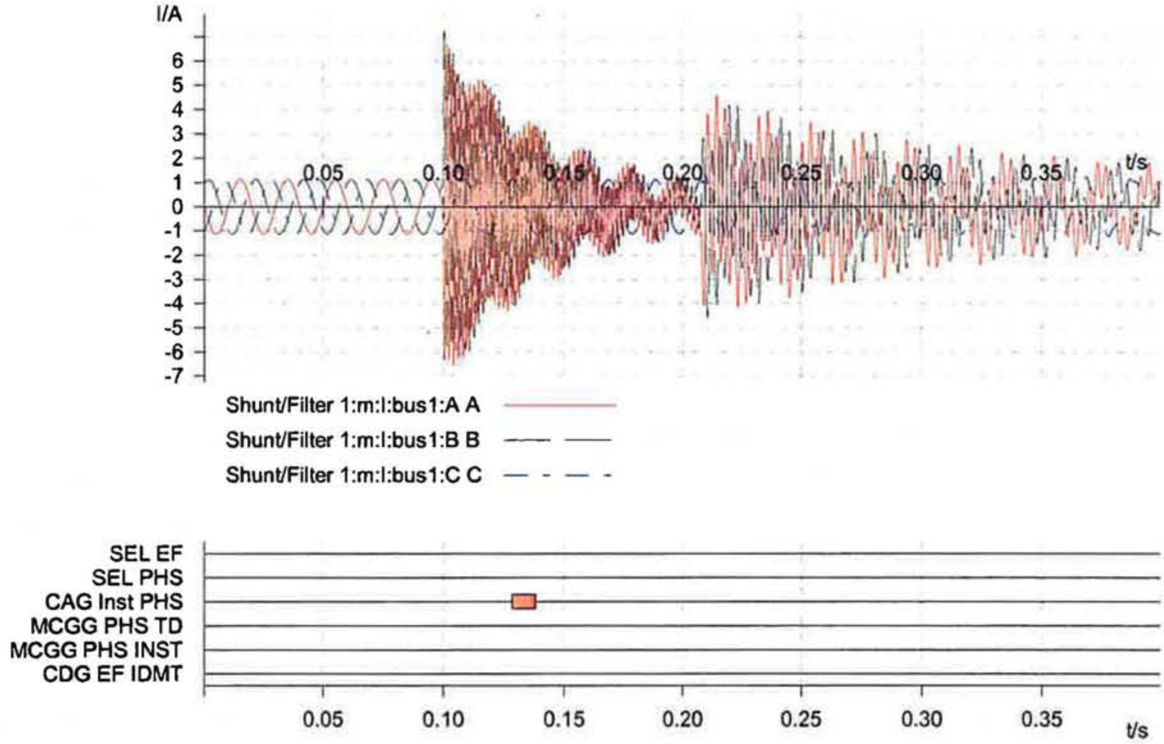

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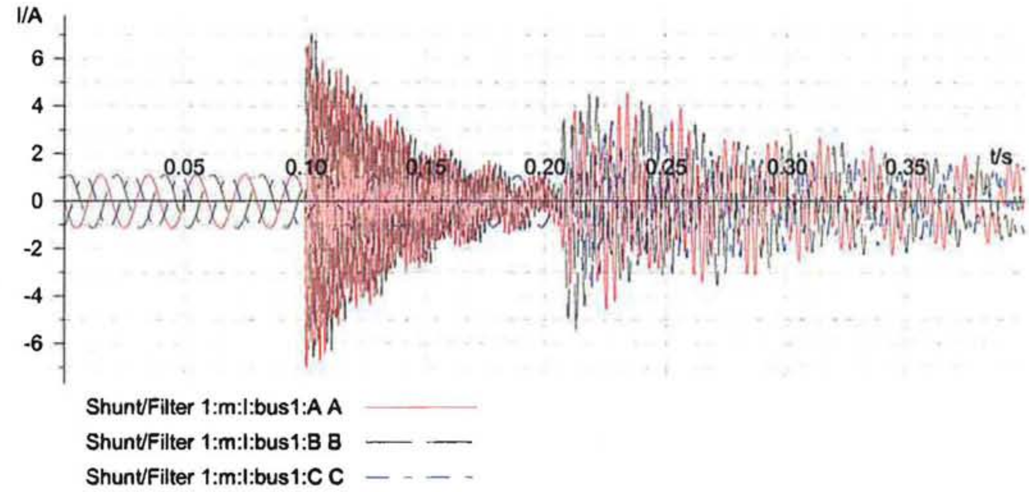

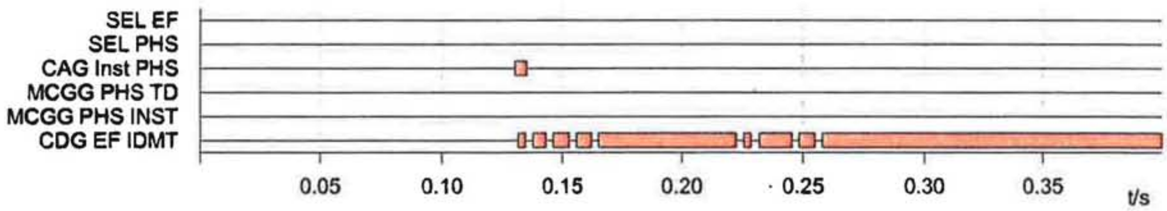

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Info:	DIgSILENT PowerFactory

Time Signal:

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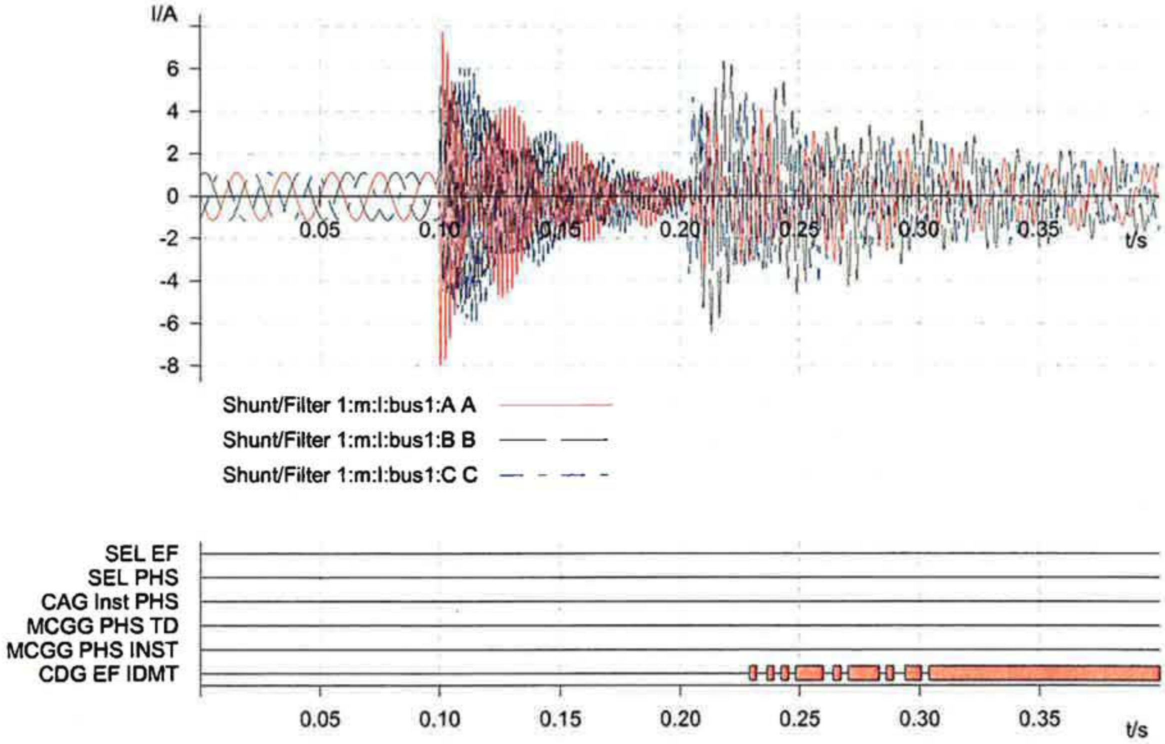

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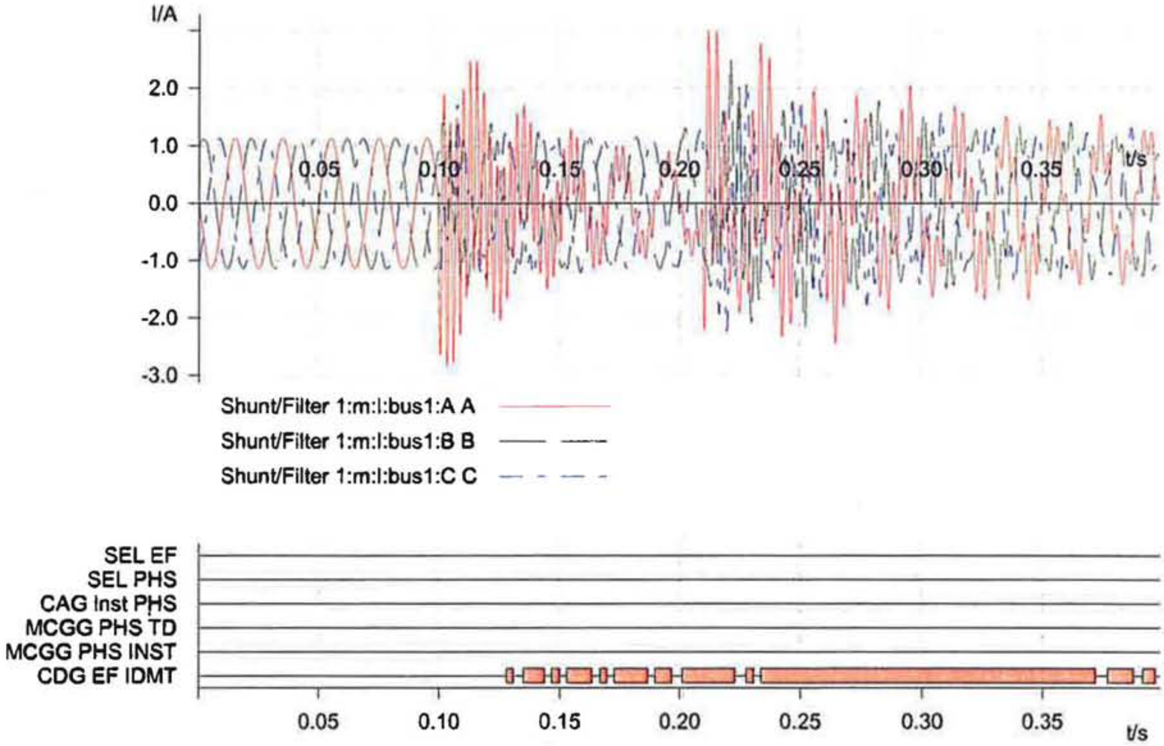

