Numerical Distance Protection Relay Commissioning and Testing

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CHALMERS

Thesis for the Degree of Master of Science, October 2005

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Chalmers University of Technology
Göteborg, Sweden

Titel
Drift sättning och provning av ett numeriskt distansskydd

Title in English
Numerical Distance Protection Relay Commissioning and Testing

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Utgivare/Publisher
Chalmers tekniska högskola
Institutionen för Energi och Miljö Avdelningen för elteknik
412 96 Göteborg, Sverige

Ämne/Subject
Power Systems

Examinator/Examiner
Prof. Jaap Daalder

Datum/Date
2005-10-06

Tryckt av/Printed by
Chalmers tekniska högskola
412 96 GÖTEBORG

Acknowledgements

This work has been carried out at the Division of Electric Power Engineering, Department of Energy and Environment, Chalmers University of Technology, Göteborg, Sweden.

We would like to thank our examiner Prof. Jaap Daalder, our supervisors Dr. Daniel Karlsson at Chalmers and Lars-Göran Andersson at ABB Company for their support during the work.

Many thanks to Massimo Bongiorno at the Division of Electric Power Engineering for all his help in running the line model. We also wish to thank Jan-Olof Lantto for his network and computer support.

Hung Manh Tran would like to thank his parents, especially his sister, brother in-law, and his girlfriend Tran Huong Lien for all their supports throughout the years.

Henry Akyea would like to extend my appreciation to my twin sister Henrietta Akyea for her financial support.

Acknowledgement

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Chapter 1

Introduction

The diploma work proposal is entitled "Numerical Distance Protection Relay Commission and Testing" with the aims to calculate appropriate settings for the protection relay, configure the relay, install, commission and testing the entire protection.

The numerical distance protection relay used is REL 511*2.3 of ABB Company, which detects both phase-to-phase and phase-to-earth faults, and it has a quadrilateral operating characteristics. The REL 511*2.3 has been connected to a network model through three single-phase voltage transformers and three current transformers. A three-phase resistive load of 9 kW has been connected to the line model.

The power line model operates at 400 V that is a three-phase model of a 400 kV transmission system, thus the voltage scale of the model is 1: 1000. The line model consists of six identical π-sections each corresponding to 150 km of 400 kV line. The π-sections are made of series reactors and shunt capacitors, which can be connected arbitrarily in series or in parallel. In this experiment the π-sections have been connected in series.

The line impedances are proportional to the line lengths and this property has been used to calculate the distance from the relay location to the fault. The relay has been fed with the measured current and voltage signals from the primary side through the current and voltage transformers, thus the secondary values have been used for the settings of all parameters.

The following function blocks have been configured into the relay with their appropriate parameter settings; distance protection function, overcurrent function, voltage and supervision function, trip logic, internal signals, binary input and output, human machine interface (HMI) LED, disturbance report and events for station control system.

The test faults performed in zones 1, 2 and 3 are three-phase fault, single-phase to ground fault, double-phase to ground fault, and double-phase fault. After each test, the disturbance report has been uploaded into a PC for evaluation using the REVAL tool made by ABB.

The relay has responded positively to all types of faults mentioned above and can be configured to suit with the line model.

Chapter 2

Line protection

2.1 Overcurrent protection

It is common to use current magnitude to detect faults in distribution networks. Faults on the system bring about very high current levels. It is possible to use these currents to determine the presence of faults and trigger protective devices, which can vary in design in relation to the complexity and accuracy required.

Overcurrent relays are the most common form of protection used to deal with excessive currents on power systems. They should not be installed purely as a means of protecting systems against overloads, which are associated with the thermal capacity of machines or lines, since overcurrent protection is primarily intended to operate only under fault conditions. However, the relay settings selected are often a compromise in order to cope with both overload and overcurrent conditions.

Based on the relay operating characteristics, overcurrent relays can be classified into three groups: definite current, definite time and inverse time. The characteristic curves of these three types are shown in Figure 2.1 [1].

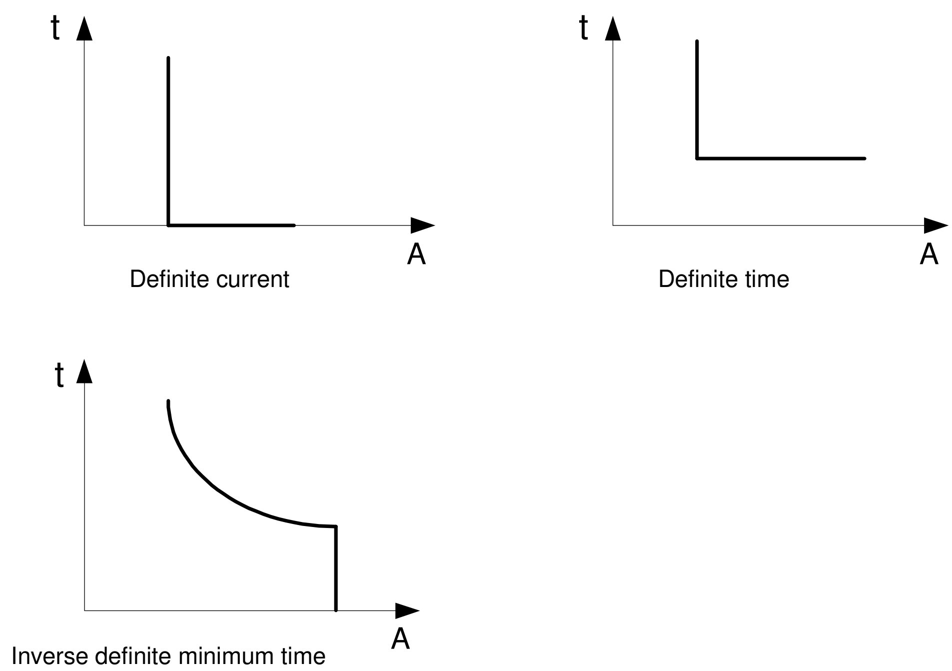

Figure 2.1 Time / current operating characteristics of overcurrent relays

2.1.1 Definite current relays

This type of relays operates instantaneously when the current reaches a predetermined value. The setting is chosen so that, at the substation furthest away from the source, the relay will operate for a low current value and the relay operating currents are progressively increased at each substation, moving towards the source. Thus, the relay with the lower setting operates first and disconnects load at the point nearest to the fault.

This type of protection has the drawback of having little selectivity at high values of short-circuit current. Another disadvantage is the difficulty of distinguishing between the fault current at one point and another when the impedance between these points is small in comparison to the impedance back to the source, leading to the possibility of poor discrimination.

Definite current relays are not used as the only overcurrent protection, but their use as an instantaneous unit is common where other types of protection are in use [1].

2.1.2 Definite-time relays

This type of relay enables the setting to be varied to cope with different levels of current by using different operating times. The settings can be adjusted in such a way that the breaker nearest to the fault is tripped in the shortest time and then the remaining breakers are tripped in succession, using longer time delays, moving back towards the source. The difference between the tripping times for the same current is called the discrimination time.

Since the operating time for definite time relays can be adjusted in fixed steps, the protection is more selective. The disadvantage with this method of discrimination is that faults close to the source, which result in bigger currents, may be cleared in a relatively long time. These relays are used a great deal when the source impedance is large compared to that of the power system element being protected, when fault levels at the relay position are similar to those at the end of the protected element [1].

2.1.3 Inverse time relays

The fundamental property of inverse time relays is that they operate in a time that is inversely proportional to the fault current. Their advantage over definite time relays is that, for very high currents, much shorter tripping times can be obtained without risk to the protection selectivity. Inverse time relays are generally classified in accordance with their characteristic curve, which indicates the speed of operation; based on this they are defined as being inverse, very inverse or extremely inverse [1]

2.1.4 Setting for overcurrent protection

The principles for setting instantaneous units differ relative to the location and on the type of system component being protected. Three groups of component can be defined – lines between substations, distribution lines and transformers [1].

Lines between substations

The setting of instantaneous units is carried out by taking at least 125% of the symmetrical root mean square (rms) current for the maximum fault level at the next substation. The procedure must start from the furthest substation, then continued by moving back towards the source.

When the characteristics of two relays cross at a particular system fault level, thus making it difficult to obtain correct coordination, it is necessary to set the instantaneous unit of the relay at the substation which is furthest away from the source to such a value that the relay operates for a slightly lower level of current, thus avoiding loss of coordination. The 25% margin avoids overlapping the down-stream instantaneous unit if a considerable DC component is present. In high voltage systems operating at 220 kV or above, a higher value should be used since the X/R ratio becomes larger, as does the DC component.

Distribution lines

The setting of the instantaneous elements of relays on distribution lines, which supply only pole-mounted MV/LV transformers, is dealt with differently to the previous case, since these lines are at the end of the MV system. They therefore do not have to fulfil the coordination conditions that have to be met by the lines between substations. Therefore, the setting for these units is 50% of the maximum short-circuit current at the relay location, or between six and ten times the rated current.

Transformer units

The instantaneous units of the overcurrent relays installed on the primary side of the transformer should be set at a value between 125 and 150 per cent of the fault current existing on the low-voltage side. This value is set higher than the transformer magnetic in rush current when energising the transformer in order to avoid lack of coordination. If the instantaneous units of the transformer secondary winding overcurrent protection and the feeder relays are subjected to the same short-circuit level, then the transformer instantaneous units need to be overridden to avoid loss of selectivity. This applies unless there are communication links between these units, which can permit the disabling of the transformer instantaneous overcurrent protection for faults detected by the feeder instantaneous overcurrent protection.

2.2 Differential protection

Differential protection operates when the vector difference of two or more similar electrical magnitudes exceeds a predetermined value.

An example of differential arrangements is shown in Figure 2.2 [1]. The secondaries of current transformers (CTs) are interconnected, and the coil of an overcurrent relay is connected across these. Although the currents I1 and I2 may be different, provided that both sets of CTs have appropriate ratios and connection then, under normal load conditions or when there is a fault outside the protection zone of the element, secondary currents will circulate between the two CTs and will not flow through the overcurrent relay.

If a fault, however, occurs in the section between the two CTs the fault current would flow towards the short-circuit point from both sides and the sum of the secondary currents would flow through the differential relay. In all cases the current in the differential relay would be proportional to the vector difference between the currents that enter and leave the protected element; if the current through the differential relay exceeds the threshold value then the relay will operate.

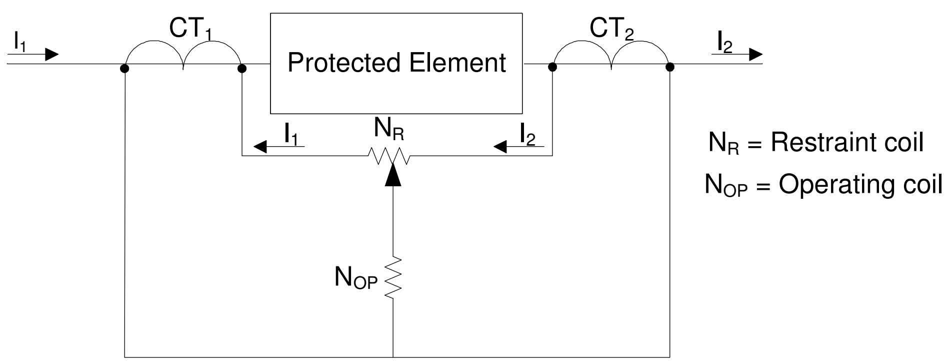

Figure 2.2 Differential relay with variable-percentage characteristics

The differential protection has the following advantages [2]

- Differential current protection does not react in principle to external short-circuits and therefore does not require the time lags to be coordinated with the protection of the adjacent sections of the line.
- Differential current protection does not react to peak currents caused by overload or swings and therefore it has high sensitivity.

The main types of differential current protection are [2]:

- Longitudinal differential current protection of lines comparing the currents at the beginning and end of the protected section,
- Transverse differential protection of parallel lines, balanced or directional comparing the currents in the parallel circuits,
- Differential current protection of bus bars.

2.2.1 Longitudinal differential

This is used on sections of small length (up to 5km in 35kV networks and up to 10km in 110kV networks) in those cases where the currents cut-offs or distance protection does not conform to requirements in speed, selectivity and sensitivity. The pilot conductors along the track of the transmission line carry out current comparison at the end of the protected section.

Phase currents are not usually compared, but rather the currents at the output terminals of summators or combined filters at the end of the protected section, which transform the three-phase system of currents into a single-phase system.

Types of longitudinal differential current protection for transmission lines are:

- Circulating currents – In a scheme with circulating currents under normal conditions and with an external short-circuit, a current circulates in the pilot conductors. The differential relays at both ends of the protected section are so connected that when there is no fault in the protected zone, braking torques arise there which prevent the relay from tripping. In the presence of short-circuit in the protected zone, the equality of the ampere-turns of the primary winding of the differential current transformer is disturbed and the relay working winding becomes energised.

- Balanced voltages – In a scheme with balanced voltages, under normal conditions and in the presence of an external short-circuit there is no current in the pilot conductors. In the presence of a short-circuit within the zone of protection, the equilibrium of the secondary winding voltages of the isolating transformer is disturbed, the secondary winding carries current and the impedance between the terminals of the primary winding is reduced. The working winding of the differential relay then takes the current of the summation, the working torque exceeds the braking torque and the relay causes tripping.

2.2.2 Transverse balanced differential

Balanced current protection is a type of transverse differential protection of parallel lines. It is based on a comparison of the magnitudes of the currents passing through the lines. It is established at that end of the line, which is constantly connected to the source.

For equal impedance parallel lines, under normal conditions, or in the presence of an external short-circuit, the balanced relays will not operate due to the similar distributed currents. In the presence of a short-circuit on one of the parallel lines, the larger part of the current from the source passes along the faulty line, while the smaller part passes along the undamaged lines. In this circumstance, the balanced relay will trip the faulty line.

At the receiving end of the parallel lines, without an additional feed source, the currents in the presence of short-circuit on one of these lines are equal in magnitude but opposite in direction. A balanced relay that reacted to the ratio of the current magnitudes and not to their direction would, in this case not operate.

2.2.3 Transverse differential directional protection

It is a type of high-speed protection of parallel lines. It can be established at any end of the parallel lines. The principle of transverse differential directional protection is illustrated in Figure 2.3 [2]. The secondary windings of the current transformers are connected cross-wise, that is, the beginning of the windings of one current transformer are connected to the end of the windings of the second current transformer. As a result we have the series connection of the windings of both current transformers as a 'figure eight'. A current relay (starting device) and a power directional relay (directional device) are connected in series between the same terminals. Thus, the relays are connected to the current difference of the protected parallel lines.

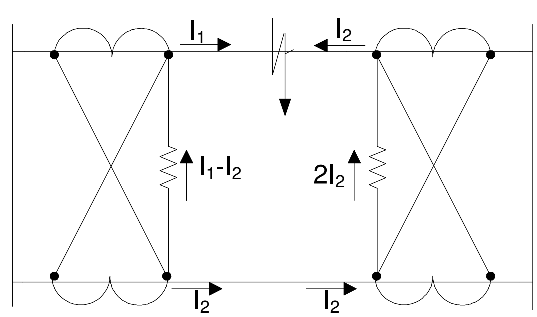

Figure 2.3 Principle of transverse differrential and directional protection

Under normal conditions or in the presence of an external short-circuit; the secondary currents along the parallel lines are the same in magnitude and direction. Thus, the resulting current in the relay is zero; the currents only circulate in the current transformer windings.

When there is short-circuit on one of the parallel lines, the equality of the current is disturbed and a current begins to pass through the relay equal to the difference of the secondary currents. If it exceeds the setting of the current relay, then the latter starts the protection, closing the voltage circuit of the power directional relay. If one of the parallel lines is taken out of service or faulted, only one power directional relay will operate, the contacts of the second directional relay remaining open.

2.2.4 Applications

Differential Protection for Bus bars

Short-circuit on bus bars can have very serious consequences for the operation of the power system. The most widely used and acceptable type of protection for 35 – 220kV bus bars is high-speed differential protection. It is based on Kirchhoff's current law that requires the sum of all currents entering the bus to sum to zero. Should an internal fault occur, however, the sum currents measured at current transformer locations will not be zero, and tripping should occur. This type of bus protection for one phase is shown in Figure 2.4 [3].

The current transformer secondaries are added together to give the sum of the currents in all four lines; and the sum is sent to the differential relay. In case a fault occurs that is external to the CT connections, say at the point 1 in the Figure 2.4, the total current flowing to that fault will be exactly equal to the total current entering the bus on lines 2, 3, 4 and no current will flow to the differential relay. However, if a fault occurs on the bus, between phases or from phase to ground, the sum of the line currents will equal the total bus fault current and the relay will correctly measure this quantity.

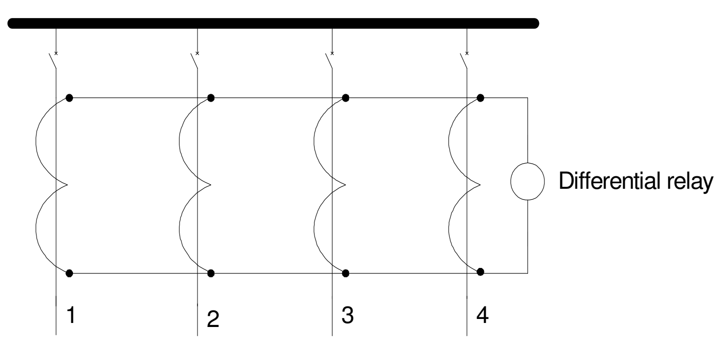

Figure 2.4 Bus differential protection

Differential Protection for Transformer

A transformer suffers from different types of stresses; overheating and short-circuit. Short-circuit protection includes internal short-circuit, such as turn-to-turn faults and turn-to-ground faults. It also includes external short circuits for example bushing flashovers that are also within the protection zone of the relays. The most common form of transformer protection is differential relaying, which treats the transformer as a unit making measurements at all of the transformer terminals.

In applying the principles of differential protection to three-phase transformers, the CT connections should be such that, the relay does not operate for normal load or for external faults and the relay must operate for internal faults of a given severity.

A rule of thumb often applied to the connection of CTs for power transformer protection is as follows:

- CTs on a wye-connected winding should be connected delta
- CTs on a delta-connected winding should be connected in wye.

Making the connection in this way ensures that, for external faults, the CT secondary currents are equal and the differential protection will not trip the transformer [3].

Differential Protection for Generators

Differential protection for generators is similar to that for transformers in many ways. Internal generator winding faults include phase-to-phase short circuits, short-circuited turns, open circuits and faults to earth and should be disconnected by opening the circuit as quickly as possible, the neutral of the generator should be well earthed, either solidly or via a resistor or a reactor. The differential protection should satisfy the following requirements, it should [1]:

- Be sensitive enough to detect damage in the winding of the generator stator, and yet not operate for faults outside the machine
- Operate quickly in such a way that the generator is disconnected before any serious damage can result
- Be designed so that the main breaker is opened as well as the neutral breaker and the field-circuit breaker.

Line Differential Protection

The form of differential protection using only one set of relays is not suitable for long overhead lines since the ends of a line are too far apart to be able to interconnect the CT secondaries satisfactorily. It is therefore necessary to install a set of relays at each end of the circuit and interconnect them by some suitable communication link. Pilot protection (indicates that there is an interconnecting channel between the ends of the lines through which information can be transmitted) is an adaptation of the principles of differential protection that can be used on such lines.

The principle of operation of pilot differential protection is similar to the differential systems for protecting generators and transformers, but the relays have different settings because the breakers at the ends of the line are more widely separated and a single relay should not be used to operate two tripping circuits. For this method of protection both ends of the line should open instantaneously for faults wherever they occur on the line. In addition, the system should not operate for faults outside the section and is therefore inherently selective [1].