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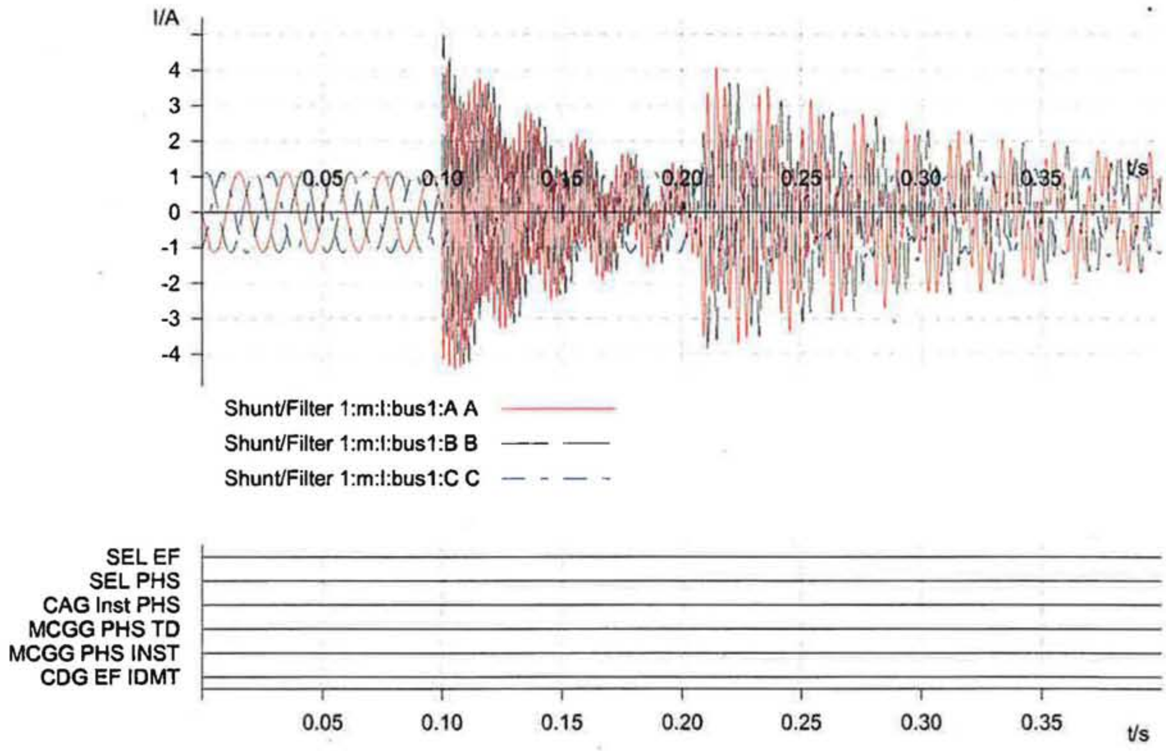

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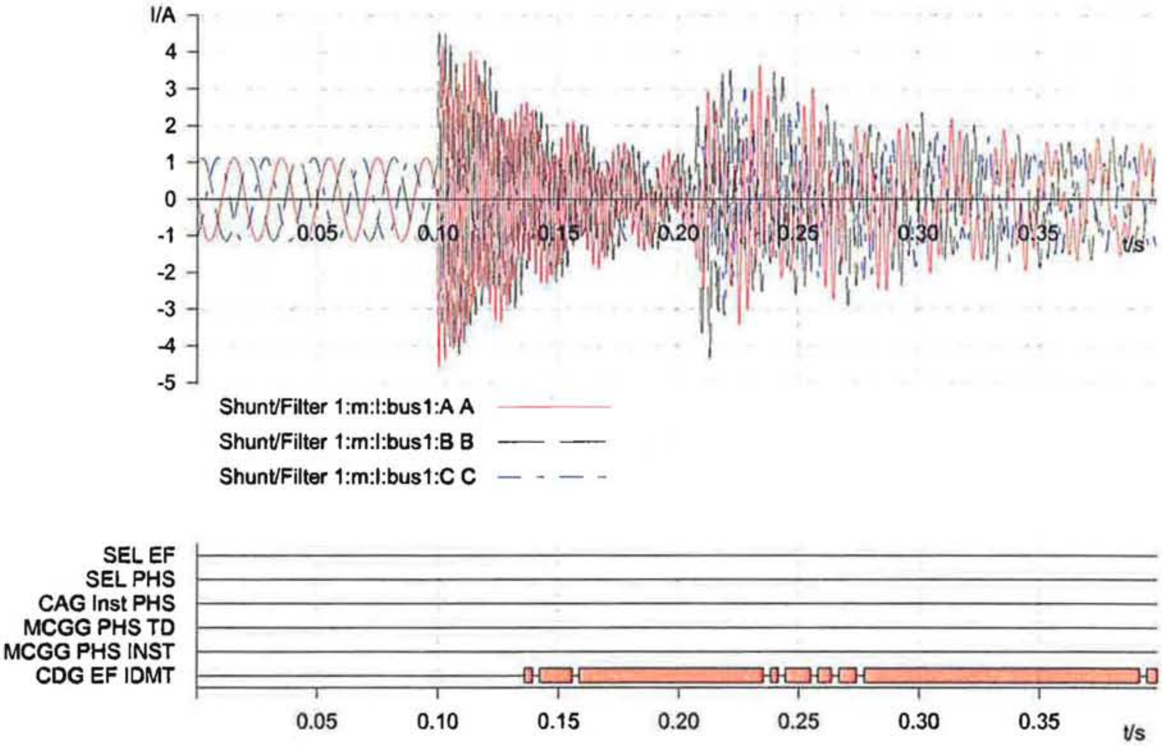

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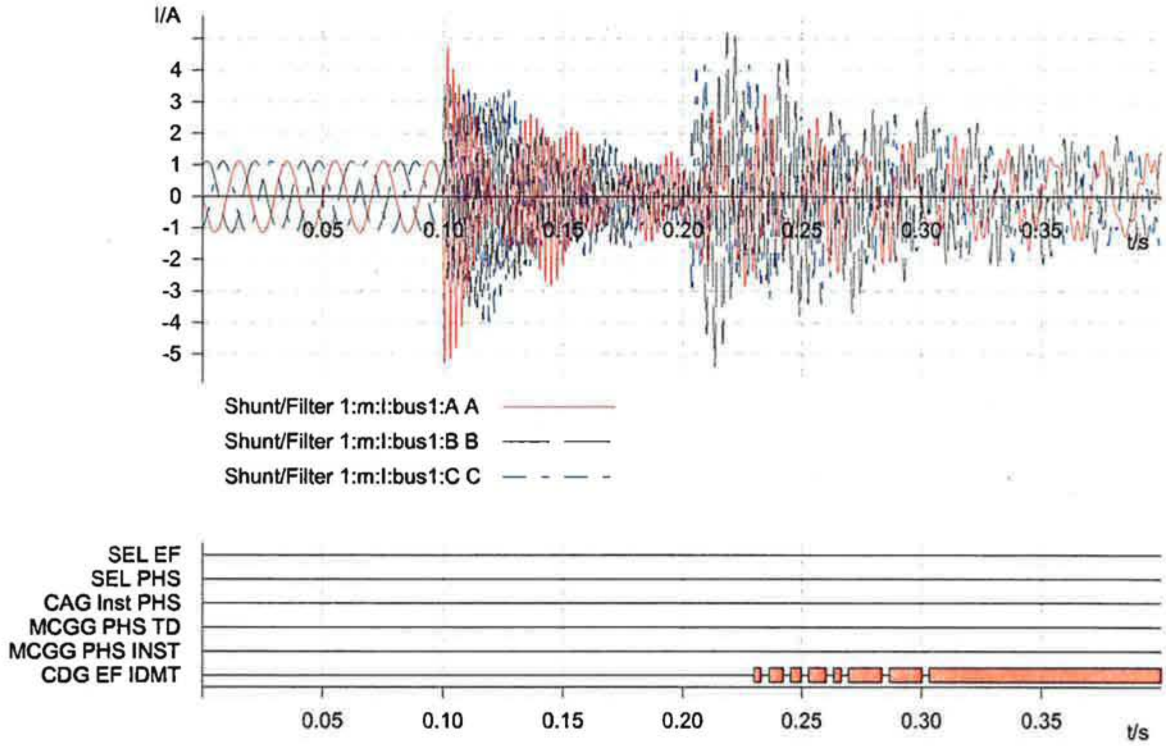