2.3 Distance protection

2.3.1 Basis principles

The distance protection relay measures the line voltage and line current at the relay location and evaluates the ratio between these quantities. We consider the relay at the station A in Figure 2.5,

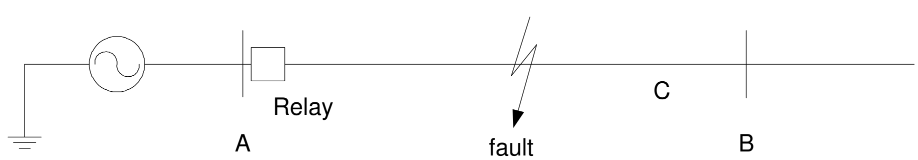

Figure 2.5 Fault occurs in a power system

When a fault occurs on the protected line the fault current I_f and voltage U_f is fed into the relay. The relay should trip for faults within a fractional distance *k,* which is called "the reach setting " of the distance relay, of the total distance between buses A and B. The reach given in distance unit, thus, is a tripping threshold.

Considering a solid fault at the threshold point C, we calculate the voltage drop along the line,

$$U_f = kZ_L I_f \tag{2.1}$$

where Z_L = total line impedance from A to B

The impedance Z_k seen by the relay is computed as follow,

$$Z_k = \frac{U_f}{I_f} = kZ_L \tag{2.2}$$

Equation (2.2) expresses the threshold or the impedance characteristic of the relay. During normal system operation, the impedance seen by the relay is approximately equal to the load impedance that is much larger than the line impedance.

If the fault is within the fraction *k,* then the measured impedance at the relay is,

$$Z < Z_k = kZ_L \tag{2.3}$$

The impedance to the fault point is now within the impedance protection characteristic and the relay will operate. Obviously, the relay will not trip for the fault beyond the fraction *k*.

The impedance characteristic of the relay can be chosen so that the reach is different for different phase angles of the apparent impedance.

2.3.2 Setting of the distance zones

Line impedances are proportional to the line lengths and this property is used to calculate the distance from the relay location to the fault. The relay, however, is fed with the current and voltage measured signals from the primary system via instrument transformers CT and VT. Therefore, the secondary value used for the setting is obtained as the following expression,

$$Z_{sec} = \frac{I_{pri}/I_{sec}}{U_{pri}/U_{sec}} Z_{pri} \quad (2.4)$$

where I_{pri}/I_{sec} and U_{pri}/U_{sec} are the transformation ratios of the current and voltage transformers, respectively.

In order to cover a section of the line and to provide back-up protection to remote sections, three main protection zones, see Figure 2.6, are set up with the following criteria:

- Zone 1: this is set to protect between 80% and 85% of the line length AB and operates without any time delay.
- Zone 2: this is set to protect 100% of the line length AB, plus at least 20% of the shortest adjacent line BC and operates with time delay t_2.
- Zone 3: this is set to protect 100% of the two lines AB, BC, plus about 25% of the third line CD and operates with time delay t_3.

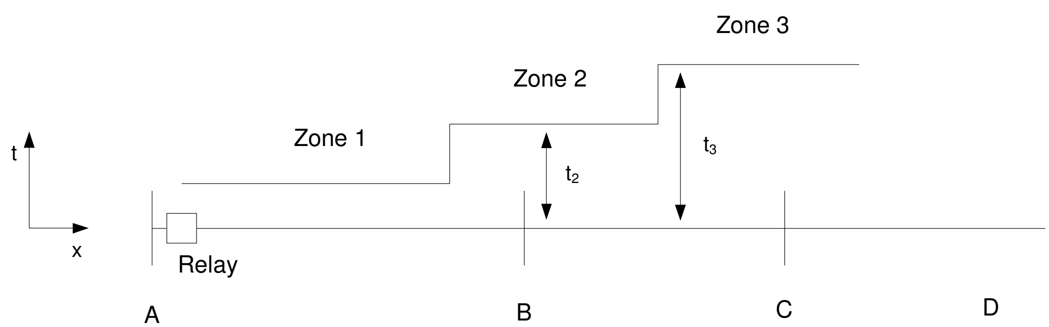

Figure 2.6 Distance-relay protection zones

2.3.3 Relay characteristics

The shape of the operation zones has developed throughout the years. Figure 2.7 [4] gives an overview of relay characteristic. Originally the operating characteristic was a circle located in the origin of the co-ordinates in the R-X plane of the impedance relay. This type of relay, however, is non-directional and sensitive to power swings and load encroachment due to the large impedance circle. Therefore, the circle diameter was reduced and its origin passed through the origin of the co-ordinates resulting in the mho relay.

Relays with combined characteristics are obtained by added a mho circle with lines parallel to the resistive and reactive axes which cross each other at the setting point Z_k .

Modern distance relays, especially the numerical types, offer quadrilateral characteristic, whose resistive and reactive reach can be set independently.

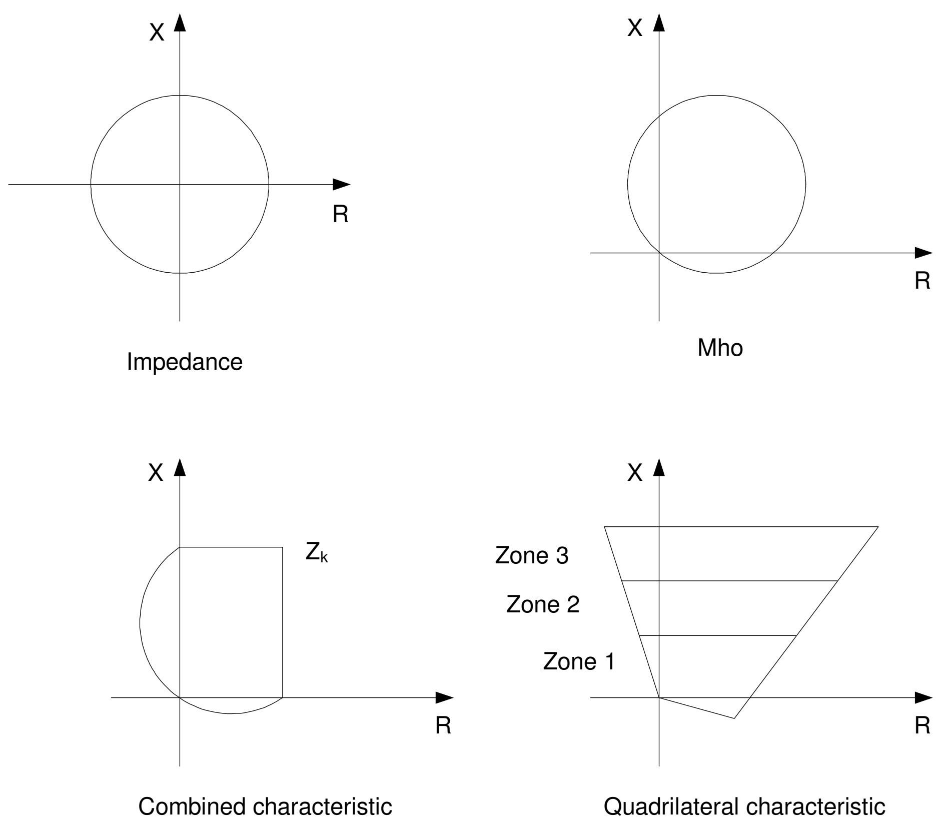

Figure 2.7 Relay characteristics

2.3.4 Distance relay types

Distance relays are categorized in two major schemes; switched scheme and full scheme. The block schemes for a switched scheme and full scheme are illustrated in Figure 2.8 [5]. In a switched relay, the start elements detect a fault. These elements together with logic blocks determine the correct input signals with respect to the fault type. Zones of operation are decided by timer block. Measuring elements and directional elements decide if the impedance is inside a certain zone and the direction to the fault, respectively. The full scheme relay does not have the start elements. It has measuring elements for each phase, each zone and both phase to phase and phase to ground faults. The operation is faster than that of switched relays.

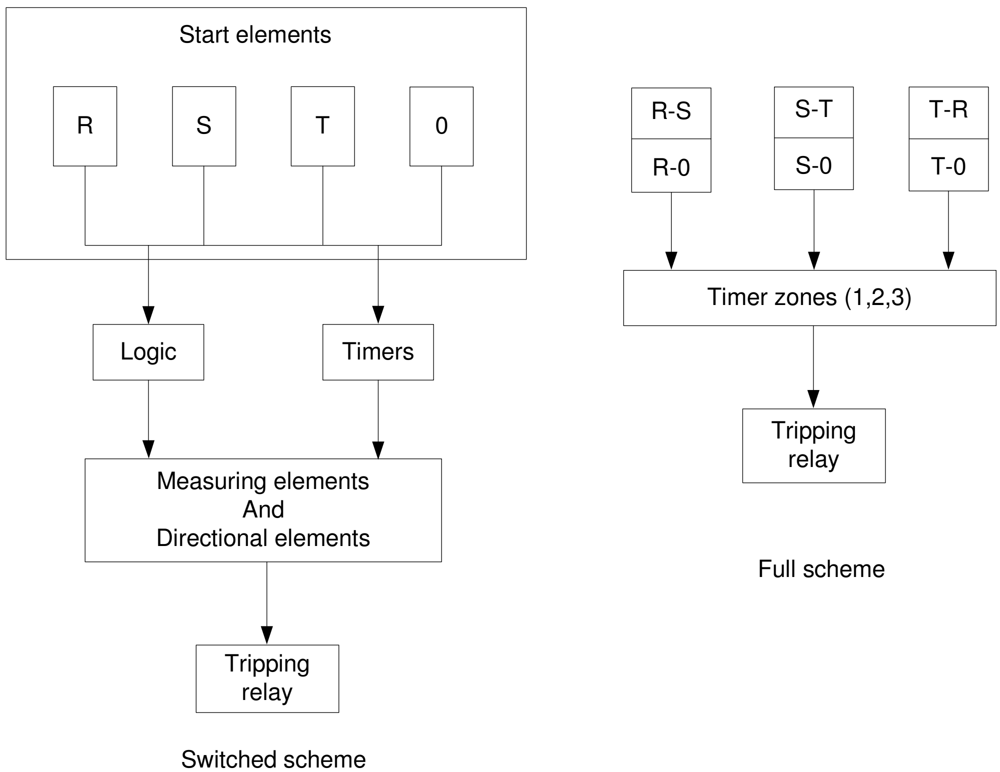

Figure 2.8 Block shemes for a switched and full scheme distance relay

2.3.5 Numerical relay

2.3.5.1 Structure of numerical relays

A numerical relay consists of the following main subsystems:

- Microprocessor
- Analog input system
- Digital output system
- Power supply

Figure 2.9 [6] shows a block scheme of a typical numerical relay

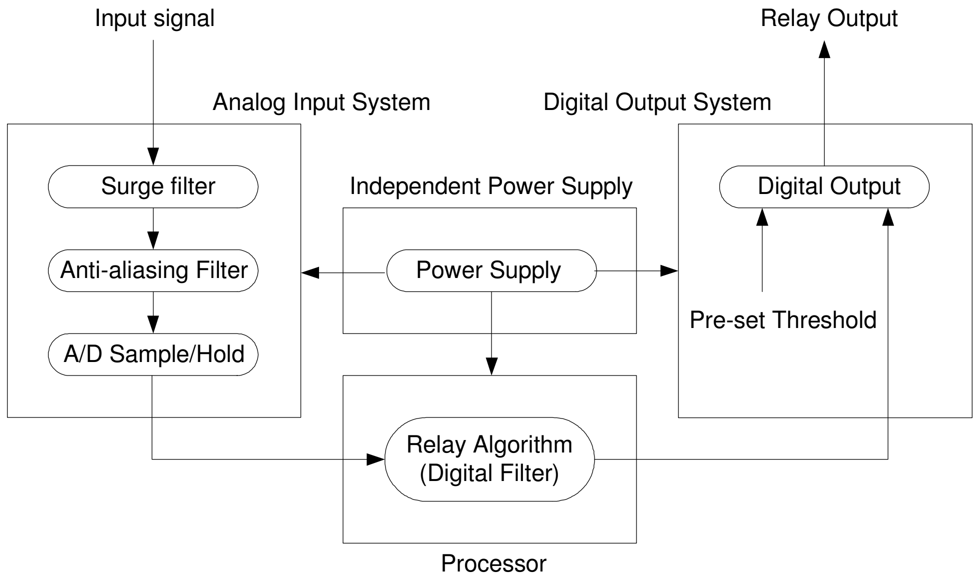

Figure 2.9 Block diagram of a numerical relay

Numerical relays operate on sampled signals and adopt digital computations. Sampling is the process of converting analog input signals, such as current and voltage, into digital input signals. These analog input signals, in case of electromechanical and static relays, are directly fed into the electromagnetic winding or electronic circuits. In order to protect the relay from large transients of the input signals a surge filter is used.

An anti-aliasing filter is used to avoid possible errors in reconstructing the input signal carried out after the A/D Sample/Hold section. Any signal having harmonic components of order $N \pm 1$, $2N \pm 1$, …, $x\ N \pm 1$, where N is the number of samples per cycle, can exhibit aliasing. Perfectly, an anti-aliasing filter has to cut off all signal components above the Nyquist rate of N/2. In practical, however, such a filter can not cut off all out of band frequencies, so the anti-aliasing filter cut off frequency is set at about N/3.

The A/D converts the sample values that represent the analog input signals into the digital input signals. However, the conversion is not instantaneous, and for this reason, the A/D system typically includes a sample-and-hold circuit. The sample-and-hold circuit provides ideal sampling and holds the sample values for quantization by the A/D converter.

The microprocessor containing the relay algorithm is the controller of the numerical relay. The microprocessor most often performs all control, computation, self-test, and communication functions. The algorithm functions as a digital filter to extract the fundamental component of the input signal, based on which the relay operation is carried out.

The signal from the digital filter is compared with the pre-set threshold in the digital output system. The relay operation is decided based on this comparison.

2.3.5.2 Relay algorithm

The algorithm is designed to remove as much as possible all of unwanted components from the input signals such as harmonic, DC, etc. Two common algorithms will be discussed here, the Discrete Fourier Transform (DFT) and the Root Mean Square (RMS) algorithm [7].

Discrete Fourier Transform (DFT)

The Discrete Fourier Transform is a discrete time version of the Fourier Transform and shown as follow,

$$X(n)_{DFT} = \sum_{k=0}^{N-1} x[k] e^{-j2\pi k \frac{n}{N}} \tag{2.5}$$

where n is the harmonic number, k is the sample, N is the number of samples per cycle, and j means it is imaginary number.

In Equation (2.5), the exponential term is,

$$e^{-j2\pi k \frac{n}{N}} = \cos(2\pi k \frac{n}{N}) - j\sin(2\pi k \frac{n}{N}) \tag{2.6}$$

The magnitude of the DFT is computed by squared root the total of the real part squaring and the imaginary part squaring. The angel of the phasor is computed by taking the arc tangent of the imaginary part over the real part.

The DFT can extract any frequency from the signal. Since the DFT is capable of rejecting everything except the frequency being measured, it has a good response to transient overshoot.

Root Mean Square (RMS)

The Root Mean Square is a method of calculating the magnitude of a periodically varying quantity. It can be calculated for a series of discrete values or for a continuously varying function.

The RMS for a collection of N values {x1, x2, ..., xN} is,

$$X_{RMS} = \sqrt{\frac{1}{N}\sum_{k=1}^{N} X_k^{\;2}} \tag{2.7}$$

and the corresponding formula for a continuous function x(t) defined over the interval $T_1 \le t \le T_2$ is,

$$X_{RMS} = \sqrt{\frac{1}{T_2 - T_1}\int_{T_1}^{T_2} x^2(t)dt} \tag{2.8}$$

The RMS algorithm is useful for applications where measuring energy content to approximate heating characteristics is desirable.

Chapter 3

Results using Line distance protection

REL 511*2.3

3.1 Laboratory set up

A single-line diagram of the laboratory setup of the testing is shown in Figure 3.2. The REL511*2.3 has been connected to the network model through three single-phase voltage transformers and three current transformers. A three-phase resistive load of 9 kW has been connected to the line model. A fault in the line can be made through a variable fault resistance by closing a contactor controlled by a timer. The timer and the contactor is also used to clear the fault. Figure 3.1 is a picture of the real setup in the laboratory.

Figure 3.1 Photo of laboratory setup

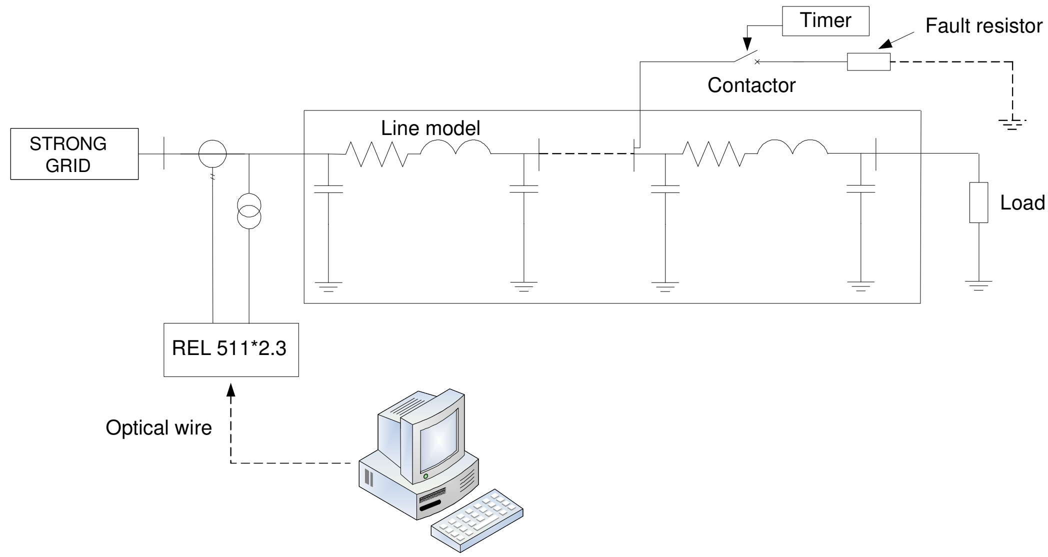

Figure 3.2 Single-line diagram of the laboratory setup

3.2 Line model

The power line model is a three-phase model of a 400 kV transmission system. The entire model operates at 400 V consequently the voltage scale is 1:1000 [8]. As can be seen in Figure 3.3, the line model can be fed using the local distribution line denoted as strong grid, or a synchronous generator.

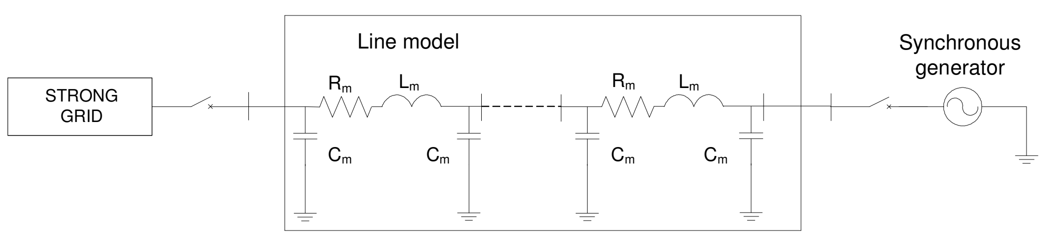

Figure 3.3 Single-line diagram of the line model

The line model consists of six identical π-sections, each corresponding to 150 km of a 400 kV line. Each section includes series reactors (denoted by R_m and L_m) and shunt capacitors (denoted by C_m). The sections can be connected arbitrarily in series or in parallel. In these experiments, the π-sections have been connected in series, and the line model has been supplied by a strong grid.

The data for the real 150 km section of the 400 kV line are,

$$X_r = 50.4\ \Omega$$
$$R_r = 4.17\ \Omega$$
$$C_r = 0.065767\ \mu\text{F}$$

An impedance scale of 1:53.2 gives the corresponding values of the line model.

3.3 Numerical relay REL 511*2.3

Numerical relay REL 511*2.3 shown in Figure 3.4 is based on a full scheme distance protection function. REL 511*2.3 detects both phase-to-phase and phase-to-earth faults and it has quadrilateral operating characteristics. A separate general fault criterion with advanced characteristics is used for phase selection and as an overall measuring function, which increases the total operating security and facilitates remote backup applications.

The numerical REL 5xx line distance protection terminals are designed for the main and backup protection, monitoring and control of power lines, cables and other primary objects. They can be used in systems with simple or complex network configurations regardless of the type of system grounding.

Figure 3.4 Photo of REL 511*2.3

3.4 Installation and set up for REL 511*2.3

3.4.1 Relay installation

DC supply

The relay uses 48V-250VDC supply. Therefore, a converter having input of 200VAC-240VAC and output of 0VDC-120VDC is used to energize the relay. The connection is shown in Figure 3.5. As shown in the figure, the converter output is connected to the relay through the terminals 11 and 13.

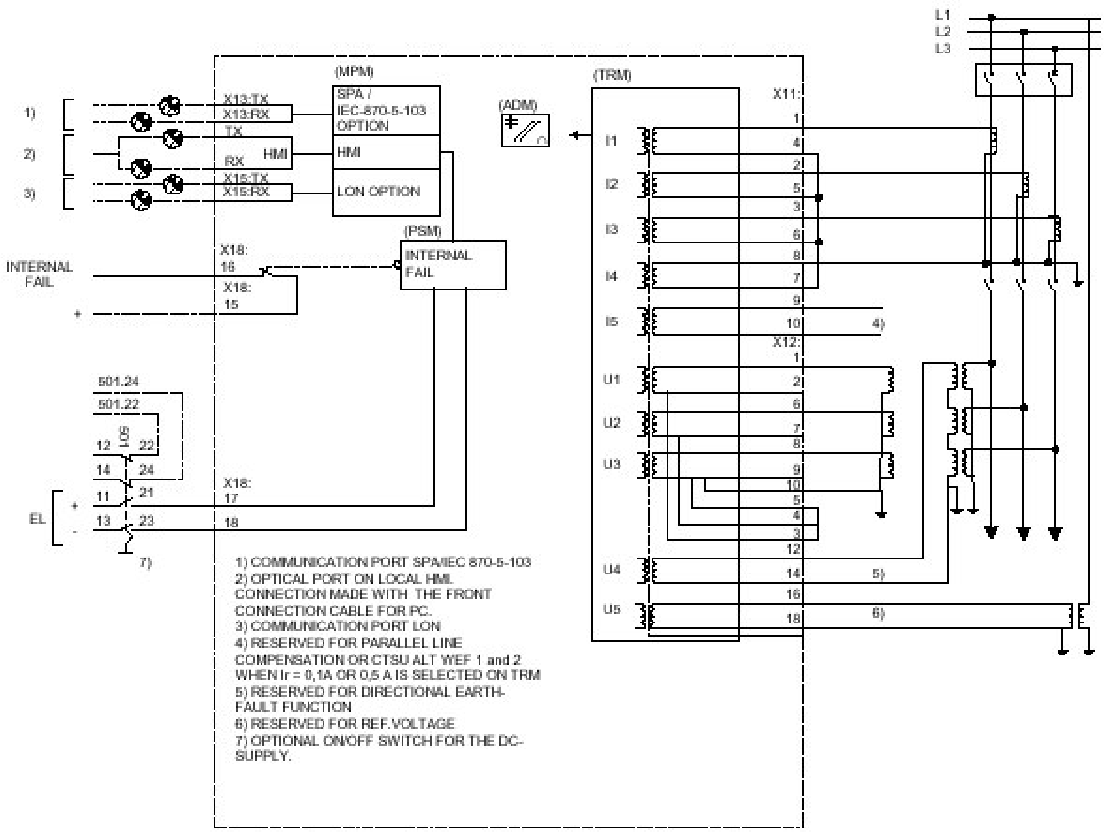

Figure 3.5 Terminal diagram for DC supply

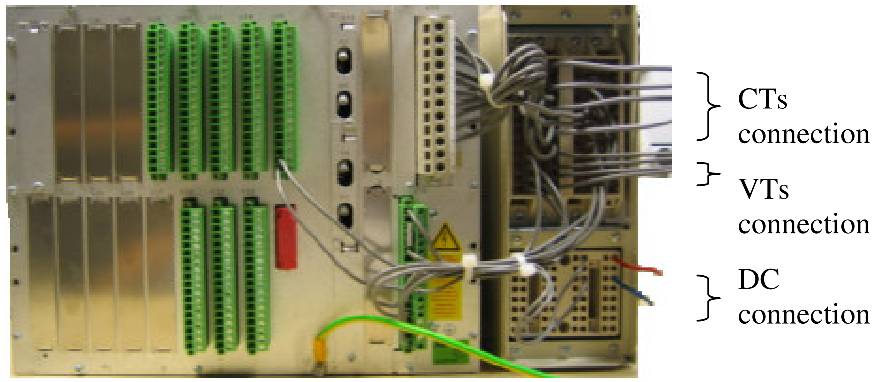

Figure 3.6 Connection on the rear side of the relay

CTs and VTs

Three single-phase voltage transformers (VTs) are connected to the line model as shown in Figure 3.1. The voltage transformer input is 230V and four outputs are 69V, 115V, 161V and 230V. Since the relay input is U_r=100-120V phase to phase, the VTs output of 69V is used.

Three current transformers (CTs) having ratio of 100/1 have already been connected in the line model, see Figure 3.7. The signals from the secondary outputs of the CTs are available in the control panel P.2.1 of the line model.

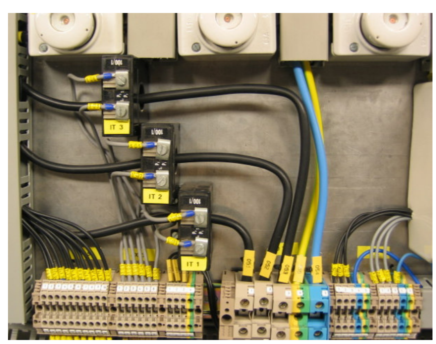

Figure 3.7 Photo of the CTs

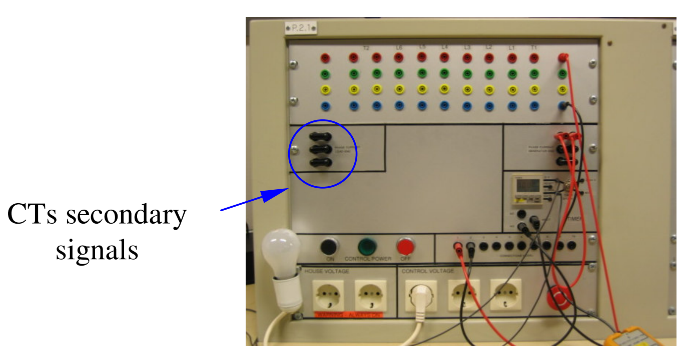

Figure 3.8 Photo of the P.2.1 control panel

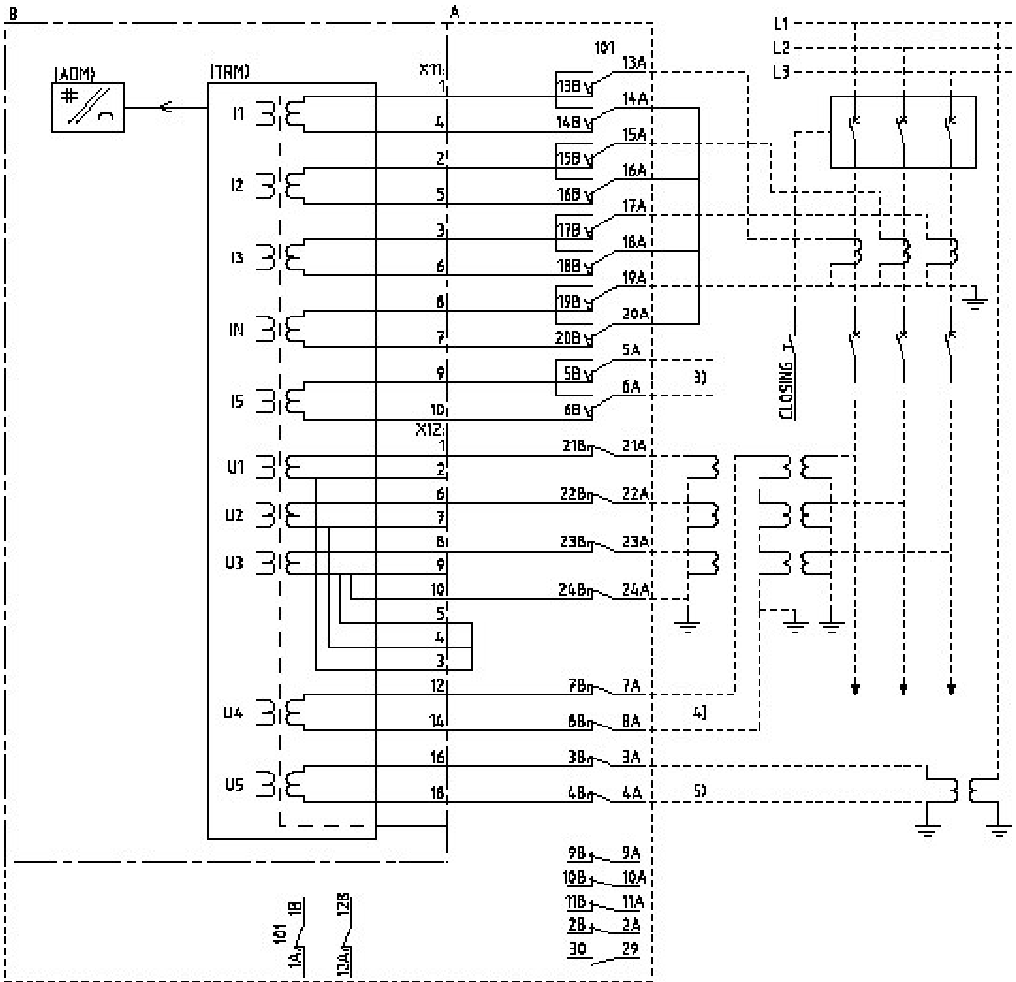

Figure 3.9 Terminal diagram for CTs and VTs connection.

PC – relay connection

The optical wire is used to make the connection between PC and the relay. Figure 3.10 shows the human-machine interface (HMI) module in which the optical wire is connected to.

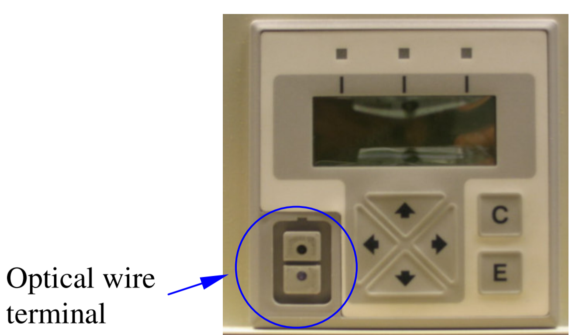

Figure 3.10 Photo of the (HMI) module

3.4.2 Configuration and tools used

The terminal REL 511*2.3 is configured using the configuration and programming tool CAP 531. This tool enables configuration management, programming and error detection and correction for the REL 5xx terminals. CAP 531 is started from within the CAP 540 [10].

CAP 531 comprise these views:

- Project tree: Organize terminal and work sheets.
- Work sheet: Create the configuration.
- Page layout: Create drawing forms for printed pages.

A new project tree can be created from within the CAP 540 [10]. A project tree in CAP 531 shown in Figure 3.11 can only have the terminal and work sheets. The graphical configuration is made in the work sheets.

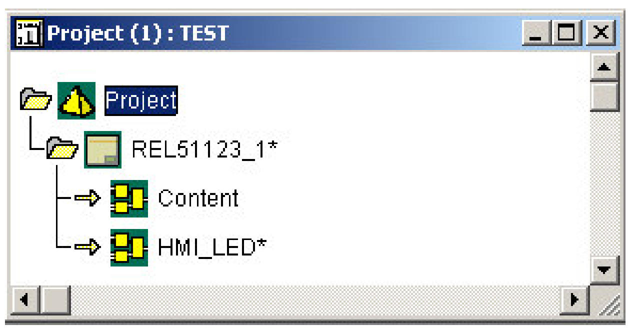

Figure 3.11 Project tree

It is important that you use the correct set of functions to work with the configuration of a terminal from the beginning. These functions are selected in the Function Selector in the Edit menu. There are many available function blocks for the same function and the Function Selector is used to choose them.

For example, I/O module01 in the CAP/REL511 program module can be configured to be either as:

- BIM Binary Input Module
- BOM Binary Output Module
- IOM Input Output Module
- IOPSM Input Output Position System Module
- DCM Differential Communication Module

A choice of these modules gives different shape of the function block for the I/O module01. For instance, the logical I/O module01 (IO01-) BIM can be compared to BOM as shown in Figure 3.12.

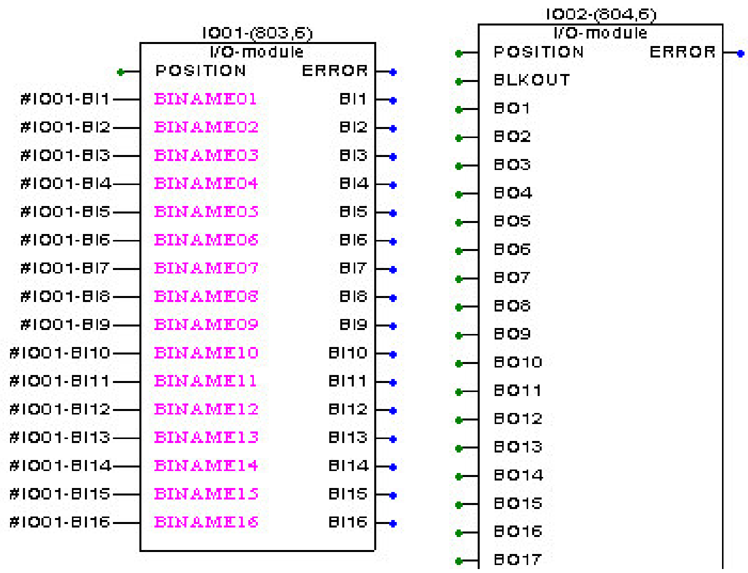

Figure 3.12 Compare the I/O module as BIM (left) or as a BOM (right)

The library is updated with a new function block when you select a module in the Function Selector tool and only that selected module can be used in the configuration. The Function Selector can be started as follows:

- Select the terminal in the Project Tree.
- Select the 'Function Selector' in the Edit menu.

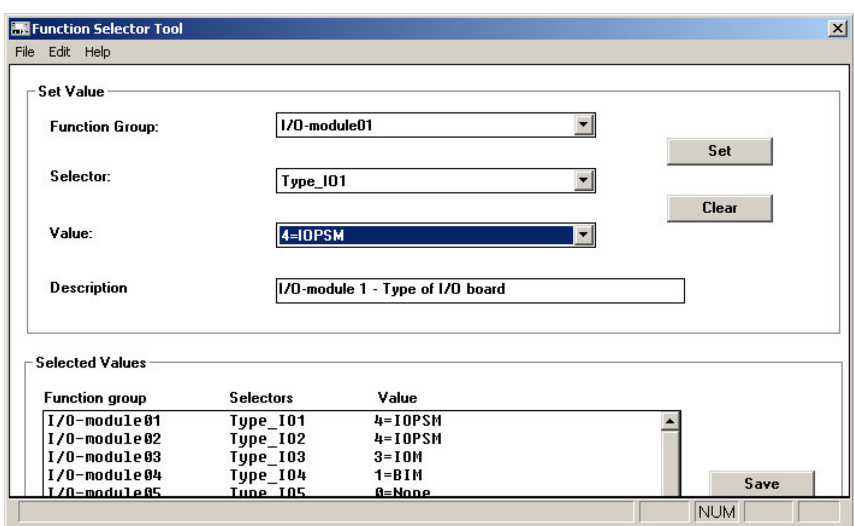

Figure 3. 13 Function Selector

The Function Selector contains the Set Value, which you use to change the function values, and the Selected Values, which give you an overview of all function.

The configuration is done in the work sheets as shown in Figure 3.14. The normal mode used when you work with the configuration in the work sheet and the debug mode is used to test the work sheet configuration.

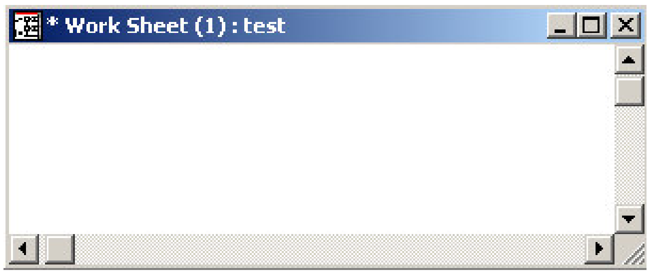

Figure 3.14 Work sheet called Test

To open a work sheet:

- Select a work sheet in the Project Tree.
- Double-click the left mouse button or press < Enter >.

Function blocks, variables, setting and text comments are considered as objects in a work sheet. In CAP 531, function blocks represent all the available functions in a terminal. The function block can be one of the following:

- Protection function.
- Control function.
- Monitoring function.
- Logic function.

The function block includes input and output parameters, a type name and function block name as shown in Figure 3.15 below.

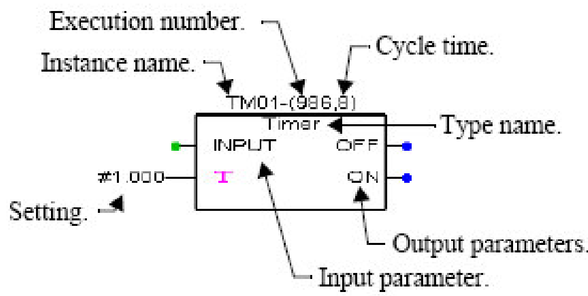

Figure 3.15 Function block in the CAP 531 work sheet

The function blocks in the work sheet can be connected together by using the connection mode [11].

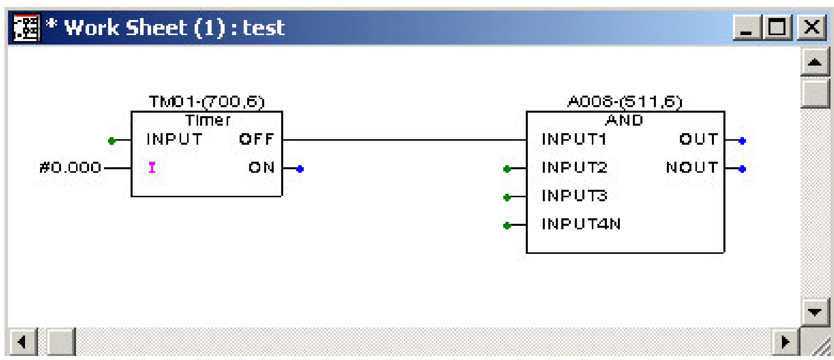

Figure 3.16 Two objects are connected

When the configuration preparation is completed, it should be compiled in order to check errors and to prepare the configuration for downloading into the terminal [11].

3.4.3 The initial set up of the relay

Initially, the relay has its default configuration and default parameters. The relay has been configured for three phase trip with the following function blocks: distance protection (five zones were set), current functions, scheme communication, voltage and supervision functions, trip logic, auto-reclosing and breaker-failure functions, internal signals, binary inputs and outputs, disturbance report and events for Station Control System (SCS).

For detailed default configuration refer to [15].

3.5 Parameter setting

The parameters can be set using the Parameter Setting Tool (PST). PST is a tool for monitoring, service values, protection and control terminal and relays. From CAP 540 the PST can be started from the project tree or from a function block within the configuration worksheet as follows:

- From the project tree in CAP 540:
    - ➢ In the project tree, select the wanted terminal instance.
    - ➢ With a right click select Parameter Setting.
- From a function block within a worksheet in CAP 531:
    - ➢ Open a worksheet for the wanted terminal instance.
    - ➢ With the right or left mouse button, double-click the wanted function block. The Function Block dialog appears.
    - ➢ Click Parameter Settings.

When the parameter tool starts, the main window according to Figure 3.17 appears.