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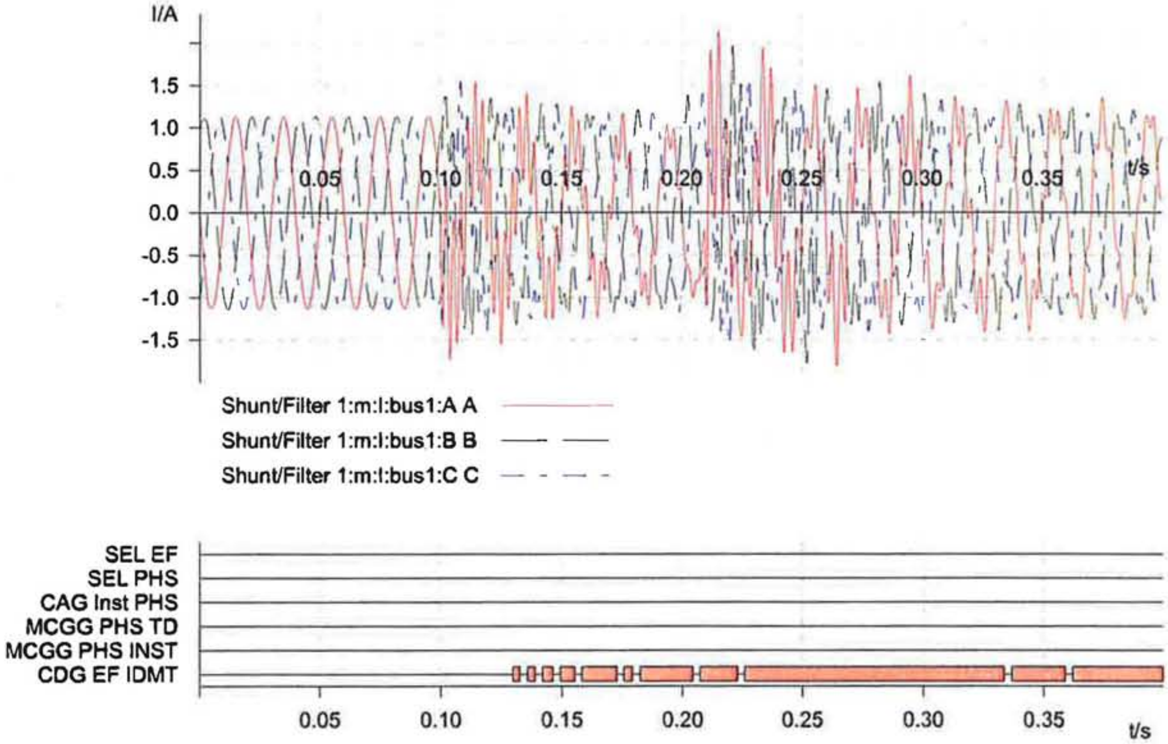
Time Signal:

Measurement no.: 1



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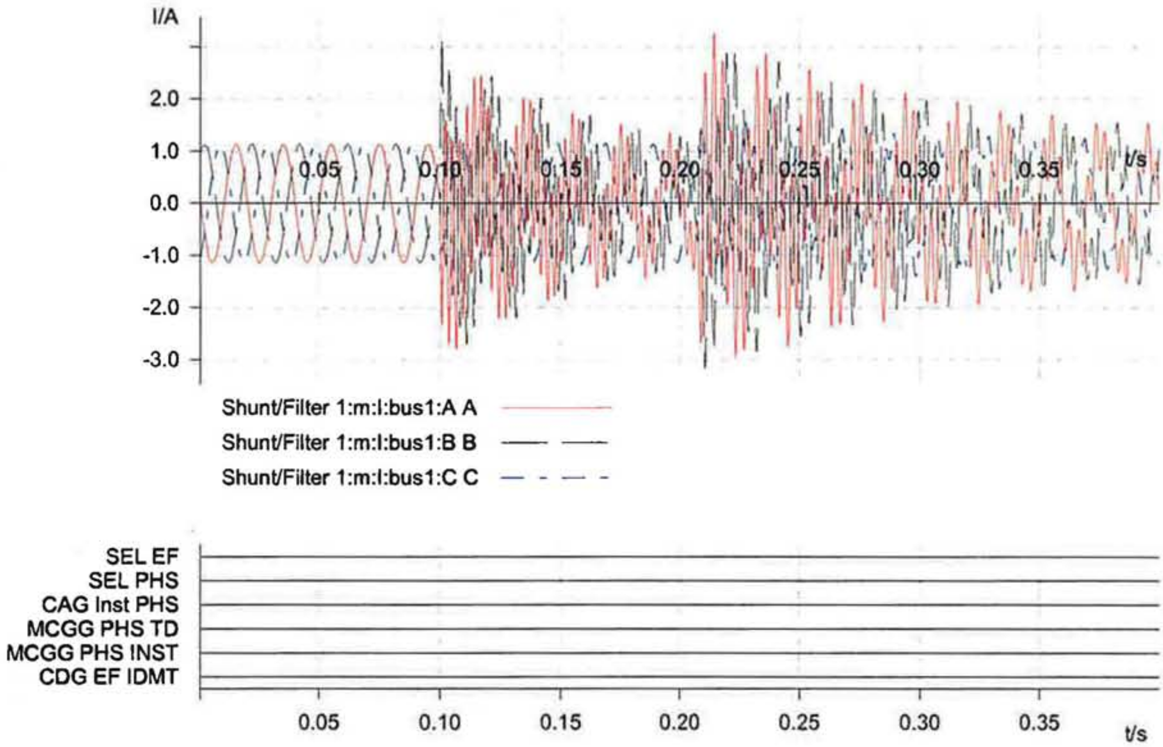
Info: DIgSILENT PowerFactory

Time Signal:

Measurement no.: 1



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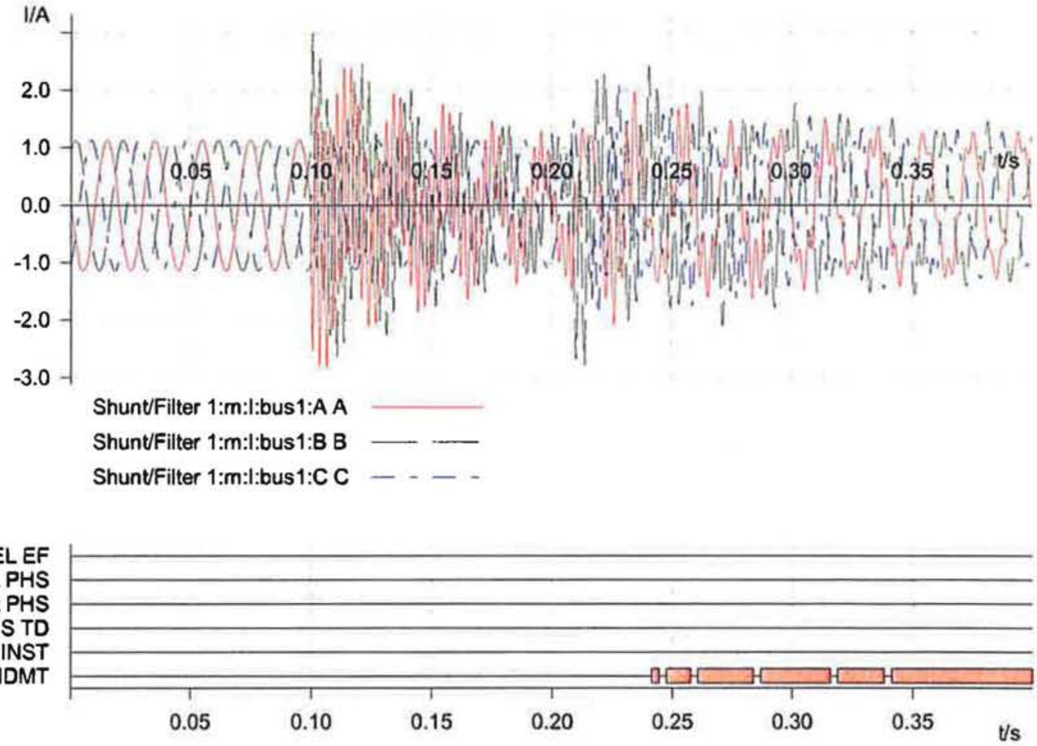
Time Signal:

Measurement no.: 1



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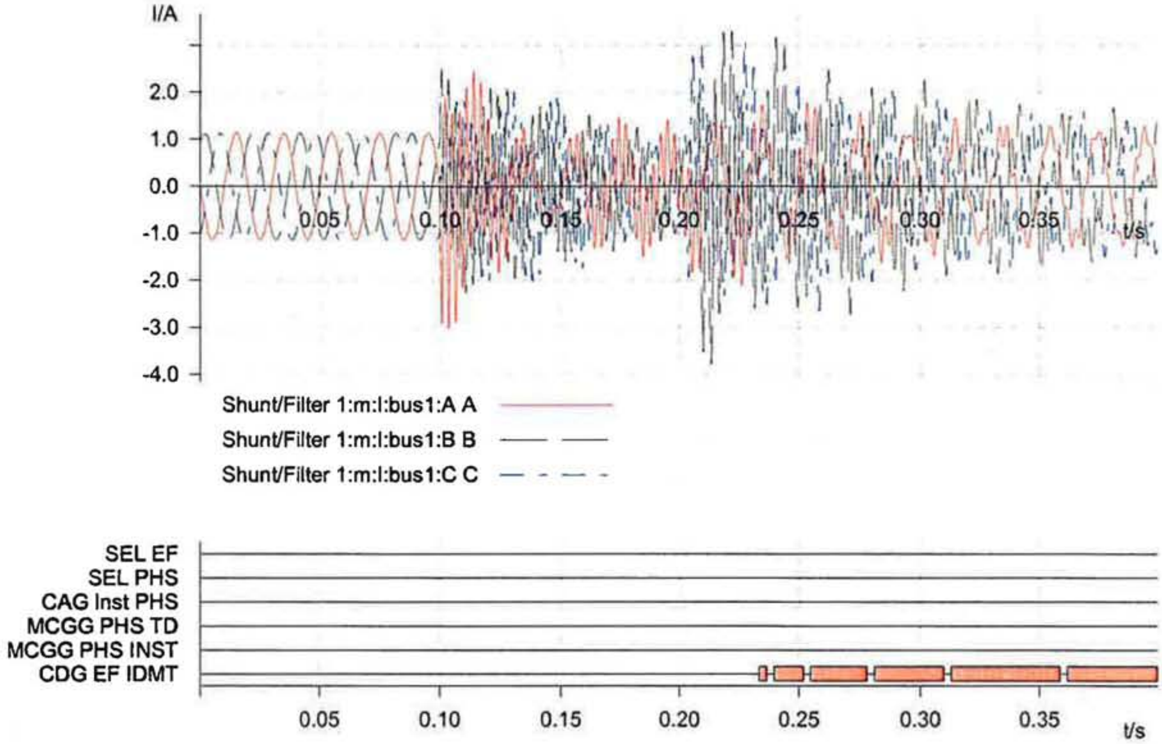