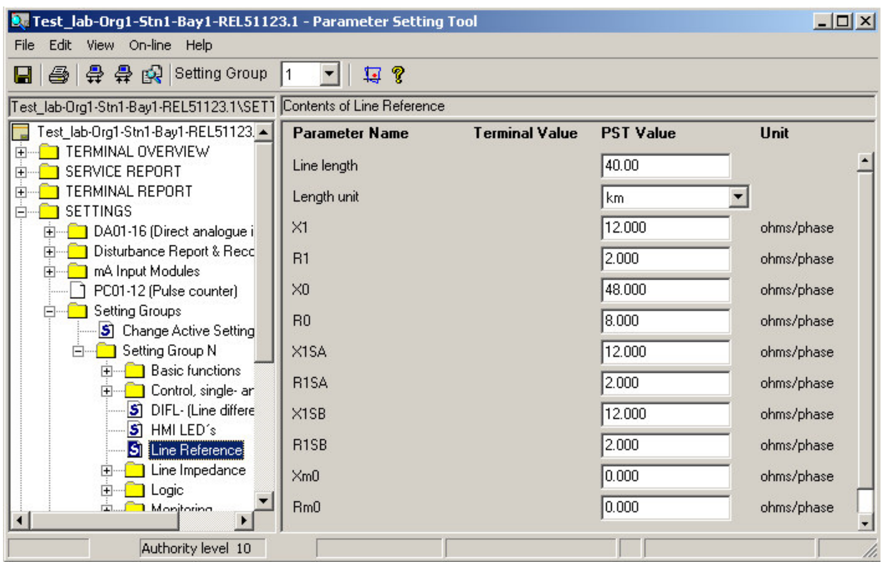

Figure 3.17 The main window of the parameter tool.

The terminal tree being on the left side of the window shows the structure in which the parameters for a terminal instance are organized. When a parameter is selected in the terminal tree, a list of parameters is shown. For each parameter the window will display its name, its value in the terminal, its value in PST and its unit. The parameter value can be edited directly in the PST Value field. A changed value is shown in bold and in the colour blue.

3.5.1 Setting for Analogue Inputs Modules

The analogue signals fed into the relay should be set in order to get the real values of the primary side of the line model. These setting values are the secondary base values and nominal primary to secondary scale values of the current transformers and voltage transformers. In this test, the base values of current and voltage are 1A and 69V, respectively. The nominal scale values for current transformers and voltage transformers are 100 and 3.347, respectively.

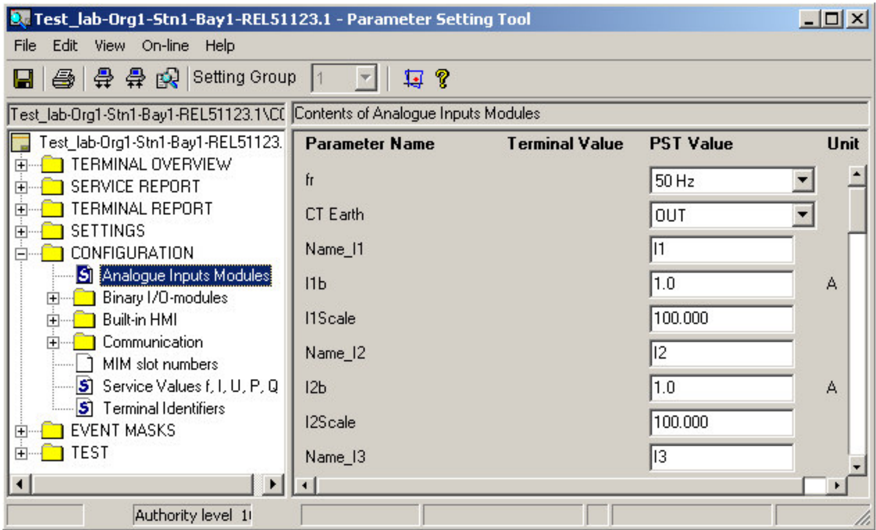

Figure 3.18 Analogue Inputs Modules parameters

3.5.2 Setting for distance zones

The fundamental rules have been discussed in the earlier chapter. The following values, see Figure 3.19, have been used for the settings,

- Zone 1: covers 85%AB, forward direction.
- Zone 2: covers 100%AB + 30%BC, forward direction.
- Zone 3: covers 100%AB + 100%BC + 25%CD, reverse direction.

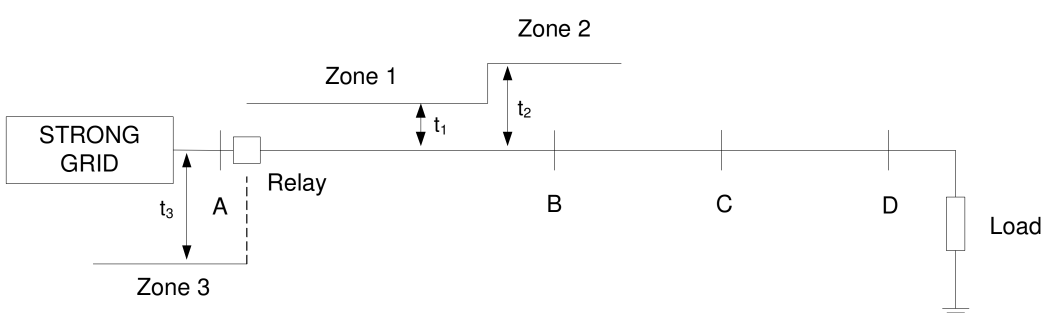

Figure 3.19 Grading chart of setting zones for testing

The data of the line model AB, BC, CD for positive sequence is given in Table 3.1.

Line	**Reactance X_1 [Ω/phase]**	**Resistance R_1 [Ω/phase]**
AB	2.84	0.23
BC	0.95	0.08
CD	0.95	0.08

Table 3.1 Data for lines AB, BC, CD

Zero sequence impedance Z_0 is three times larger than that of the positive sequence Z_1. The setting values are calculated by using the expression (2.4).

Table 3.2 Parameter setting for zones

Parameter	Zone 1		Zone 2		Zone 3		Unit	Description
	Primary	**Secondary**	**Primary**	**Secondary**	**Primary**	**Secondary**		
X1PP	2.42	73.52	3.12	95.15	4.03	122.54	Ω/ph	Positive sequence reactive reach of distance protection zone *n* for Ph-Ph faults
R1PP	0.20	6.08	0.26	7.87	0.33	10.14	Ω/ph	Positive sequence line resistance reach of distance protection zone *n* for Ph-Ph faults
RFPP	5.00	152.17	5.00	152.17	5.00	152.17	Ω/loop	Resistive reach of distance protection zone *n* for Ph-Ph faults
X1PE	2.42	73.52	3.12	95.15	4.03	122.54	Ω/ph	Positive sequence reactive reach of distance protection zone *n* for Ph-E faults
R1PE	0.20	6.08	0.26	7.87	0.33	10.14	Ω/ph	Positive sequence line reactance included in distance protection zone *n* for Ph-E faults
X0PE	7.25	220.56	9.36	285.45	12.09	367.62	Ω/ph	Zero sequence line reactance included in distance protection zone *n* for Ph-E faults
R0PE	6.08	18.24	0.78	23.61	0.99	30.42	Ω/ph	Zero sequence line resistance included in distance protection zone *n* for Ph-E faults
RFPE	5	152.17	5.00	152.17	5.00	152.17	Ω/loop	Resistive reach of distance protection zone *n* for Ph-E faults
tPP/ tPE	0.00/ 0.00		0.15/ 0.15		0.25/ 0.25		s	Time delayed trip operation of the distance protection zone *n* for Ph-Ph / Ph-E faults

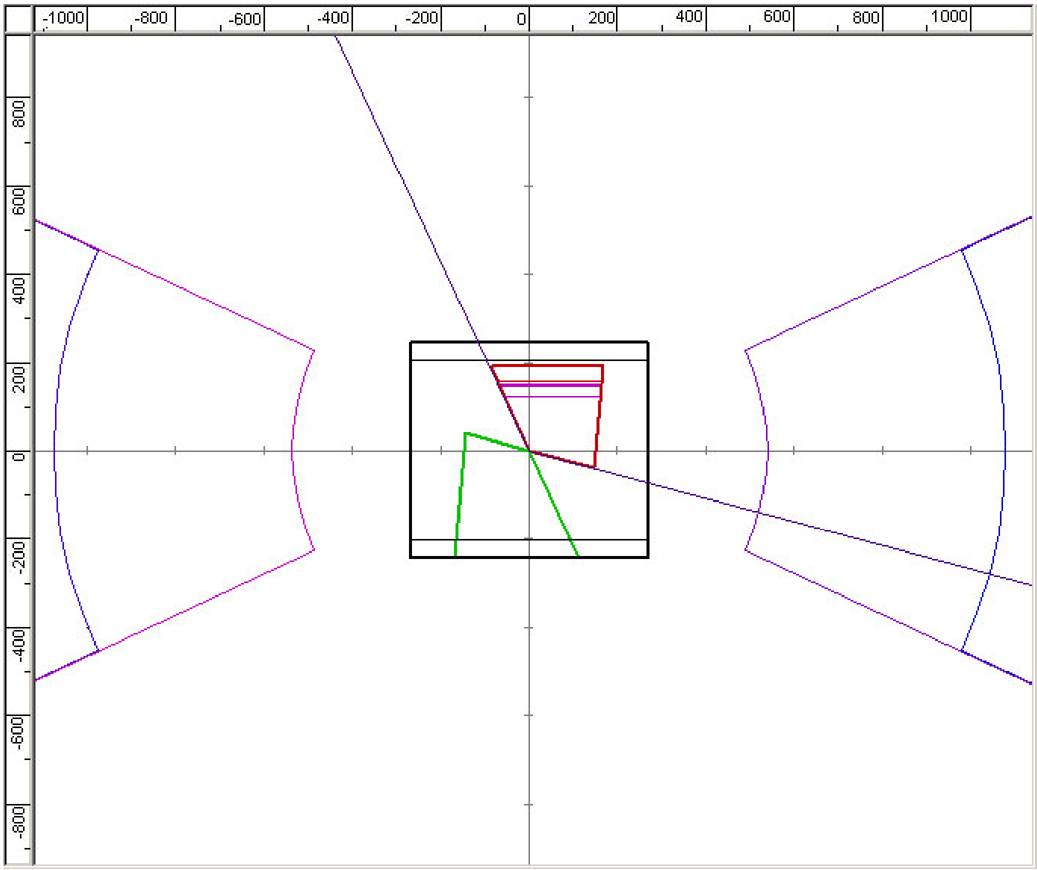

Figure 3.20 Load and impedance zone characteristics

Impedance Zone 1 [ZM1] Ph-E Loop
Impedance Zone 1 [ZM1] Ph-Ph Loop
Impedance Zone 2 [ZM2] Ph-E Loop
Impedance Zone 2 [ZM2] Ph-Ph Loop
Impedance Zone 3 [ZM3] Ph-E Loop
Impedance Zone 3 [ZM3] Ph-Ph Loop
General Fault Criteria [GFC] Ph-E Loop
General Fault Criteria [GFC] Ph-Ph Loop
Directional angles Ph-E Ph-Ph Loop Phase
Load
Load
Load
Load

3.5.3 Setting for the general fault criteria GFC function block

Parameter	Setting value	Unit	Description
ARGLd	25	degrees	Load angle determining the load impedance area
RLd	270.50	Ω/loop	Limitation of resistive reach within the load impedance area
X1RvPP	122.54	Ω/Ph	Positive sequence reactive reach in reverse direction for Ph-Ph faults
X1FwPP	122.54	Ω/Ph	Positive sequence reactive reach in forward direction for Ph-E faults
RFPP	152.17	Ω/loop	Resistive reach (forward and reverse) for Ph-Ph measurement
X1RvPE	122.54	Ω/Ph	Positive sequence reactive reach in reverse direction for Ph-E faults
X1FwPE	122.54	Ω/Ph	Positive sequence reactive reach in forward direction for Ph-E faults
X0RvPE	367.62	Ω/Ph	Zero sequence reactance of reach in reverse direction for Ph-E faults
X0FwPE	367.62	Ω/Ph	Zero sequence reactance reach in forward direction for Ph-Ph faults
RFPE	152.17	Ω/loop	Resistive reach (forward and reverse) for Ph-E measurement
INReleasePE	10	% of I_{ph}Max	3I0 limit for releasing Ph-E measuring loops
INBlockPP	20	% of I_{ph}Max	3I0 limit for blocking Ph-Ph measuring loops
IP>	20	% of I1b	Set operate value for measured phase currents
IN>	10	% of I1b	Set operate value for measured residual currents
tPP/ tPE	0/ 0	s	Time delay of trip for Ph-Ph/ Ph-E faults

Table 3.3 Parameter setting for GFC

3.5.4 Setting for the fault locator FLOC function block

Parameter	Secondary	Unit	Description
Line length	900	km	Line length value
X1	173.00	Ω/Ph	Positive sequence line reactance
R1	14.31	Ω/Ph	Positive sequence line resistance
X0	519.00	Ω/Ph	Zero sequence line reactance
R0	42.93	Ω/Ph	Zero sequence line resistance

Table 3.4 Parameter setting for FLOC

3.5.5 Setting for the miscellaneous function blocks

Function block	Parameter	Set value	Unit	Description
IOC Instantaneous overcurrent protection	IP>>	65	% of I1b	Operating phase current
	IN>>	50	% of I1b	Operating residual current
TOC Time delayed overcurrent protection	IP>	30	% of I1b	Operating phase overcurrent
	tP	10	s	Time delay of phase overcurrent function
	IN >	100	% of I4b	Operating residual current
	tN	10	s	Time delay of residual overcurrent function
TOV Time delayed overvoltage protection	UPE<	120	% of U1b	Operate value for the phase overvoltage function
	t	5	s	Time delay of the phase overvoltage function
	3U0>	30	% of U1b	Operate value for the neutral overvoltage function
	t	5	s	Time delay of the neutral overvoltage function
TUV Time delayed undervoltage protection	UPE<	80	% of U1b	Operate phase voltage
	t	5	s	Time delay
TEF Definite and inverse time-delayed residual overcurrent protection	IN>	5	% of I1b	Start current for TEF function
	Imin	100	% of IN	Minimum operating current
	t1	0	s	Independent time delay
THOL Thermal overload protection	I_{Base}	15	% of I1b	Base current
	T_{Base}	50	°C	Temperature rise at base
	t_{au}	5	min	Thermal time constant
	TAlarm	80	°C	Alarm level
	TTrip	120	°C	Trip level
DLD Dead line detection	U<	50	% of U1b	Operating phase voltage
	IP<	10	% of I1b	Operating phase current

Table 3.5 Parameter setting for miscellaneous function

3.6 Results using numerical relay REL 511*2.3

In the following figures, the upper part shows analog input signals coming from the line model, whereas the lower one displays the binary output signals of numerical relay. These output signals will be used to activate circuit breakers or fault clearing equipment.

Measured phase voltages as denoted in the figures are *U1, U2, U3* and that of currents are *I1, I2, I3*. Ground current *I4* appears when there is a fault between phase and ground.

During a fault, the current in the faulted phases increases. The current becomes larger when the fault is closer to the source. Phase voltages are always unchanged since they are measured at the strong grid point.

Distance protection zone outputs such as, *ZM1-TRIP, ZM2-TRIP, ZM3-TRIP*, operate when the corresponding pre-set times are reached.

3.6.1 Three-phase faults

In this section, the response of the relay to three-phase faults is studied. Figures 3.21, 3.22, and 3.23 show the responses with an applied three-phase fault in zone 1, zone 2 and zone 3, respectively.

As shown in Figures 3.21, at t = 0 ms a three-phase fault occurs in zone 1, the corresponding measured impedance of loops are within the set boundaries of the characteristic, thus *GFC-TRIP* signal and all of general fault criteria-forward operation signals, *GFC-STFWL1, GFC-STFWL2, GFC-STFWL3*, are activated instantaneously. Then at t = 15 ms the general trip signal *TRIP-TRIP*, zone 2 start signal *ZM2-START* and trip signal from zone 1 *ZM1-TRIP* are activated. At t = 165 ms, time delayed trip operation of zone 2 is reached, thus trip signal by distance protection zone 2 *ZM2-TRIP* is activated. These signals have normally different reset times. They, however, reset approximately at the time of fault clearance (at t = 400 ms). Figure 3.22 shows the case of a fault applied in zone 2. In the figure the only difference is that *ZM1-TRIP* is not activated.

Figure 3.23 shows another result where the fault is applied in reverse direction. As seen, the fault is applied at t = 0 ms, and the general fault criteria-reverse operation signals, *GFC-STRVL1, GFC-STRVL2, GFC-STRVL3*, are activated instead of the activation of the general fault criteria-forward direction. After 250 ms activation of *ZM3-START* signal, trip signal by distance protection zone 3 *ZM3-TRIP* is sent out.

3.6.1.1 Zone1

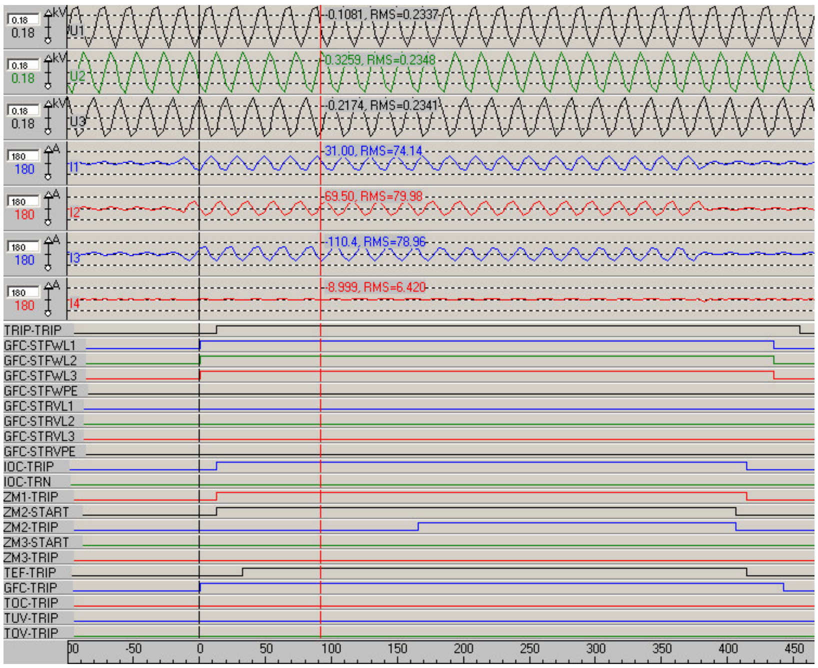

Figure 3.21 Three-phase fault in zone 1

3.6.1.2 Zone 2

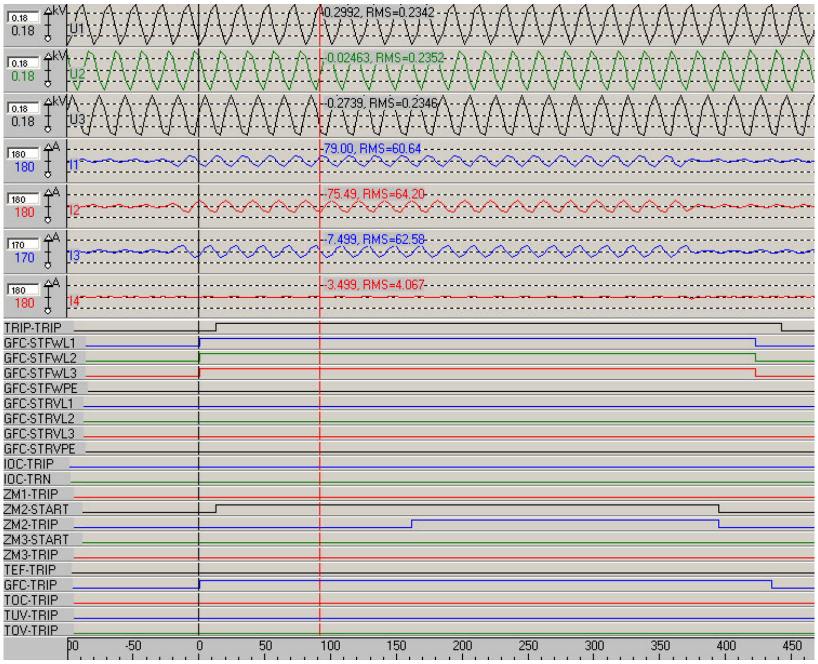

Figure 3.22 Three-phase fault in zone 2

3.6.1.3 Zone 3

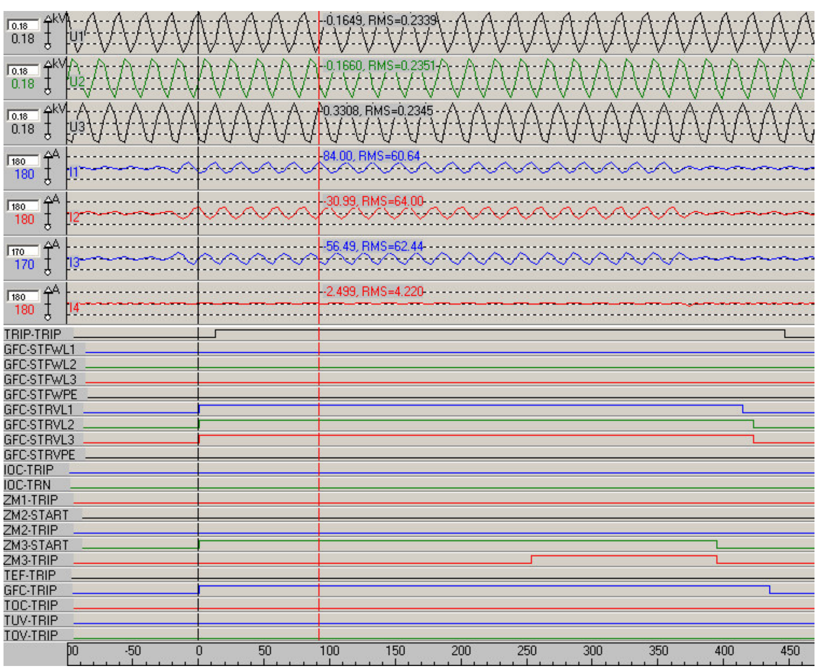

Figure 3.23 Three-phase fault in zone 3

3.6.2 Single-phase to ground faults

In this section, the operation of the relay in the case of single-phase to ground faults is shown.

Figures 3.24, 3.25 and 3.26 show the presence of a single-phase to ground fault within the first zone of protection in forward direction. The application of a ground fault results in not only the activation of the general fault criteria-forward operation of *Ph-E* loop *GFC-STFWPE* but also the corresponding general fault criteria-forward operation in phase *L1* (*GFC-STFWL1*), or *L2* (*GFC-STFWL2*), or *L3* (*GFC-STFWL3*) is operated, as well. The Figures 3.27, 3.28 and 3.29 show the operation of relay in zone 2 with the presence of fault in phase *L1, L2, L3* to ground, respectively. The Figures 3.30, 3.31 and 3.32 illustrate the cases of a fault in zone 3 where the corresponding general fault criteria-reverse operation in phase *L1* (*GFC-STRVL1*), or *L2* (*GFC-STRVL2*), or *L3* (*GFC-STRVL3*) is operated.

3.6.2.1 Zone 1

- Phase L1 to ground

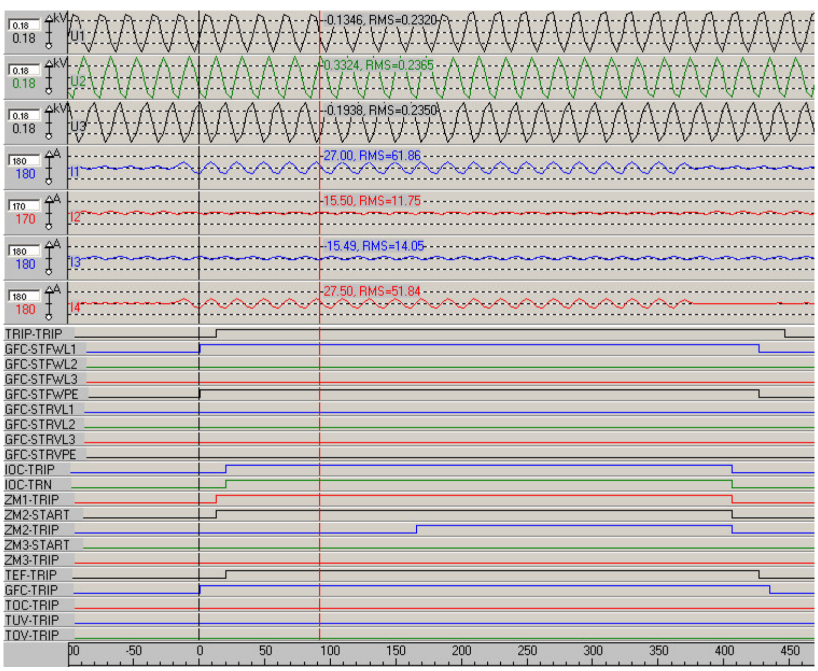

Figure 3.24 Phase L1 to ground fault in zone 1

- Phase L2 to ground

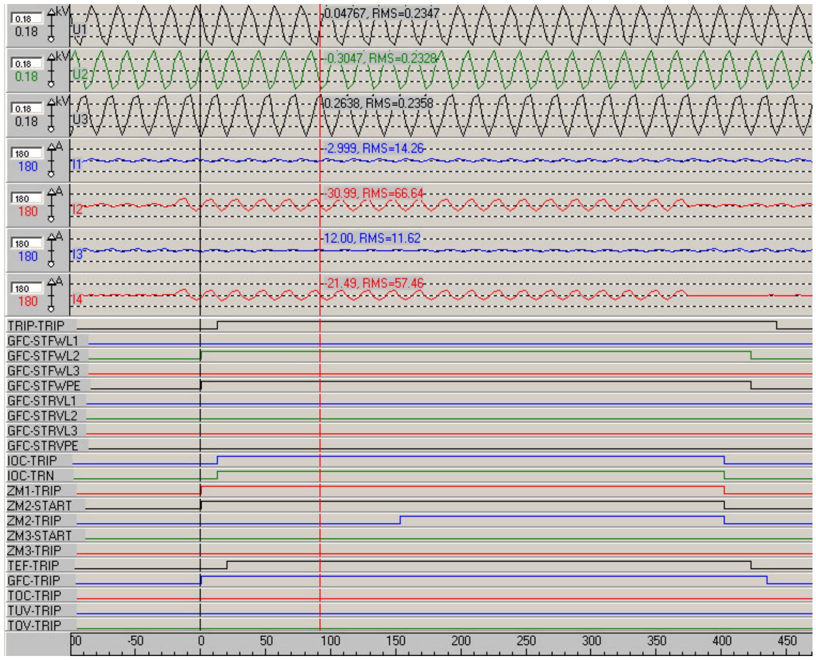

Figure 3.25 Phase L2 to ground fault in zone 1

- Phase L3 to ground

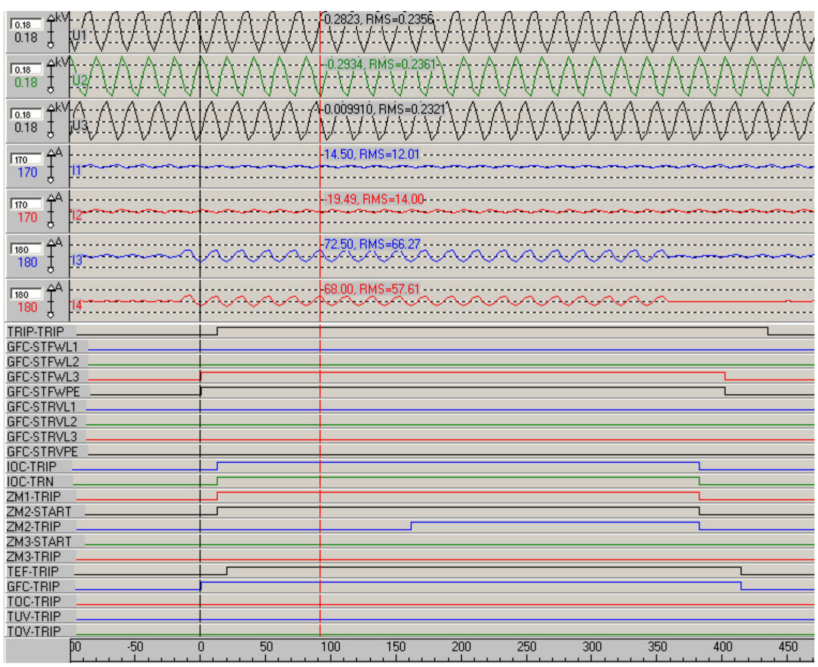

Figure 3.26 Phase L3 to ground fault in zone 1

3.6.2.2 Zone 2

- Phase L1 to ground

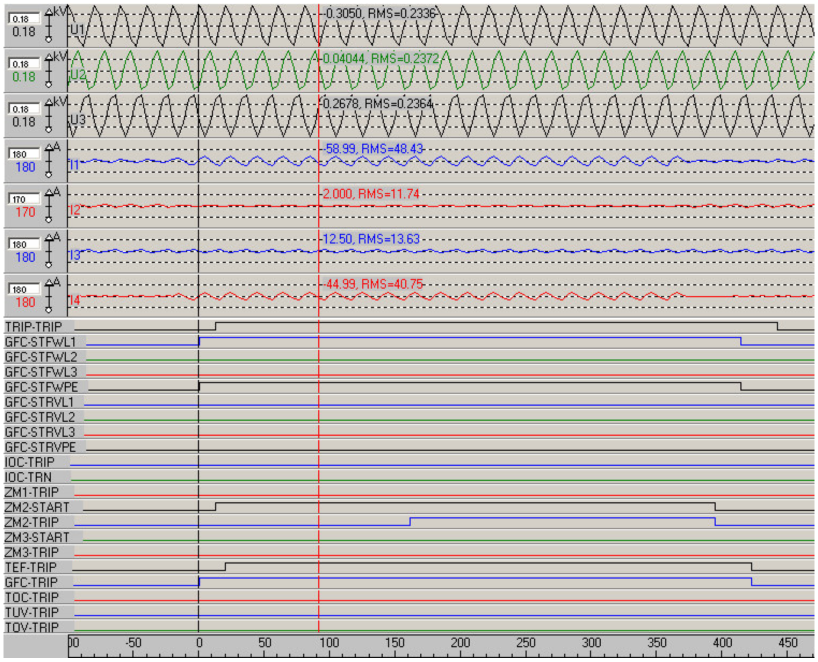

Figure 3.27 Phase L1 to ground fault in zone 2

- Phase L2 to ground

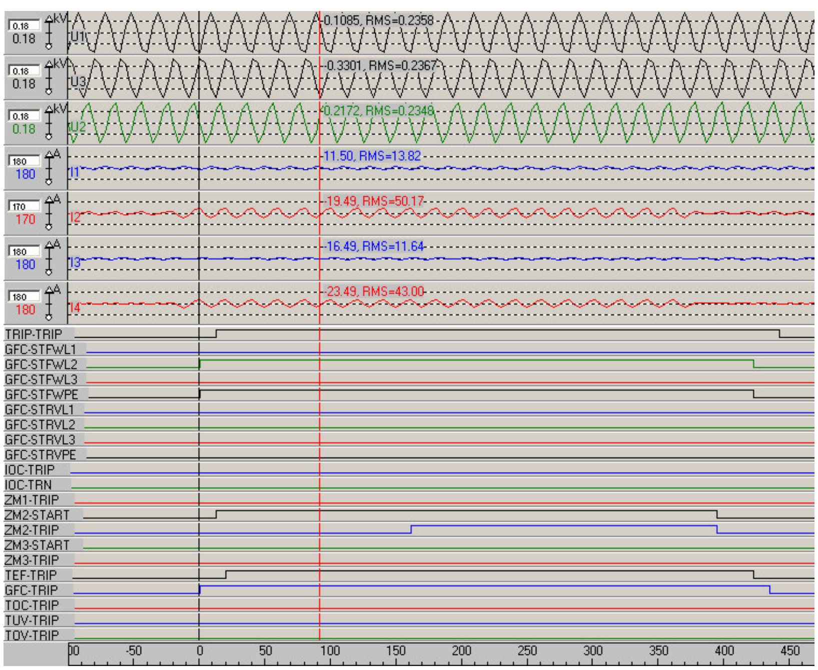

Figure 3.28 Phase L2 to ground fault in zone 2

- Phase L3 to ground

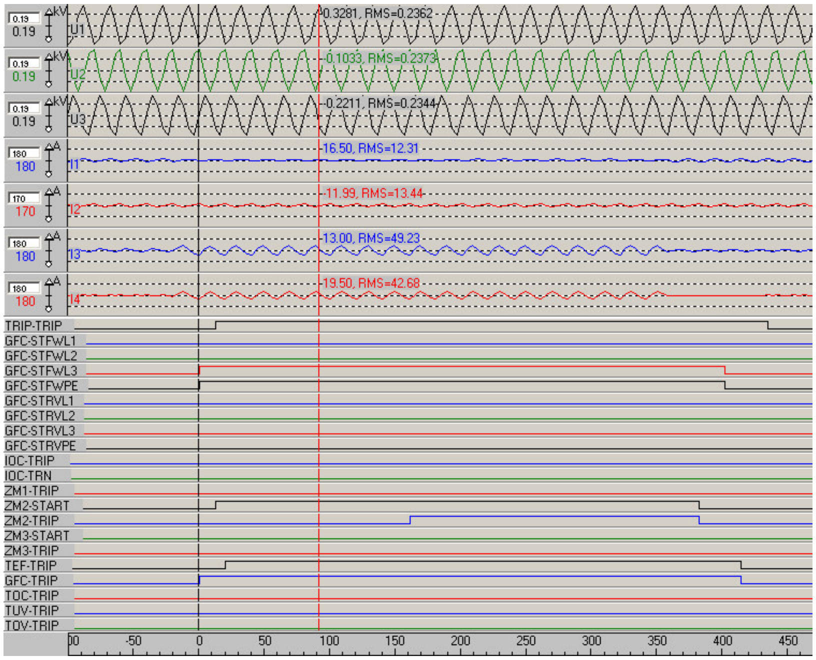

Figure 3.29 Phase L3 to ground fault in zone 2

3.6.2.3 Zone 3

- Phase L1 to ground

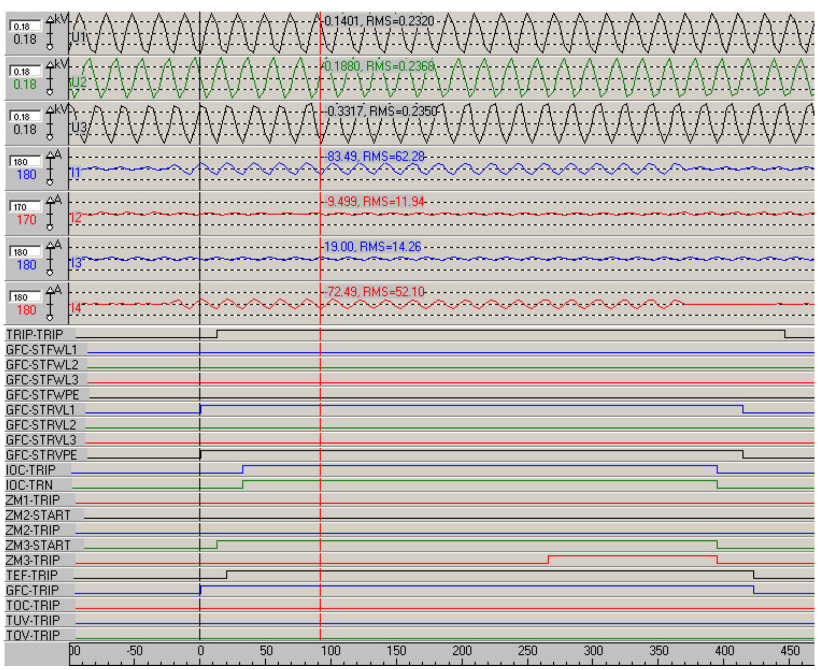

Figure 3.30 Phase L1 to ground fault in zone 3

- Phase L2 to ground

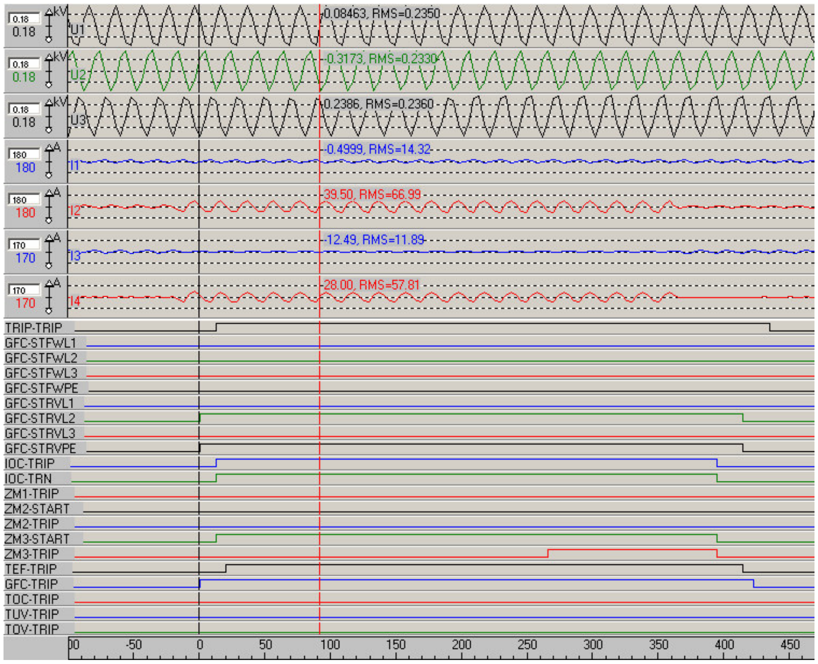

Figure 3.31 Phase L2 to ground fault in zone 3

- Phase L3 to ground

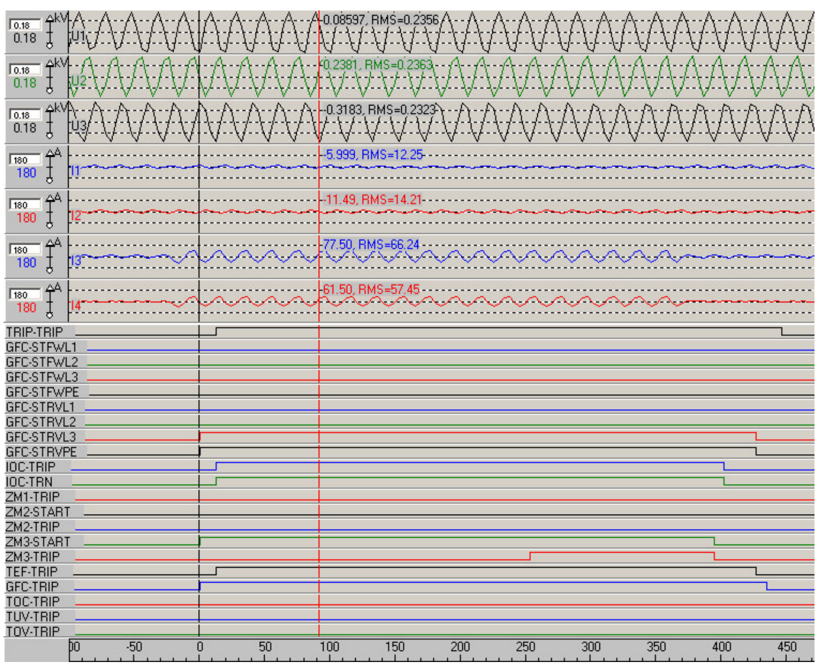

Figure 3.32 Phase L3 to ground fault in zone 3

3.6.3 Double-phase to ground faults

In this section, the operation of the relay in the case of double-phase to ground faults is shown.