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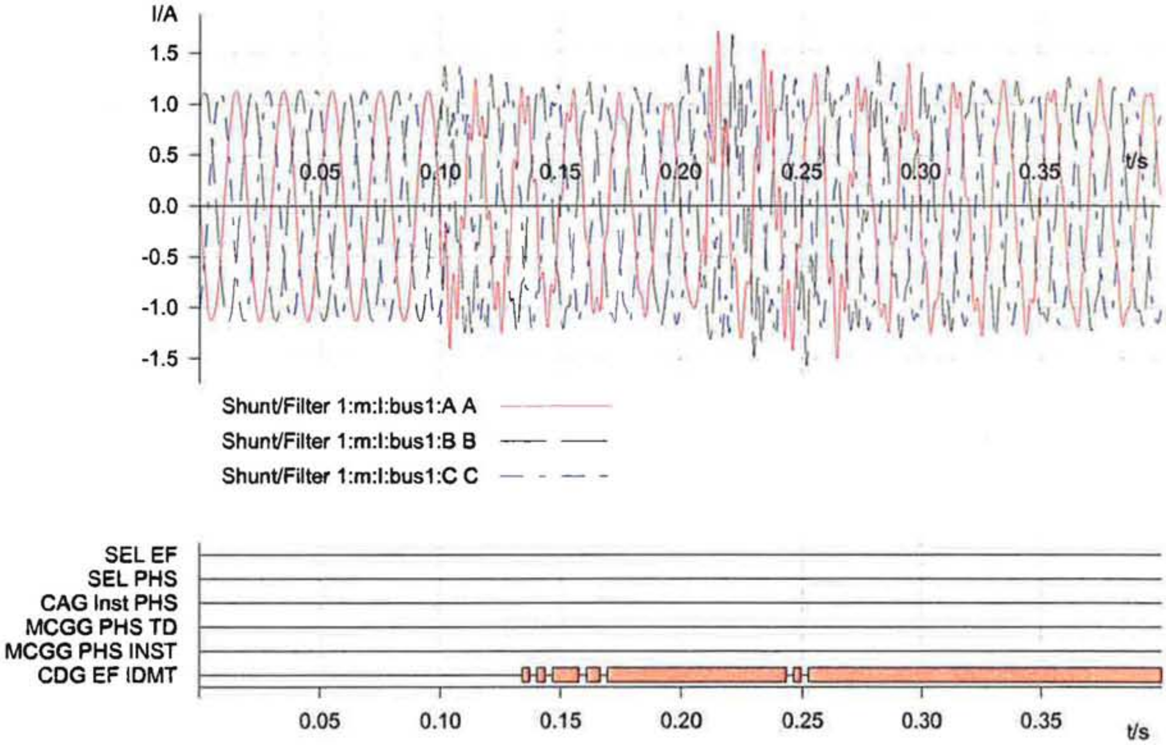
Info: DIgSILENT PowerFactory

Time Signal:

Measurement no.: 1



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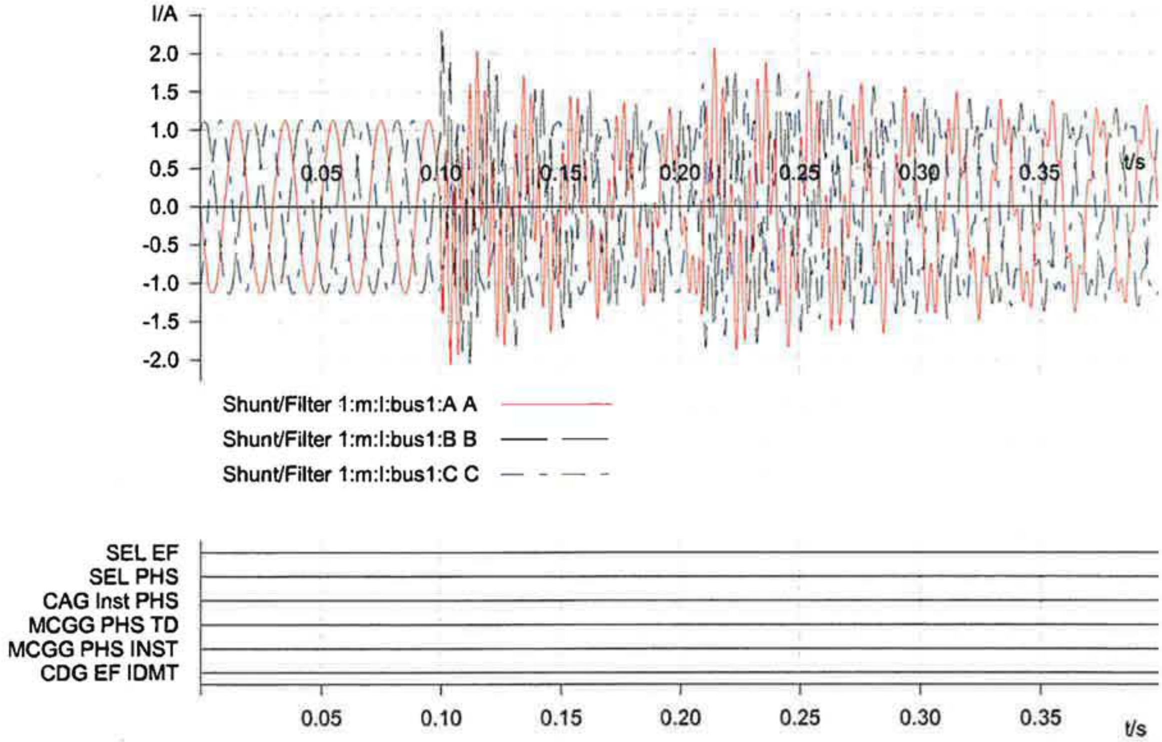
Info: DIgSILENT PowerFactory

Time Signal:

Measurement no.: 1



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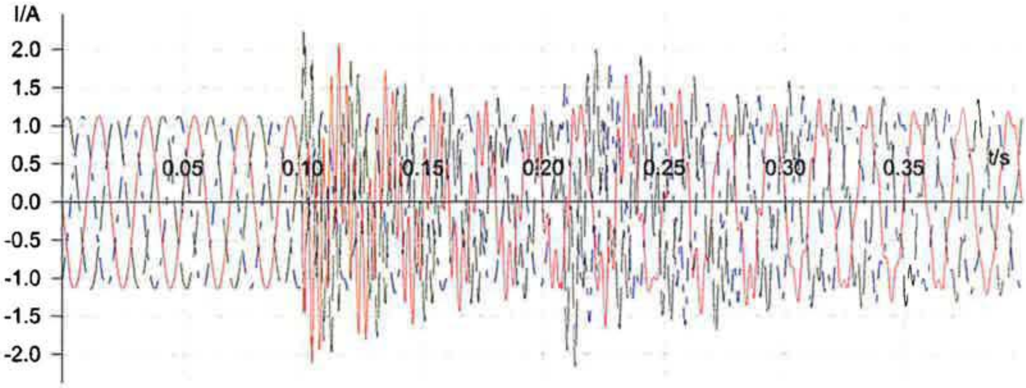
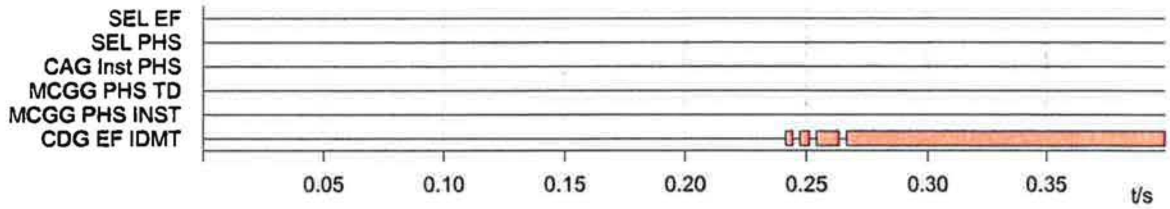
Info: DIgSILENT PowerFactory

Time Signal:

Measurement no.: 1





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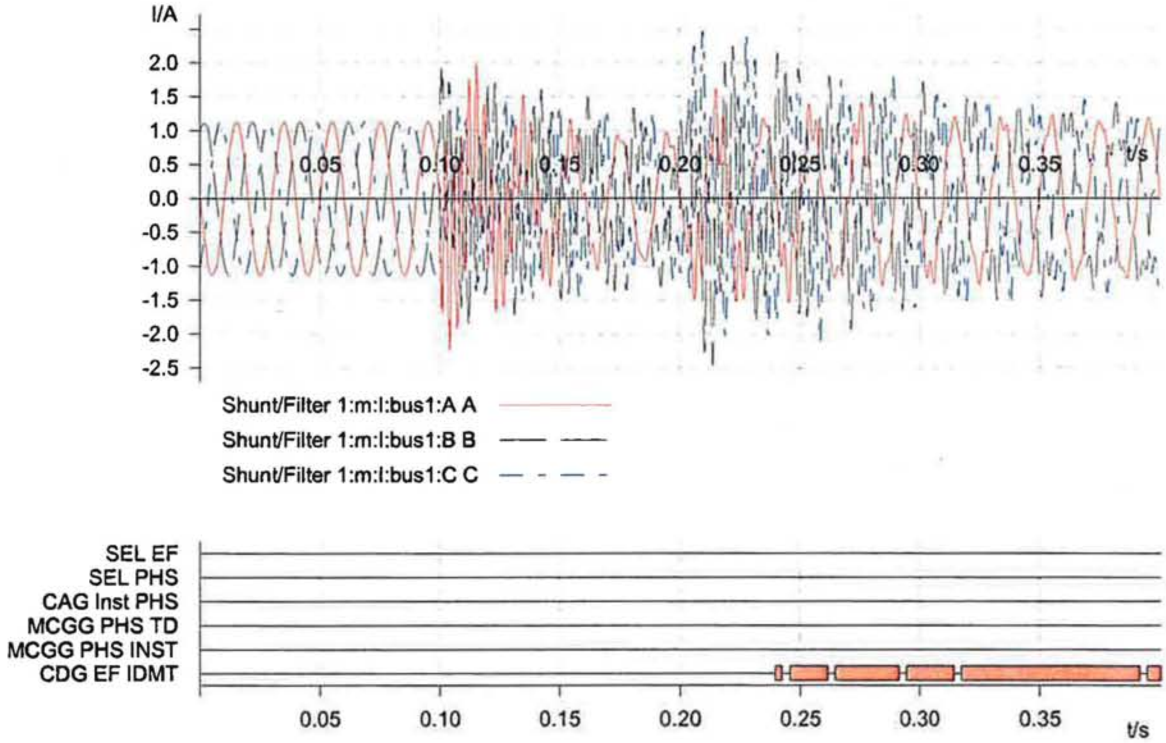
Time Signal:

Measurement no.: 1



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Info: DIgSILENT PowerFactory

Time Signal:

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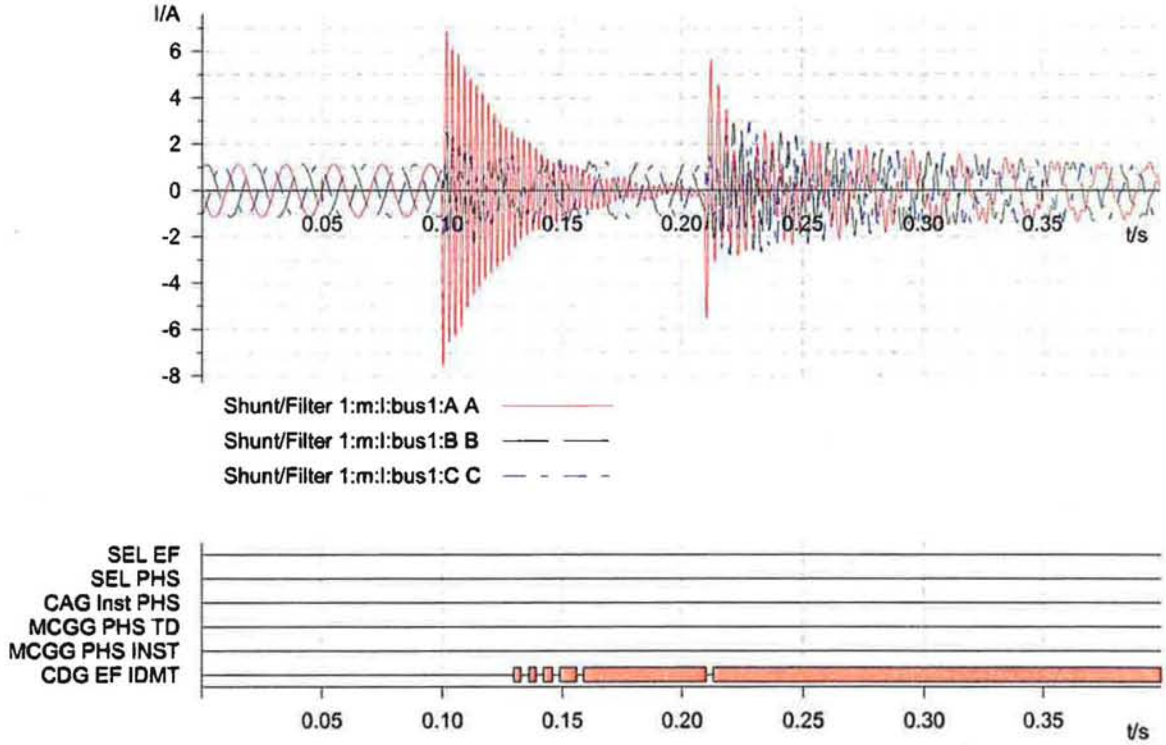

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Info:	DIgSILENT PowerFactory

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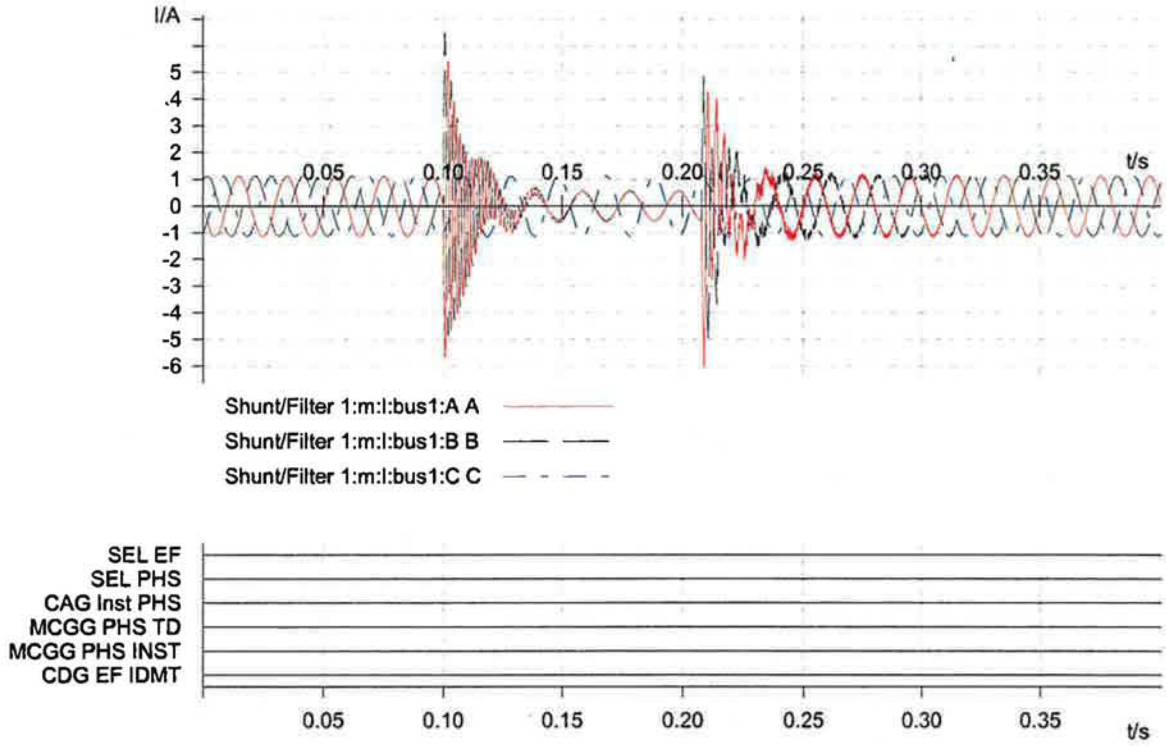
Measurement no.: 1



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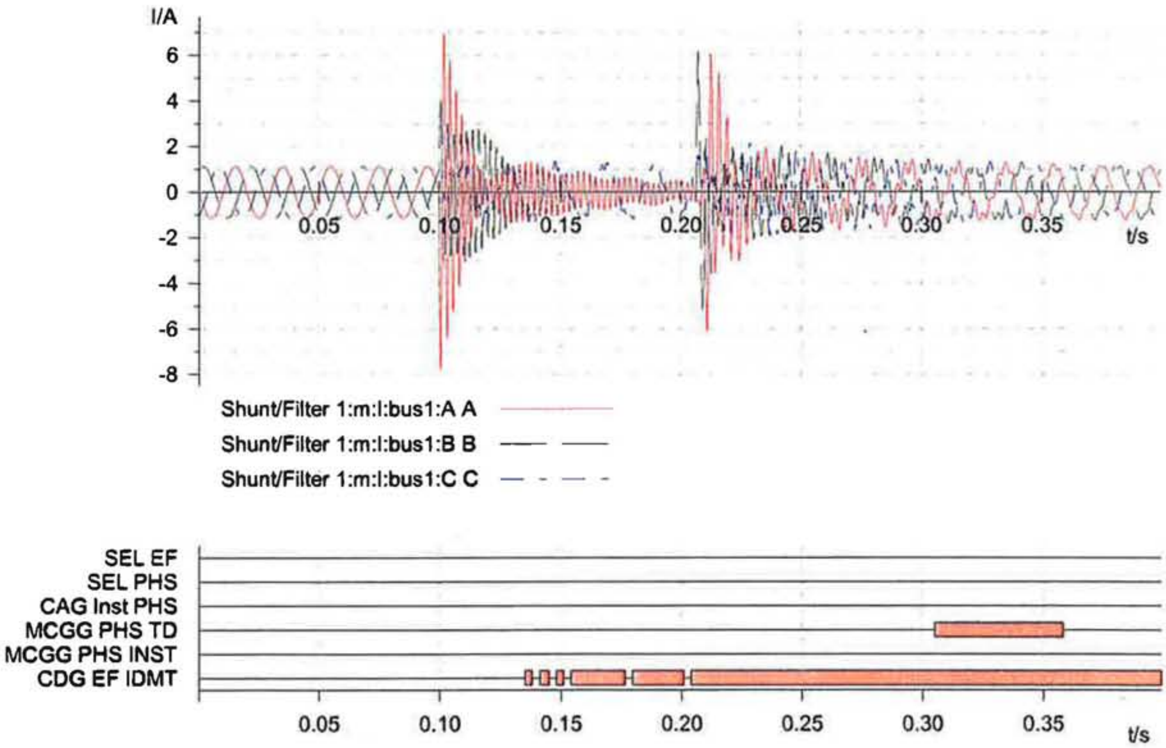
Info:	DIgSILENT PowerFactory

Time Signal:

Measurement no.: 1



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Info: DIgSILENT PowerFactory

Time Signal:

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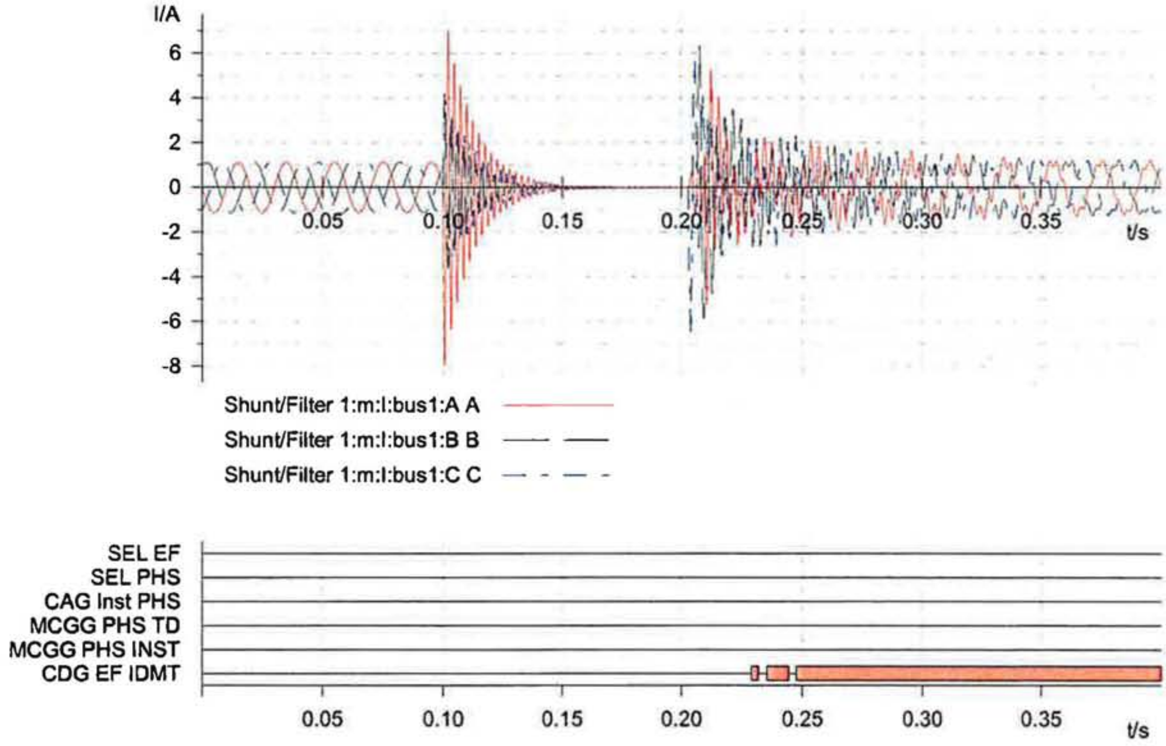