Figures 3.33, 3.34 and 3.35 show the relay response for double-phase *L1-L2, L1-L3* and *L2-L3* to ground faults, respectively. Again, the general fault criteria-forward operation of *Ph-E* loop *GFC-STFWPE* is activated. Due to the double-phase fault occurrence, the corresponding general fault criteria-forward operation in double-phase *L1-L2* (*GFC-STFWL1, GFC-STFWL2*), or *L1-L3* (*GFC-STFWL1, GFC-STFW-L3*), or *L2-L3* (*GFC-STFWL2, GFC-STFWL3*) is fulfilled and activated simultaneously. The Figures 3.36, 3.37 and 3.38 show the operation of relay in zone 2 with the presence of a fault in double-phase *L1-L2, L1-L3, L2-L3* to ground, respectively. The Figures 3.39, 3.40 and 3.41 illustrate the cases of a fault in zone 3. Instead of the operation of general fault criteria-forward operation outputs, the corresponding general fault criteria-reverse operation in double-phase *L1-L2* (*GFC-STRVL1, GFC-STRVL2*), or *L1-L3* (*GFC-STRVL1, GFC-STRVL3*), or *L2-L3* (*GFC-STRVL2, GFC-STRVL3*) is operated.

3.6.3.1 Zone 1

- Phase L1-L2 to ground

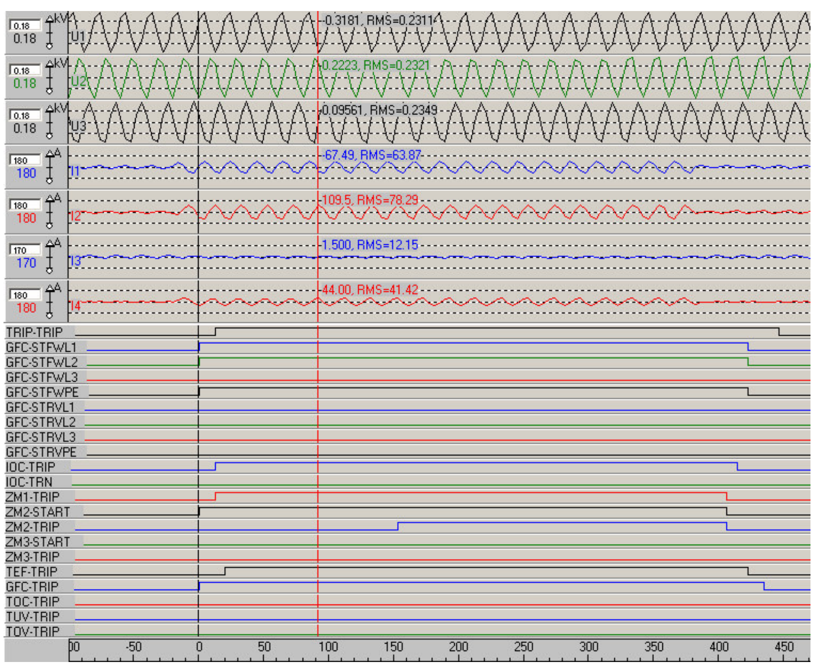

Figure 3.33 Double-phase L1-L2 to ground in zone 1

- Phase L1-L3 to ground

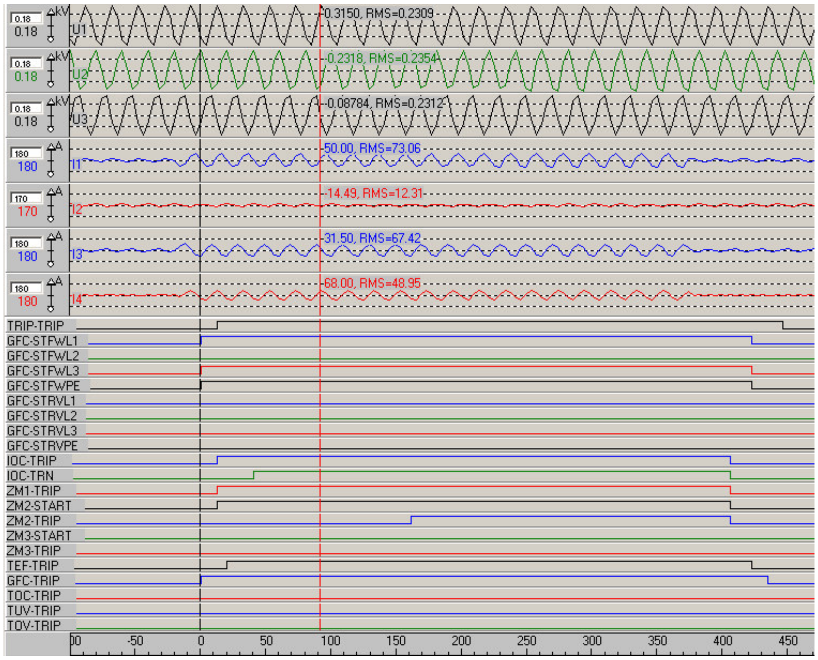

Figure 3.34 Double-phase L1-L3 to ground in zone 1

- Phase L2-L3 to ground

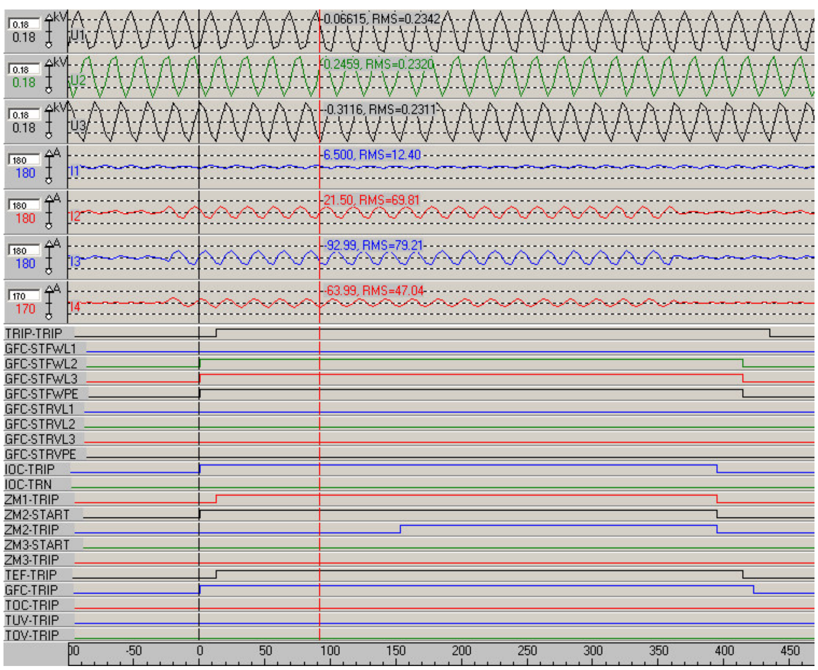

Figure 3.35 Double-phase L2-L3 to ground in zone 1

3.6.3.2 Zone 2

- Phase L1-L2 to ground

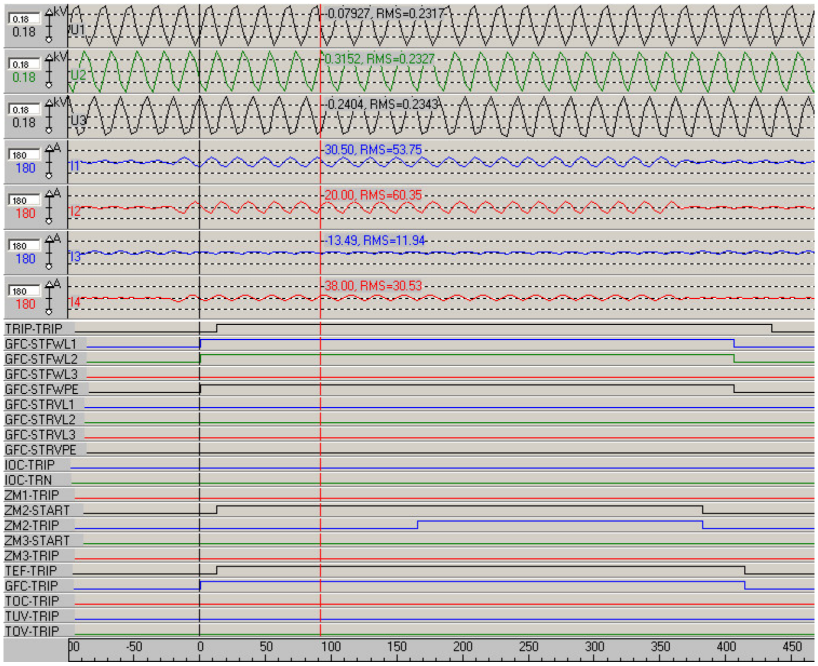

Figure 3.36 Double-phase L1-L2 to ground in zone 2

- Phase L1-L3 to ground

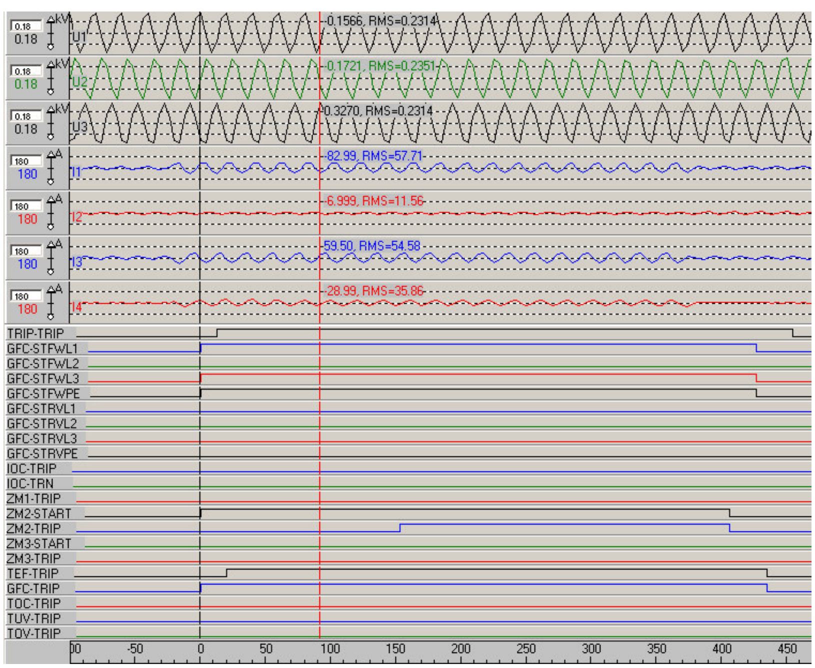

Figure 3.37 Double-phase L1-L3 to ground in zone 2

- Phase L2-L3 to ground

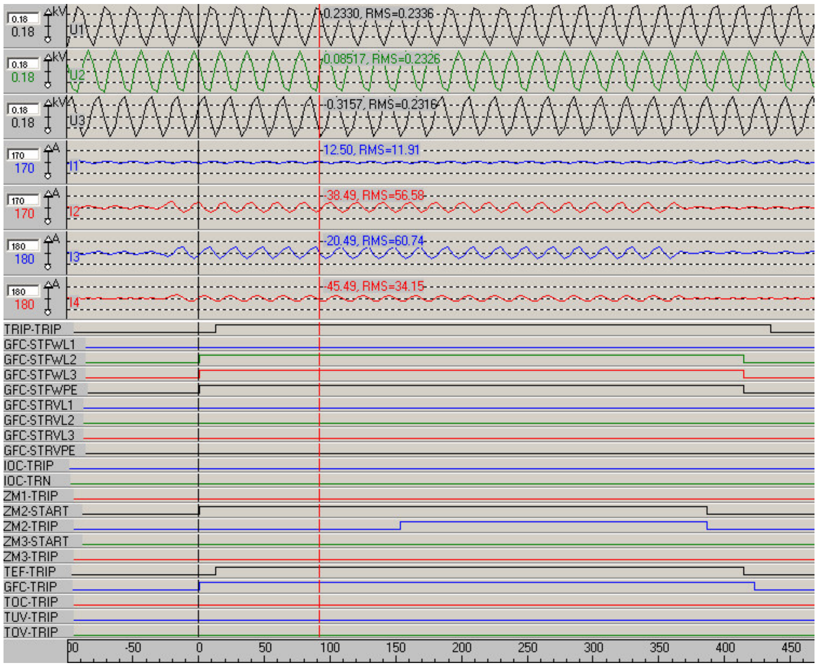

Figure 3.38 Double-phase L2-L3 to ground in zone 2

3.6.3.3 Zone 3

- Phase L1-L2 to ground

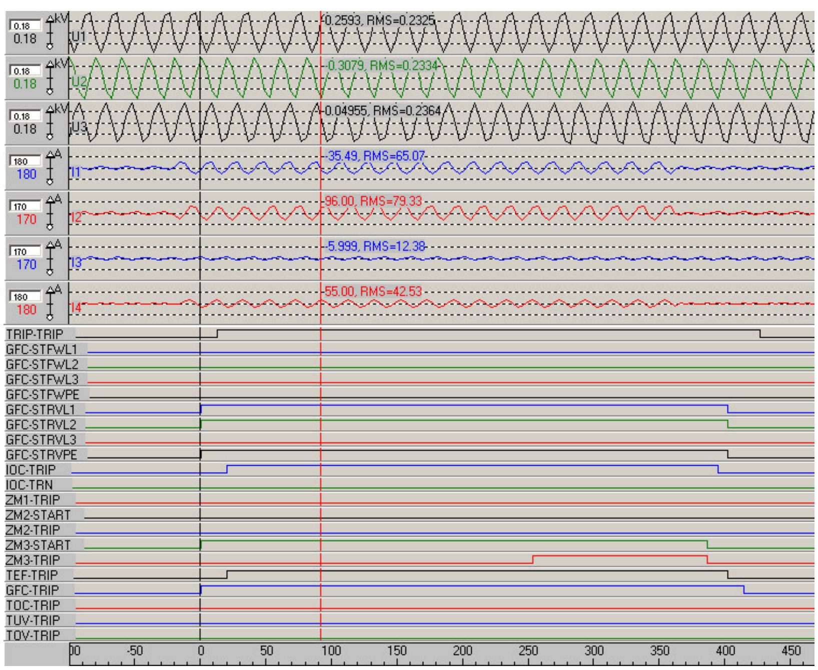

Figure 3. 39 Double-phase L1-L2 to ground in zone 3

- Phase L1-L3 to ground

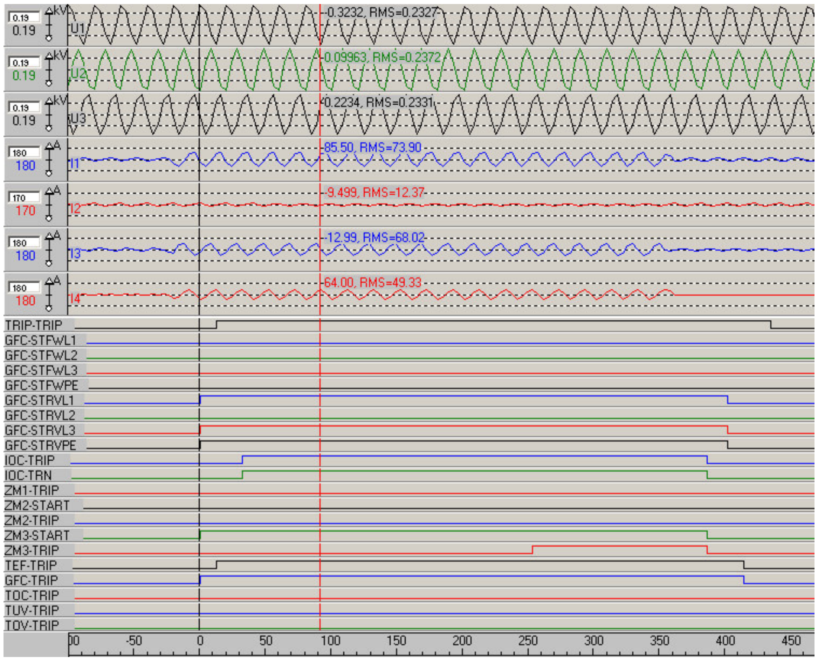

Figure 3.40 Double-phase L1-L3 to ground in zone 3

- Phase L2-L3 to ground

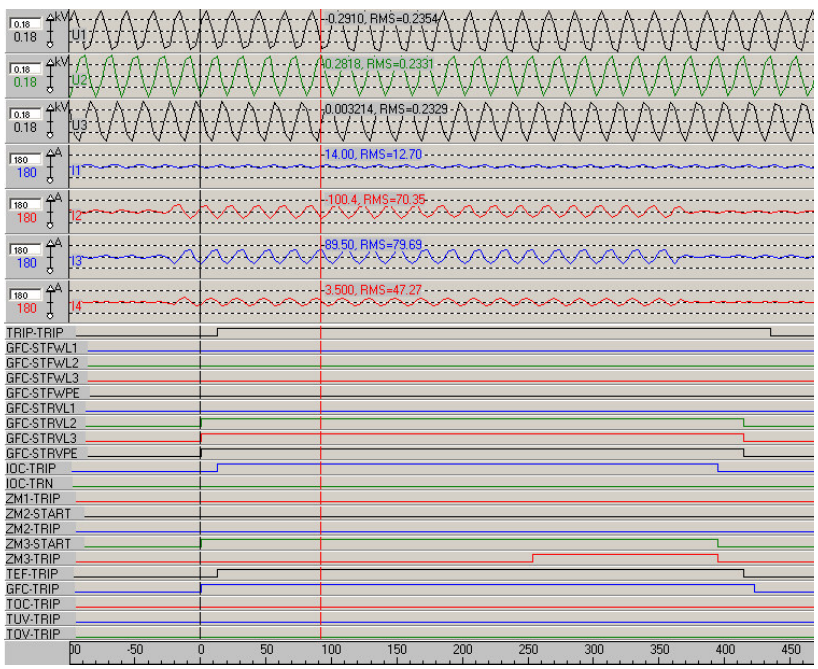

Figure 3.41 Double-phase L2-L3 to ground in zone 3

3.6.4 Double-phase faults

In this section the relay response to double-phase faults is demonstrated. In Figures 3.42, 3.43 and 3.44, results are shown where double-phase faults *L1-L2*, *L1-L3* and *L2-L3* are applied in zone 1, respectively. The faults occur between phase to phase, so only the corresponding general fault criteria-forward operation in phase is activated, i.e., double-phase *L1-L2* (*GFC-STFWL1, GFC-STFWL2*), or *L1-L3* (*GFC-STFWL1, GFC-STFW-L3*), or *L2-L3* (*GFC-STFWL2, GFC-STFWL3*). The Figures 3.45, 3.46 and 3.47 show the operation of the relay in zone 2 with the presence of a fault in double-phase *L1-L2, L1-L3, L2-L3*, respectively. The Figures 3.48, 3.49 and 3.50 illustrate the cases of a fault in zone 3 where the corresponding general fault criteria-reverse operation in double-phase *L1-L2* (*GFC-STRVL1, GFC-STRVL2*), or *L1-L3* (*GFC-STRVL1, GFC-STRVL3*), or *L2-L3* (*GFC-STRVL2, GFC-STRVL3*) is operated.

3.6.4.1 Zone 1

- Phase L1-L2

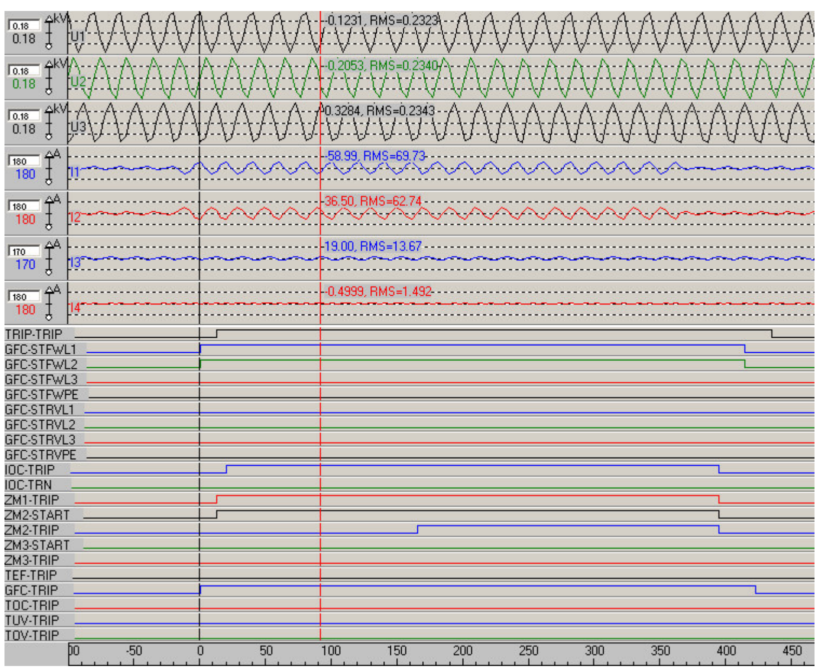

Figure 3.42 Double-phase L1-L2 fault in zone 1

- Phase L1-L3

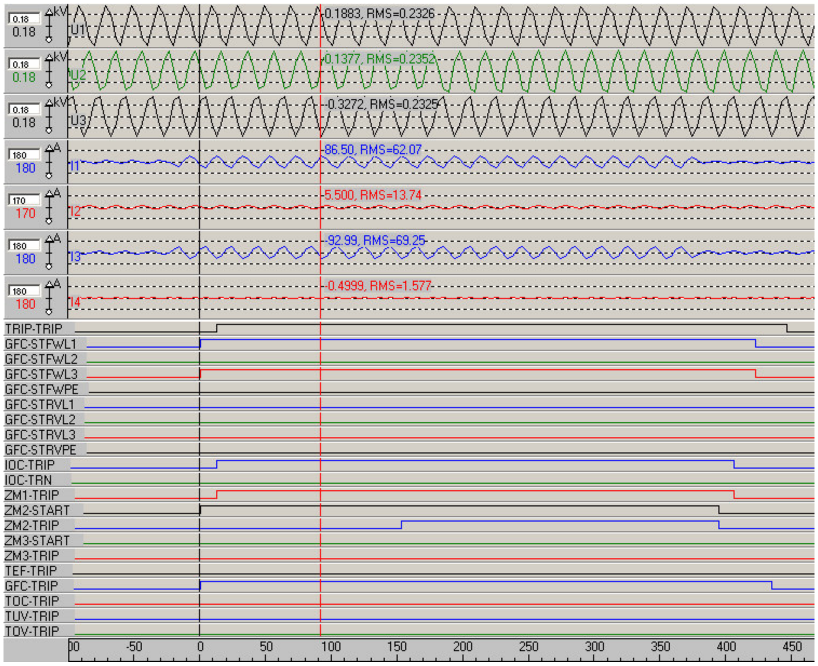

Figure 3.43 Double-phase L1-L3 fault in zone 1

- Phase L2-L3

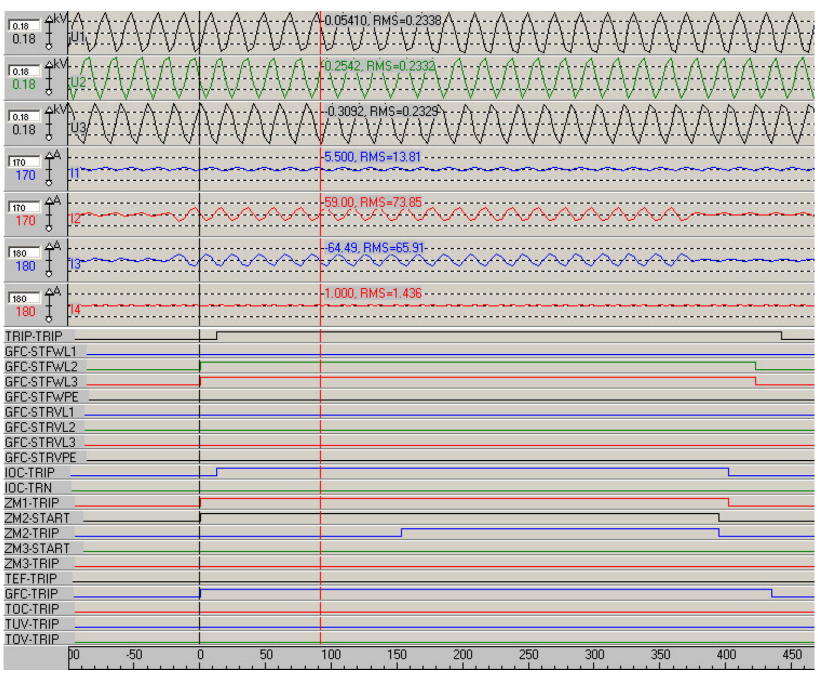

Figure 3.44 Double-phase L2-L3 fault in zone 1

3.6.4.2 Zone 2

- Phase L1-L2

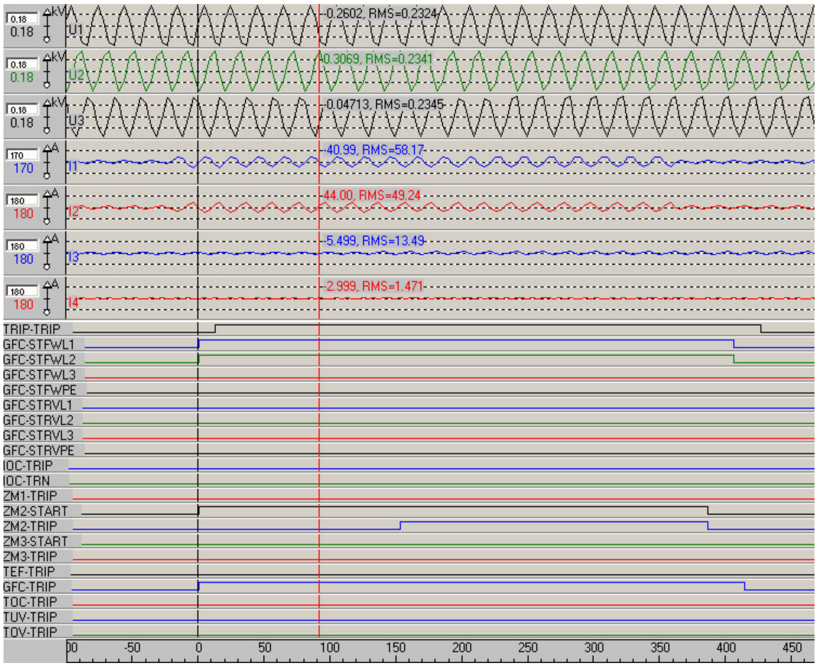

Figure 3.45 Double-phase L1-L2 fault in zone 2

- Phase L1-L3

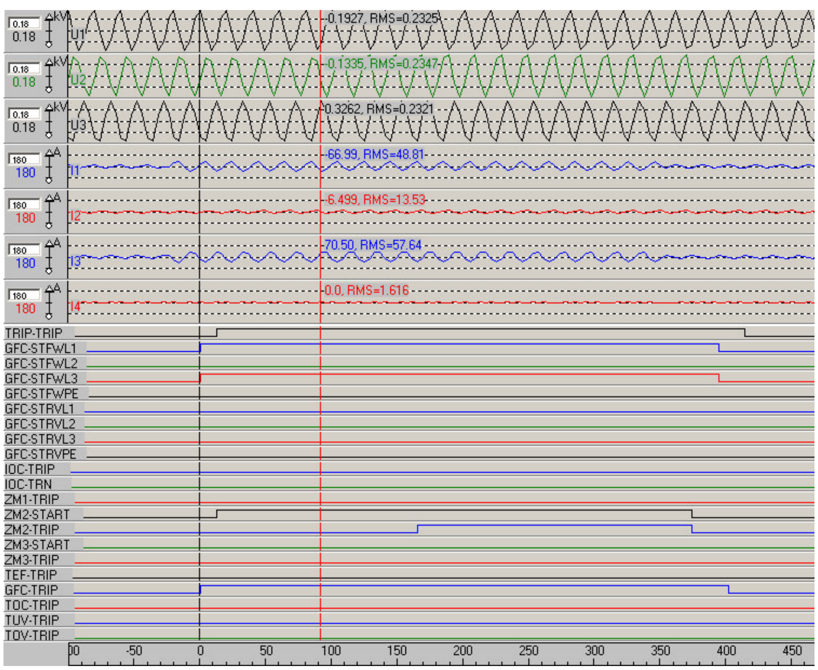

Figure 3.46 Double-phase L1-L3 fault in zone 2

- Phase L2-L3

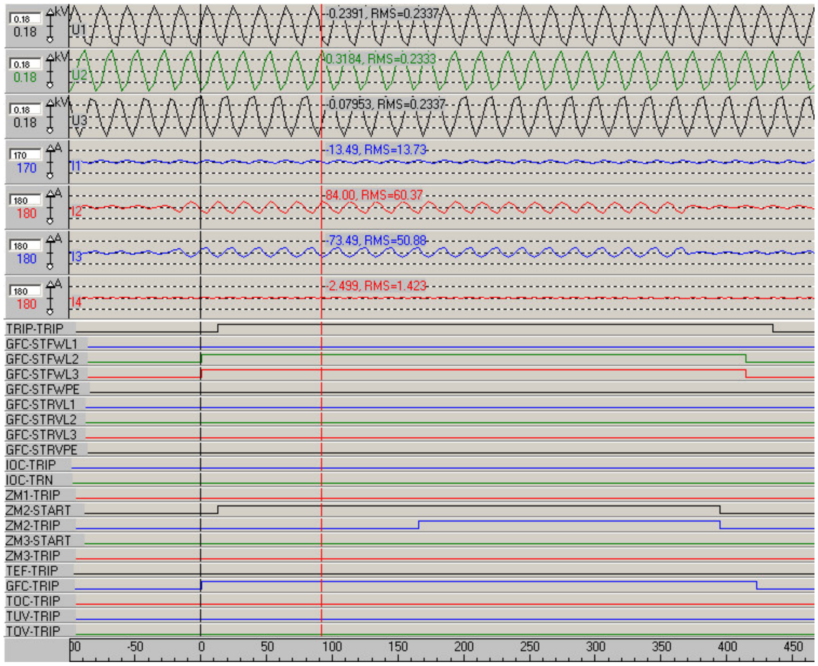

Figure 3.47 Double-phase L2-L3 fault in zone 2

3.6.4.3 Zone 3

- Phase L1-L2

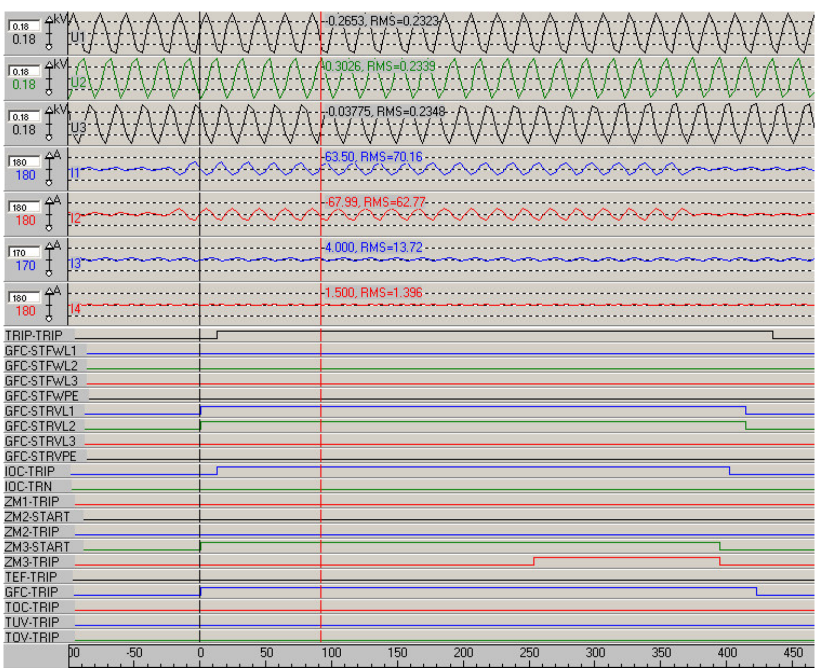

Figure 3.48 Double-phase L1-L2 fault in zone 3

- Phase L1-L3

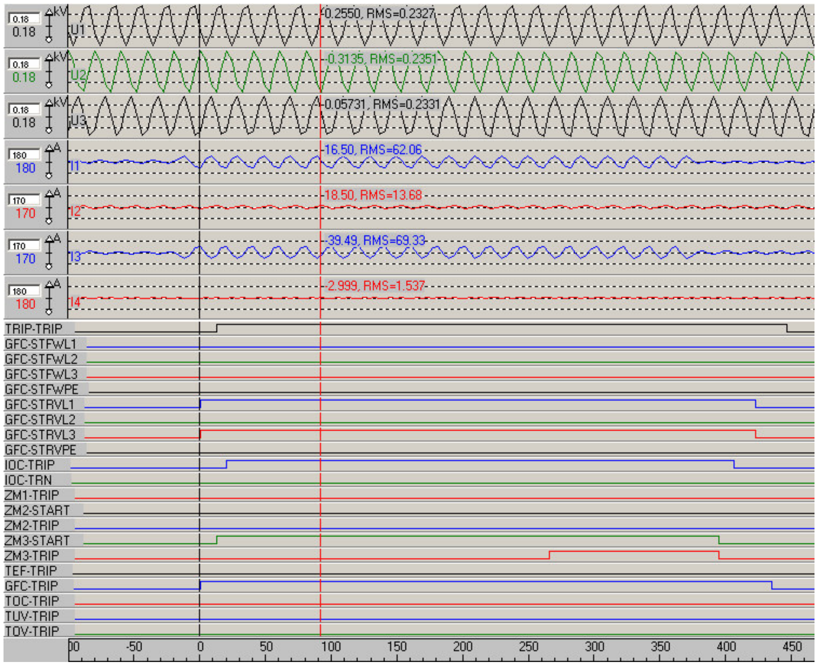

Figure 3.49 Double-phase L1-L3 fault in zone 3

- Phase L2-L3

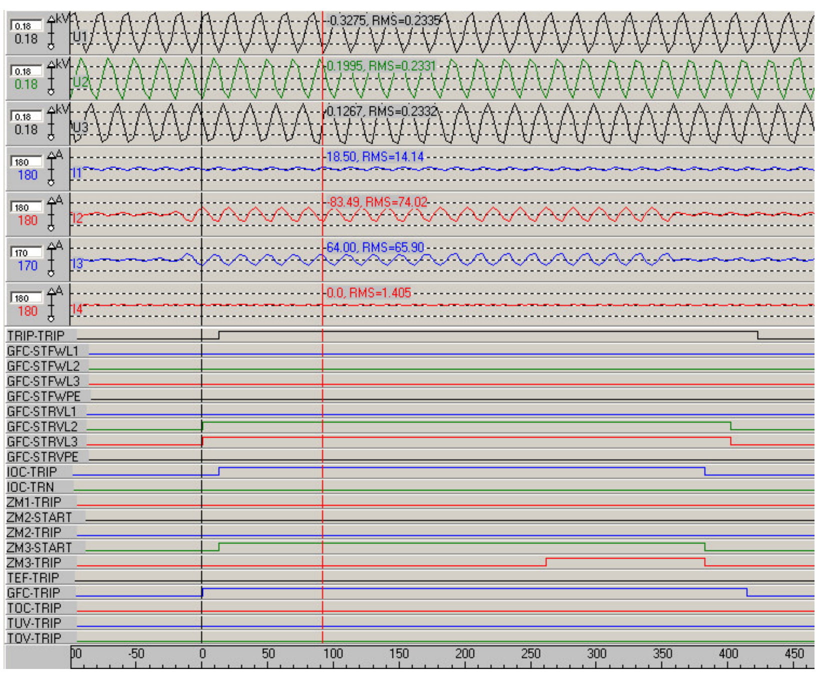

Figure 3.50 Double-phase L2-L3 fault in zone 3

Chapter 4

Conclusions and further work

4.1 Conclusions

In this thesis, the calculation of the setting values has been included and all types of faults that may occur in the power system have been tested. The proper operation of the numerical distance relay has also been demonstrated.

In presence of a fault within the zone protection, the measured impedance of the GFC function block is within the set boundaries of the characteristic. This results in the operation of the GFC start condition (*STCND*) output that activates the selected loop of the distance protection measuring zones. When the corresponding delay time is reached, these zones send out the trip signal.

In case of a three-phase fault in forward or reverse direction, all the general fault criteria-forward operation signals, *GFC-STFWL1*, *GFC-STFWL2*, *GFC-STFWL3*, or general fault criteria-reverse operation signals, *GFC-STRVL1*, *GFC-STRVL2*, *GFC-STRVL3* in all the three phases are activated. With the double-phase fault, both in forward and reverse direction, it has been shown that only the general fault criteria-forward operation signals or general fault criteria-reverse operation signals of the involved phases are activated.

In the presence of a ground fault, beside the activation of the general fault criteria operation output in phases, the general fault criteria operation of *Ph-E* loop output has also been activated. The operation of the numerical relay when the single-phase to ground fault occurs has also been investigated. It has been shown that successful activation of the general fault criteria operation output of the involved phase and general fault criteria operation of *Ph-E* loop output, in both directions, are achieved. The same result has been obtained with the case of double-phase to ground fault.

Problems experienced

When everything was done and we started to test the relay, the relay was not picking any of the earth faults because the fault resistor was not connected to the ground. This problem was rectified when we connected the fault resistor to ground.

Then also the relay did not calculate the distance to fault on the disturbance report. We realised that the setting parameters of the Fault locator function block (*FLOC*) were wrong because we had omitted to multiply the reactance and resistance values of the line model by a factor of six. The factor of six should be multiplied to the reactance and the resistance values of the line model because the line model is divided into six equal π-sections. After we had done the multiplication, the relay recorded the distance to fault in the disturbance report.

4.2 Further work

The following problems should be implemented as the further woks:

- Use the output signals sent out by the functional blocks to control the circuit breaker or fault clearing equipment.
- Study evolving faults, e.g., faults starting as phase to ground fault, but developing to double-phase to ground fault.
- Study power system oscillations.
- Test the relay with source impedance variations.

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Appendix A

Laboratory for undergraduate student

TESTING A NUMERICAL DISTANCE PROTECTION RELAY

by

Tran Manh Hung

Henry Akyea

All questions marked with ***H*** should be answered before attending the laboratory exercise.

Participant: Date:

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Approved by:

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1 Introduction

Any kind of power system shunt fault results in customers being disconnected if not cleared quickly. Distance protection meets the requirements of speed and reliability needed to protect electric circuits, thus distance protection is used to a large extend on power-system networks.

It is a universal short-circuit protection. Its mode of operation is based on the measurement of electrical quantities (current and voltage) and evaluation of the impedance towards the fault, which basically is proportional to the distance to the fault.

Numerical distance protection is utilization of microprocessor technology with analogue to digital conversion of the measured values (current and voltage), computed (numerical) distance determination and digital processing logic.

2 Aim of the Exercise

The objective of this exercise is to test a modern numerical relay for various faults within the distance zones under consideration.

Three zones are set; zone one is an under-reaching instantaneous tripping zone set in the forward direction, zone two is an over-reaching zone with single time-delay also set in the forward direction and zone three is an over-reaching zone with double time-delay set in the reverse direction.

3 Power system model description

The power system model used in this exercise is a three-phase model of a 400 kV transmission, and two loads (two 9 kW three phase resistive loads). The entire model operates at 400 V.

The line model consists of six identical π-sections; each corresponds to 150 km of a 400 kV line. The sections can be connected arbitrarily in series or parallel.
The data for a real 150 km section are:
$X_1 = 50.4\Omega$/phase,
$R_1 = 4.17\Omega$/phase.