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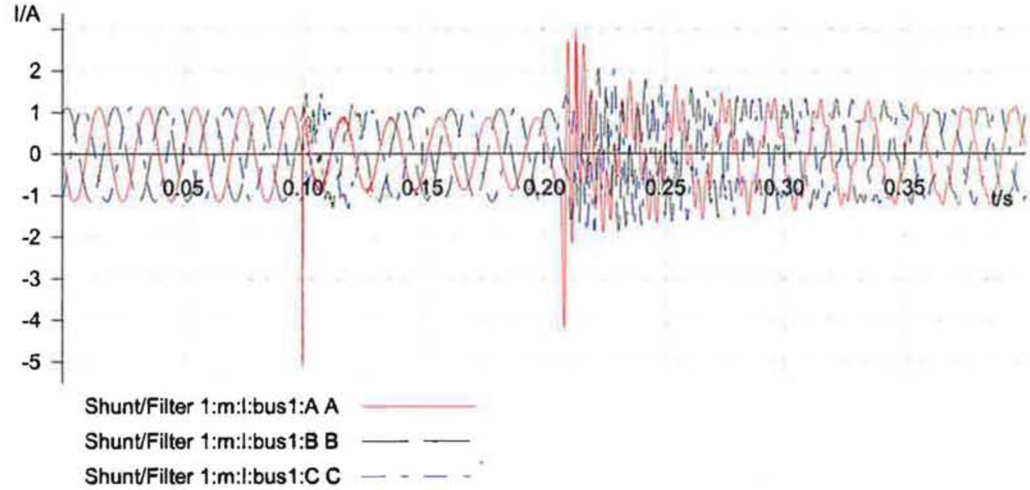
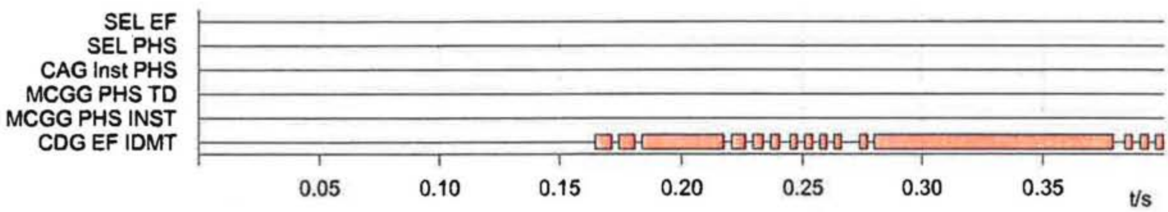
File: YN_132KVBB_1P_5OHMS.CFG
Info: DIgSILENT PowerFactory

Time Signal:

Measurement no.: 1





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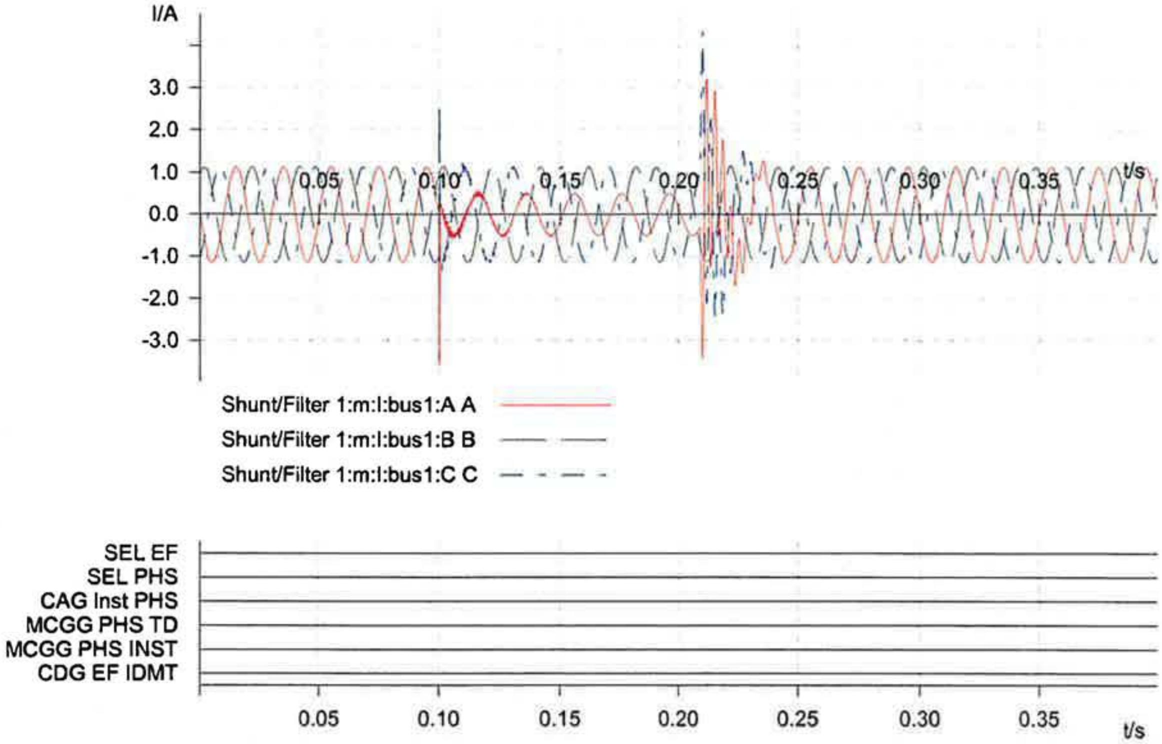
Info:	DIgSILENT PowerFactory

Time Signal:

Measurement no.: 1



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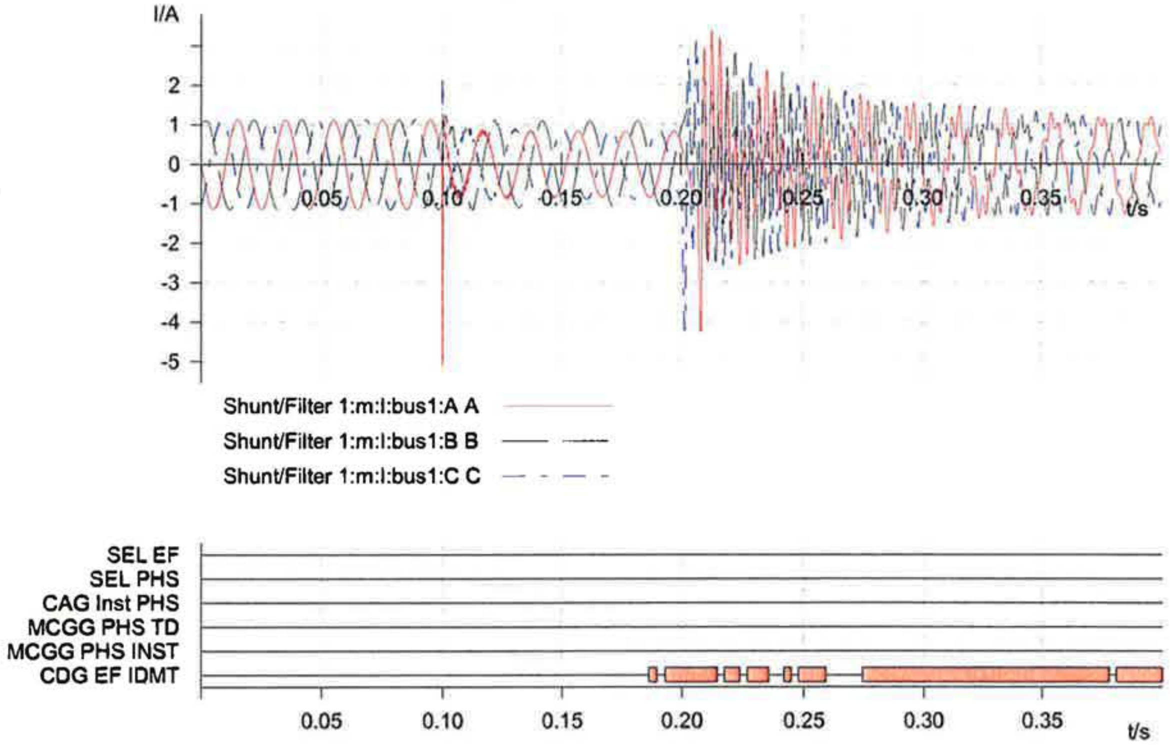

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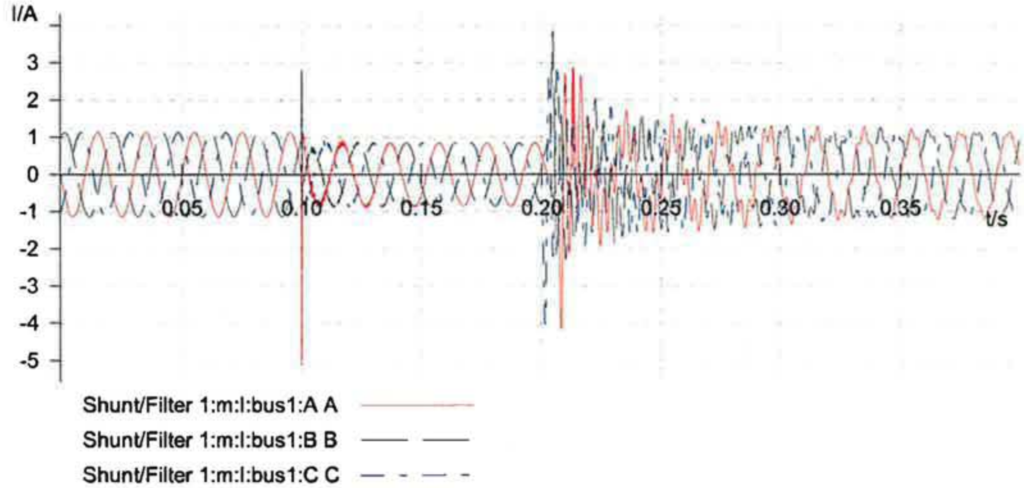

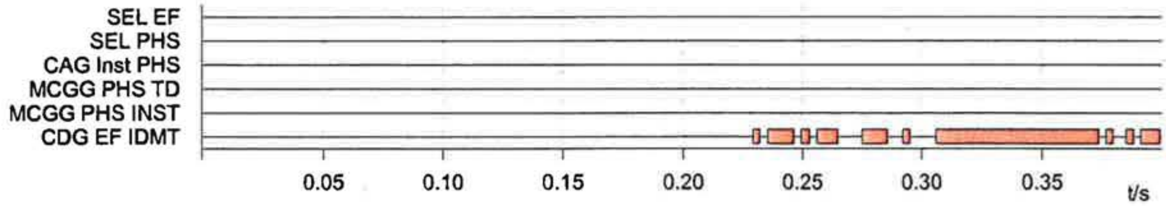

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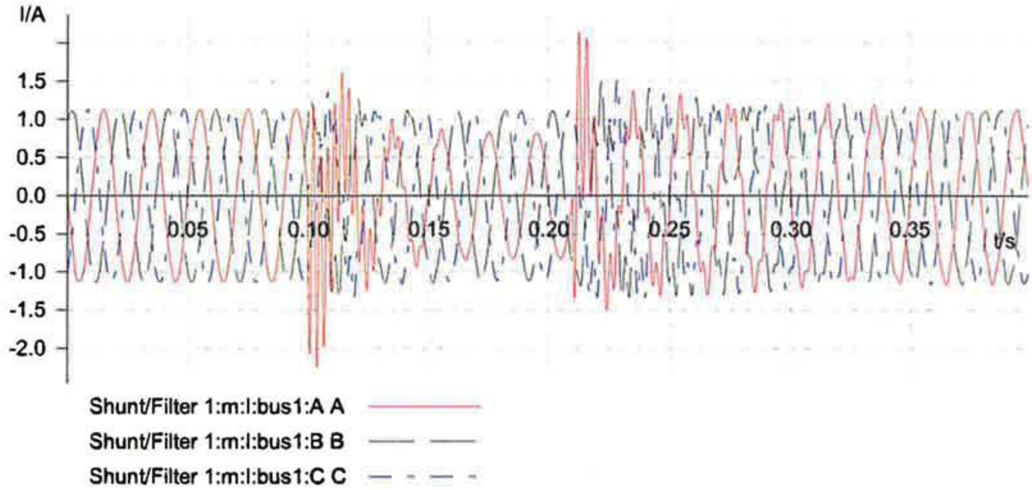
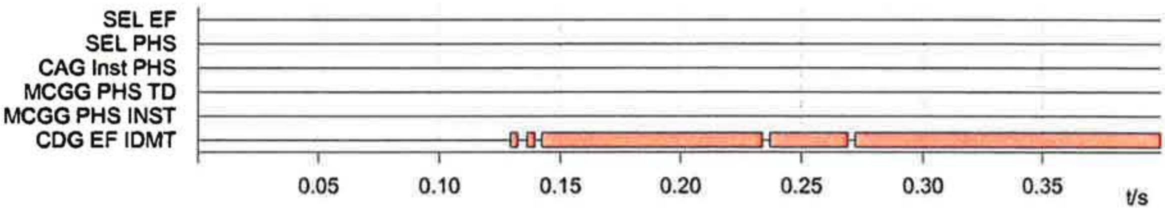
File: YNCAP_FAULTATWG44KVBB1P_100MS.CFG
Info: DIgSILENT PowerFactory

Time Signal:

Measurement no.: 1





revana.tra

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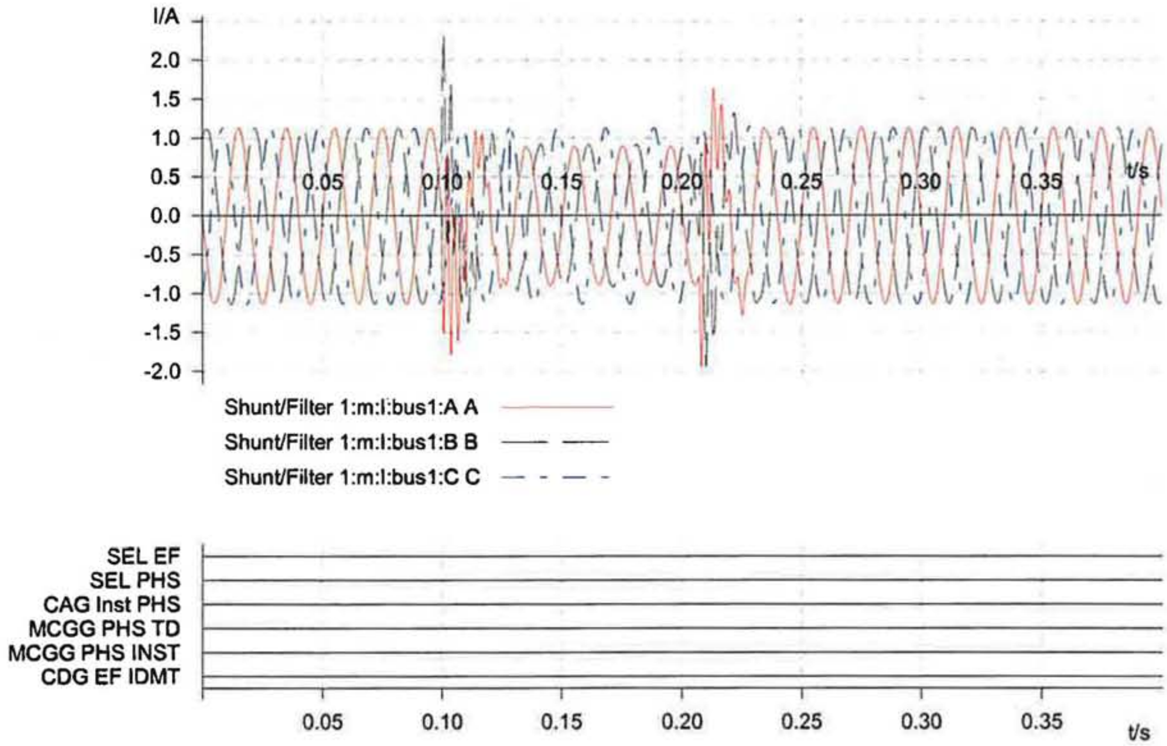
Info: DIgSILENT PowerFactory

Time Signal:

Measurement no.: 1



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Info: DIgSILENT PowerFactory

Time Signal:

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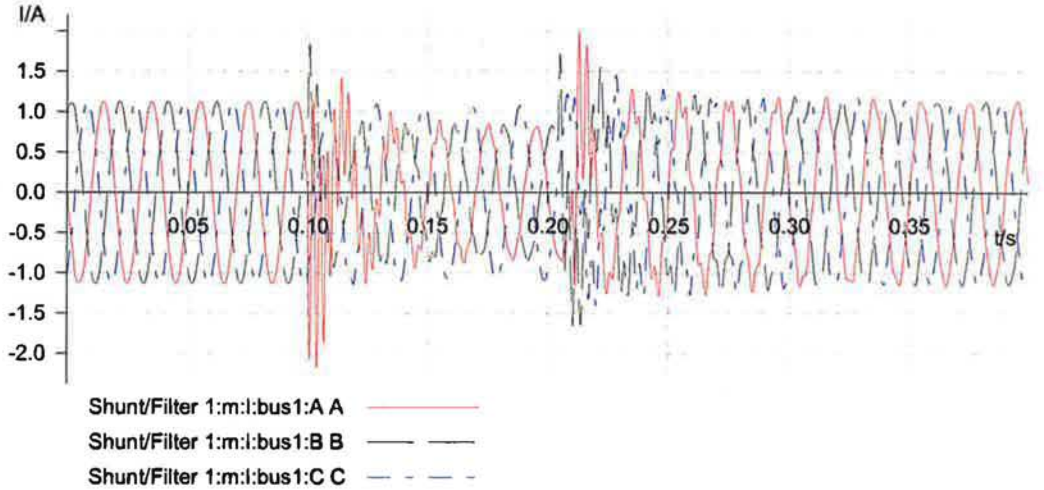

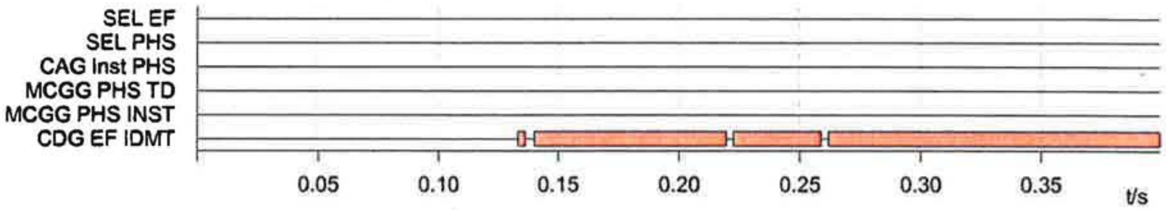

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Data source:

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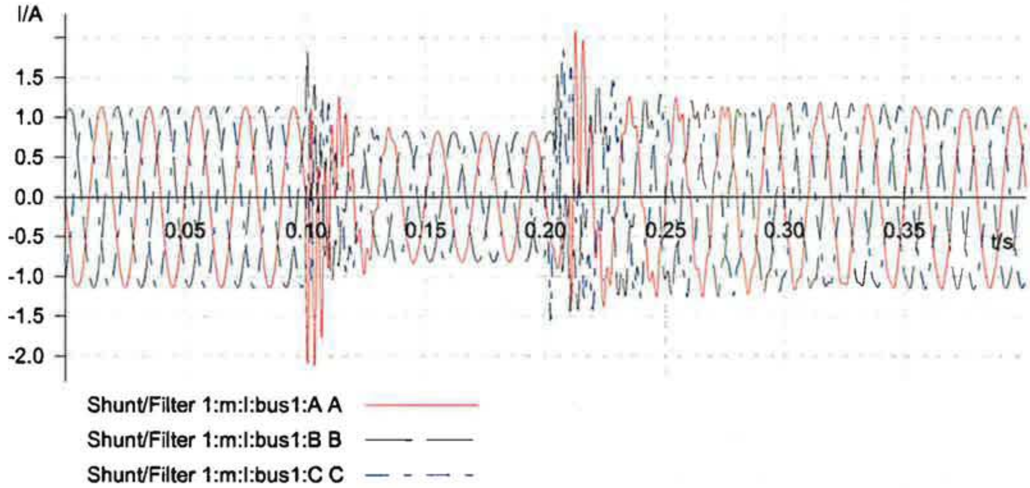
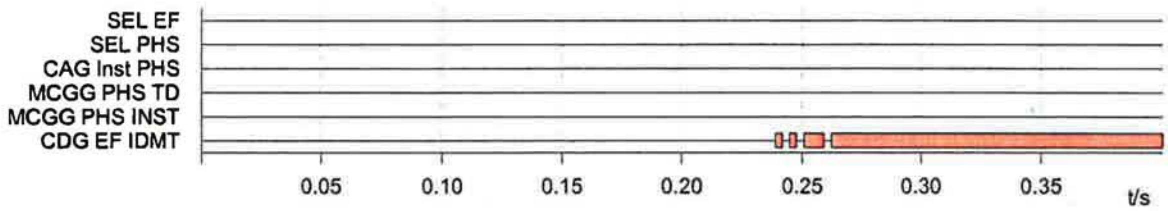
Info: DIgSILENT PowerFactory

Time Signal:

Measurement no.: 1





revana.tra

Data source:

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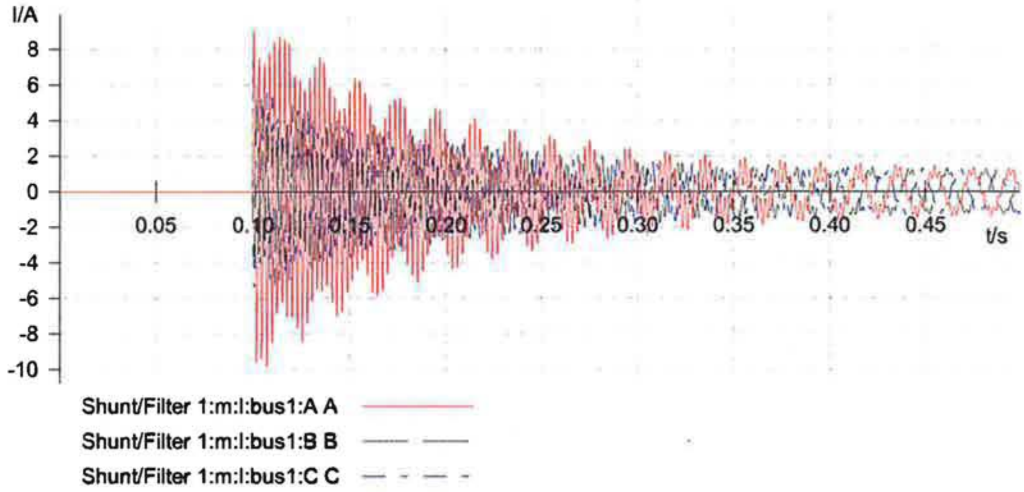
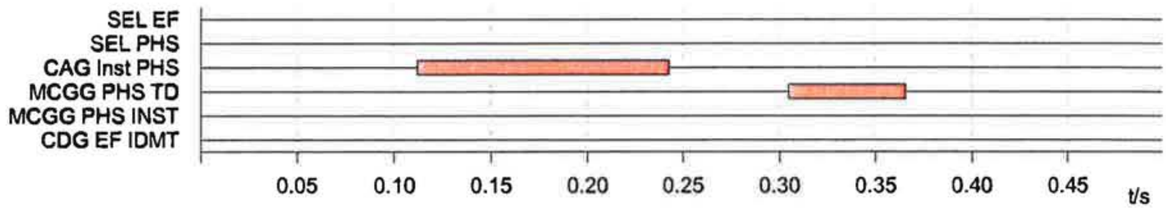
File:	SWITCHING IN BANK.CFG
Info:	DIgSILENT PowerFactory

Time Signal:

Measurement no.: 1





revana.tra

Data source:

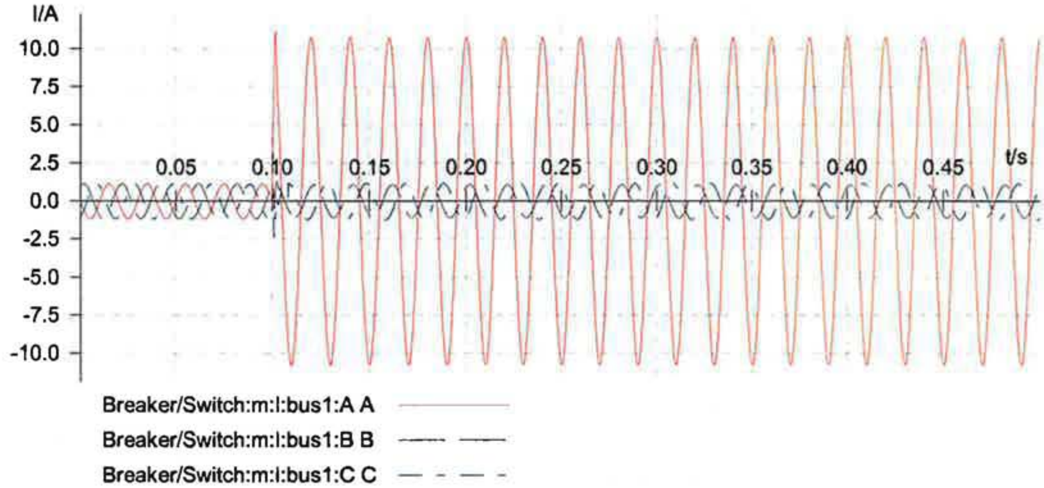
Path: D:\DOCUMENTS AND SETTINGS\STANDBY\MY DOCUMENTS\REVANA\WESTGATESIMS\

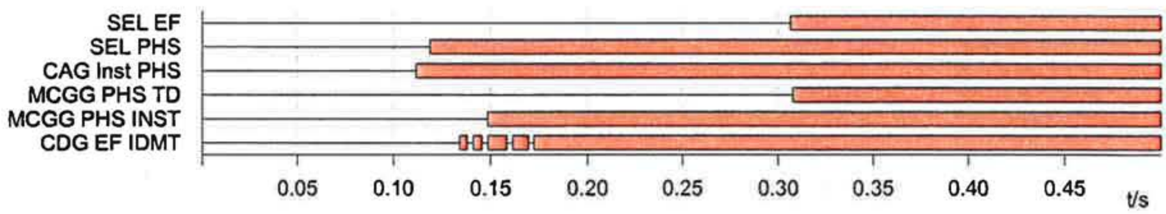
File: INTERNALFAULT.CFG

Info: DIgSILENT PowerFactory

Time Signal:

Measurement no.: 1





revana.tra

Data source:

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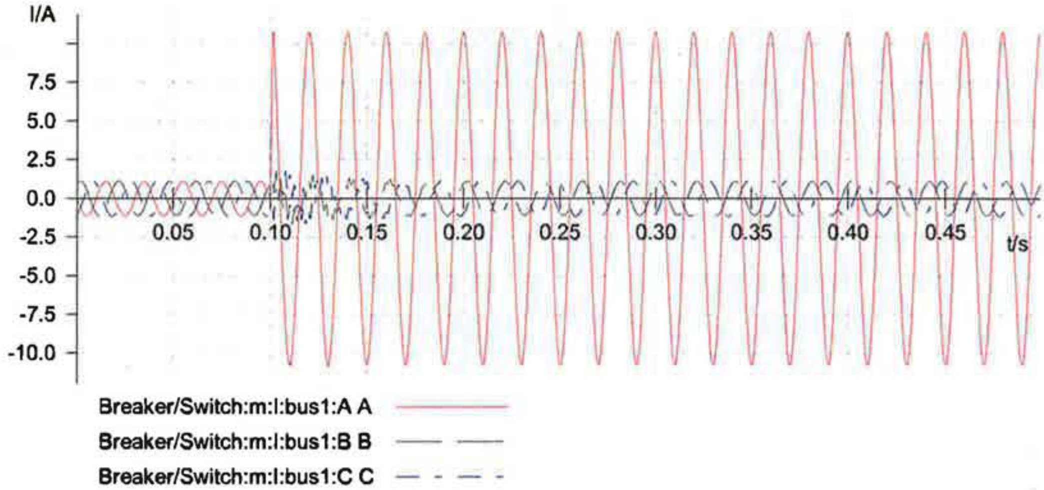
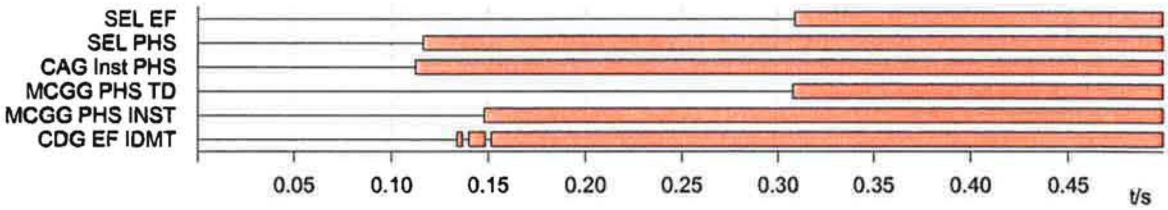
File: YN_INTERNALFAULT.CFG
Info: DIgSILENT PowerFactory

Time Signal:

Measurement no.: 1





Equipment list

DigSILENT: TX Master Project 2008_10_20.dz File
The following can be located in the ESKOM Transmission Test Laboratory, Simmerpan
GEC MCGG63 relay: Serial Number 621301C
SEL387
GEC CDG16: Serial Number 4019332
GEC CAG39
Omicron injection test set : CMC 256-6
Amplifier: CMS 525
DC Power supply : Sorenson DCR