Zero sequence impedance $Z_0 = 3Z_1$
The impedance scale of the line model is given as 1:53.2.

The numerical relay used in this laboratory is the Line distance protection relay REL 511*2.3 from ABB. The REL 511*2.3 is based on a full scheme distance protection function that detects both phase-to-phase and phase-to-earth faults and has a quadrilateral operating characteristics. A separate general fault criterion with advanced characteristics is used for phase selection and as an overall measuring function, which increases the total operating security and facilitates remote backup applications.

The numerical relay REL 511*2.3 line distance protection terminal is designed for main and backup protection, monitoring and control of power lines, cables and other primary objects. It can be used in systems with simple or complex network configurations regardless of the type of system grounding.

Relay parameters:

Current: Rated $I_r = 1A$
Nominal range: (0.2 -30) * I_r
Operative range: (0.004 - 100)*I_r
Permissive overload: 4*I_r continuous, 100*I_r for 1 s

Voltage: Rated $U_r = 110V$,
Nominal range: (80 -120)% of U_r
Operative range: (0.001 – 1.5)* U_r
Permissive overload: 1.5* U_r continuous, 2.5* U_r for 1 s
DC supply for relay: 48 – 250 V.

Figure A1 shows the line model used for the laboratory.

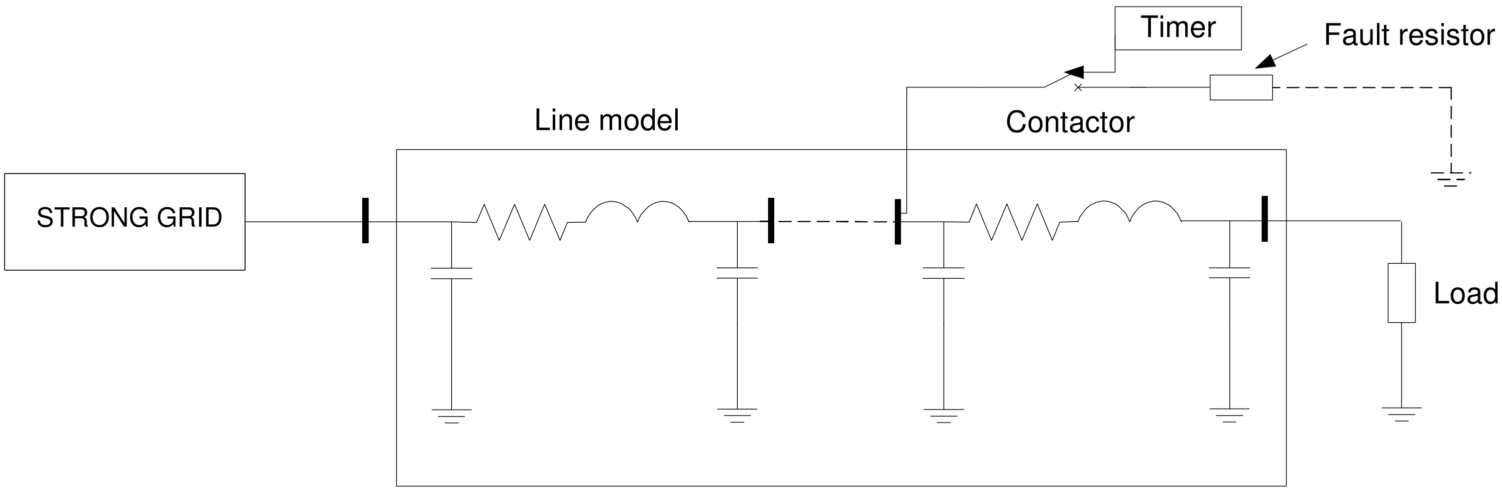

Figure A1: Power system model of the laboratory exercise

4 Distance zones

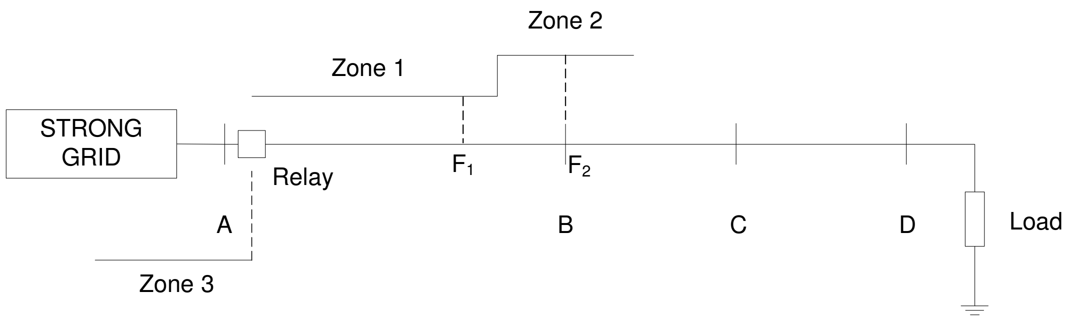

Figure A2 Grade distance zones

Zone 1: 85% AB, time delayed = 0, forward direction.

Zone 2: AB + 30% BC, time delayed = 0.25 s, forward direction.

Zone 3: AB + BC + 25% CD, time delayed = 0.35 s, reverse direction.

Load P = 9 kW

AB = 3 π-sections

BC = CD = 1 π-section

F_1, F_2: Faults locations in Zone 1 and Zone 2, respectively.

Fault resistor $R_f = 5\Omega$.

Timer is set to be 0.5 s.

Setting for zone parameters can be done on the local human-machine interface (HMI) unit under the menu:

Setting / Functions / Group 1 / Impedance / ZM *n*

n = 1,2,3.

H: Calculate the setting values for the impedance fault detection of the three zones, according to Figure 2 and the given data.

⚠ *Note:* All of the setting values are calculated for the secondary side based on the following expression:

$$Z_{\sec} = \frac{I_{pri}/I_{\sec}}{U_{pri}/U_{\sec}} Z_{pri}$$

where $I_{pri}/I_{\sec}$ and $U_{pri}/U_{\sec}$ are the transformation ratios of the current and voltage transformers, with nominal values of 100/1 and 230/69, respectively.

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5 Setting for General Fault Criteria (GFC)

The general fault criteria serve as an overall fault detection and phase selection element in all kinds of networks. The signals produced by the GFC measuring elements serve for different parts of the distance protection. These are indication of the faulty phases, phase selection for the zone measuring elements, general criteria for the operation of the trip logic and time delayed trip as a backup function to the zone measuring elements.

As can be seen in Figure A3, the zone measuring element characteristics is within that of the GFC, thus to get a trip signal the GFC must be fulfilled.

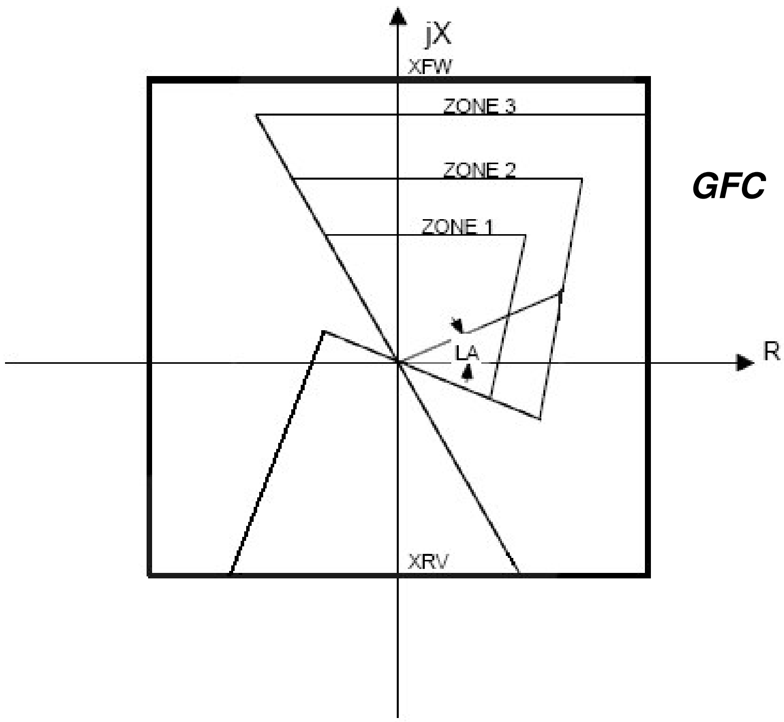

Figure A3 Operating characteristics of the GFC and zone measuring elements

H: Calculate and set the parameters of the GFC. (For definition of the parameters refer to page 71)

RLd…………………………………………………………………………………...
X1RvPP…………………………………………………………………………….
X1FwPP…………………………………………………………………………….
RFPP………………………………………………………………………………….
X1RvPE…………………………………………………………………………….
X1FwPE…………………………………………………………………………...
X0RvPE…………………………………………………………………………….
X0FwPE…………………………………………………………………………...
RFPE…………………………………………………………………………….

The default values are used for the following parameters: ARGLd, INReleasePE, INBlockPP, IP>, IN>.
The following values should be used:
tPP = 0 s, tPE = 0 s.

⚠ ***Note:*** The setting range of GFC should cover all of the zone characteristics.

Setting of the GFC parameters can be done on the local human-machine interface (HMI) unit under the menu:

Setting / Functions / Group 1 / Impedance / GenFltCriteria.

6 Setting of line reference for the Fault Locator (FLOC)

The FLOC provides the distance to the fault together with information about the measuring loop that has been used in the calculation.

H: Calculate the setting values for the FLOC. (For definition of the parameters refer to page 72)

X1…………………………………………………………………………………

………………………………………………………………………………………….

X0…………………………………………………………………………………

………………………………………………………………………………………….

R1…………………………………………………………………………………

………………………………………………………………………………………….

R0…………………………………………………………………………………

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The following values should be used:

X1SA = 0.001 Ω, R1SA = 0.001 Ω, X1SB = 1500 Ω, R1SB = 1500 Ω, Xm0 = 0Ω, Rm0 = 0 Ω.

Setting of the FLOC parameters can be done on the local human-machine interface (HMI) unit under the menu:

Setting / Functions / Group 1 / Line Reference.

7 Exercise in the Laboratory

Carry out the following tests:

i. Three-phase fault
ii. Double-phase fault
iii. Double-phase-ground fault
iv. Single-phase-ground fault

Faults are applied by closing the contactor, according to Figure A1.

Observe the LED on the relay during the tests and upload disturbance reports from the relay to the PC after each type of fault by using CAP 540, under the menu:

Programs / Disturbance Handling / Terminal list

Note: To upload the disturbance report from the terminal to the PC the procedure below must be followed:

- Plug the cable to the optical contact under the local HMI of the terminal.
- Plug the other end of the cable to the COM port of the PC. The COM port of the PC are two, therefore if you plug the cable to COM port 1 or COM port 2 it must be then set on the PC as COM 1 or COM 2 respectively. This can be done by opening the CAP 540 project Test_lab, highlight the Stn1 then set it at:
  Settings / Communication settings / Communication parameters
- Set the slave number and the baud rate to 30 and 9600, respectively in the terminal. The slave number and the baud rate settings in the terminal can be done on the local HMI at:
  Configuration / TerminalCom / SPACom / Front
- Set the slave number and the baud rate in the PC by opening the CAP 540 project Test_lab. Highlight the Stn1 then set it at:
  Settings / Communication settings / Communication parameters

The slave number and the baud rate must be the same for both the PC and the relay.

Describe and explain the results.

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v. Switch-on the Dead line detection (DLD), remove one of the three-phase lines that used to connect the relay to the voltage transformers and observe the LED. Then switch-off the DLD.

Operating mode for DLD can be changed on the local HMI under the menu:

Setting / Functions / Group 1 / DeadlineDet

vi. Increase the load to 18 kW and observe the LED.

The following manuals provide complementary information:

1. Cap 540 Navigator, User's Manual
2. Cap 531 (Configuration and Programming Tool), User's Manual
3. PST (Parameter setting tool), User's Manual
4. Technical reference manual

All of the manuals are available online: http://www.abb.com/substationautomation

Setting parameters, zone 1-3

Parameter	Description
X1PP	Positive sequence reactive reach of distance protection zone *n* for Ph-Ph faults
R1PP	Positive sequence line resistance reach of distance protection zone *n* for Ph-Ph faults
X1PE	Positive sequence reactive reach of distance protection zone *n* for Ph-E faults
RIPE	Positive sequence line reactance included in distance protection zone *n* for Ph-E faults
X0PE	Zero sequence line reactance included in distance protection zone *n* for Ph-E faults
R0PE	Zero sequence line resistance included in distance protection zone *n* for Ph-E faults
RFPP	Resistive reach of distance protection zone *n* for Ph-Ph faults
RFPE	Resistive reach of distance protection zone *n* for Ph-E faults
t*n*PP	Time delayed trip operation of the distance protection zone *n* for Ph-Ph faults
t*n*PE	Time delayed trip operation of the distance protection zone *n* for Ph-E faults

The ZM distance protection function provides fast and reliable protection for overhead lines and power cables in all kinds of power networks. For each independent distance protection zone, full scheme design provides continuous measurement of impedance separately in three independent phase-to-phase measuring loops as well as in three independent phase-to-earth measuring loops.

Phase-to-phase distance protection is suitable as a basic protection function against two-and three-phase faults in all kinds of networks, regardless of the treatment of the neutral point. Independent setting of the reach in the reactive and the resistive direction for each zone separately, makes it possible to create fast and selective short circuit protection in power systems.

Phase-to-earth distance protection serves as basic earth fault protection in networks with directly or low impedance earthed networks. Together with independent phase preference logic, it also serves as selective protection function at cross-country faults in isolated or resonantly earthed networks.

Independent reactive reach setting for phase-to-phase and for phase-to-earth measurement secures high selectivity in networks with different protective relays used for short-circuit and earth-fault protection.

The distance protection zones can operate, independently of each other, in directional (forward or reverse) or non-directional mode. This makes it suitable, together with different communication schemes, for the protection of power lines and cables in complex network configurations, such as double-circuit, parallel lines and multiterminal lines. Zone 1, 2 and 3 can issue phase selective signals, such as start and trip.

Basic distance protection function is generally suitable for use in non-compensated networks. A special addition to the basic functions is available optionally for use on series compensated and adjacent lines where voltage reversals might disturb the correct directional discrimination of a basic distance protection.

The figure below shows the operating characteristic for one distance protection zone in the forward direction.

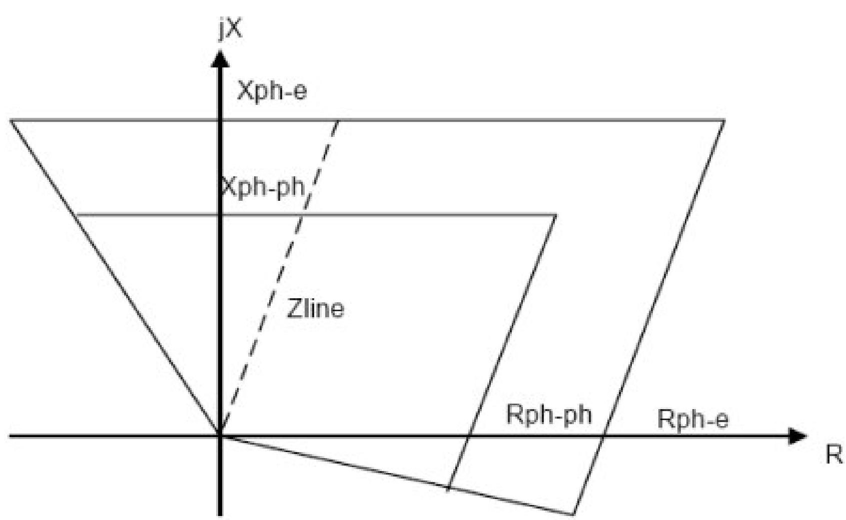


Figure A4 Schematic presentation of the operating characteristics for one distance protection zone in the forward direction

Where:

Xph-e = reactive reach for Ph-E faults

Xph-ph = reactive reach for Ph-Ph faults

Rph-e = resistive reach for Ph-E faults

Rph-ph = resistive reach for Ph-Ph faults

Zline = line impedance

Setting parameters, GFC

Parameter	Description
ARGLd	Load angle determining the load impedance area
RLd	Limitation of resistive reach within the load impedance area
X1RvPP	Positive sequence reactive reach in reverse direction for Ph-Ph faults
X1FwPP	Positive sequence reactive reach in forward direction for Ph-Ph faults
RFPP	Resistive reach (forward and reverse) for Ph-Ph measurement
X1RvPE	Positive sequence reactive reach in reverse direction for Ph-E faults
X1FwPE	Positive sequence reactive reach in forward direction for Ph-E faults
X0RvPE	Zero sequence reactance of reach in reverse direction for Ph-E faults
X0FwPE	Zero sequence reactance reach in forward direction for Ph-E faults
RFPE	Resistive reach (forward and reverse) for Ph-E measurement
IP>	Set operate value for measured phase currents
IN>	Set operate value for measured residual currents
INReleasePE	3I0 limit for releasing Ph-E measuring loops
INBlockPP	3I0 limit for blocking Ph-Ph measuring loops
tPP	Time delayed of trip for Ph-Ph faults
tPE	Time delayed of trip for Ph-E faults

Setting parameters, FLOC

Parameter	Description
X1	Positive sequence line reactance
X0	Zero sequence line reactance
R1	Positive sequence line resistance
R0	Zero sequence line resistance
X1SA	Positive sequence source reactance, near end
R1SA	Positive sequence source resistance, near end
X1SB	Positive sequence source reactance, far end
R1SB	Positive sequence source resistance, near end
Xm0	Mutual reactance from parallel line
Rm0	Mutual resistance from parallel line

Appendix B

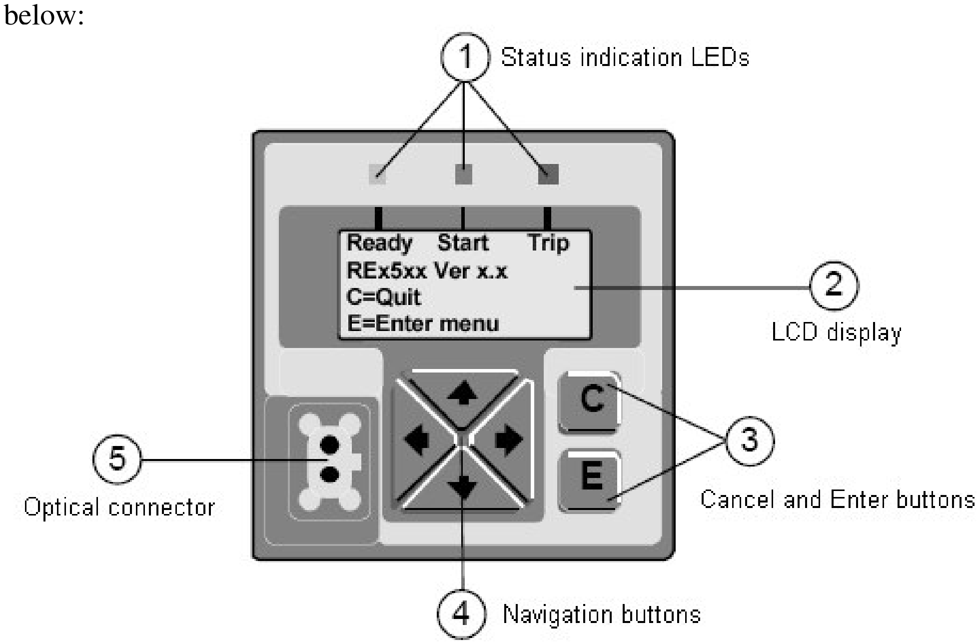
Relay set up manual

1 Energising the terminal

After checking the connection to the external circuitry, when the terminal is energised the window on the local HMI remains dark. After a few seconds the green LED starts flashing and then the window lights up. Then after some seconds the window displays 'Terminal Startup' and the main menu is displayed. The upper row should indicate 'Ready'. A steady green light indicates a successful start-up.

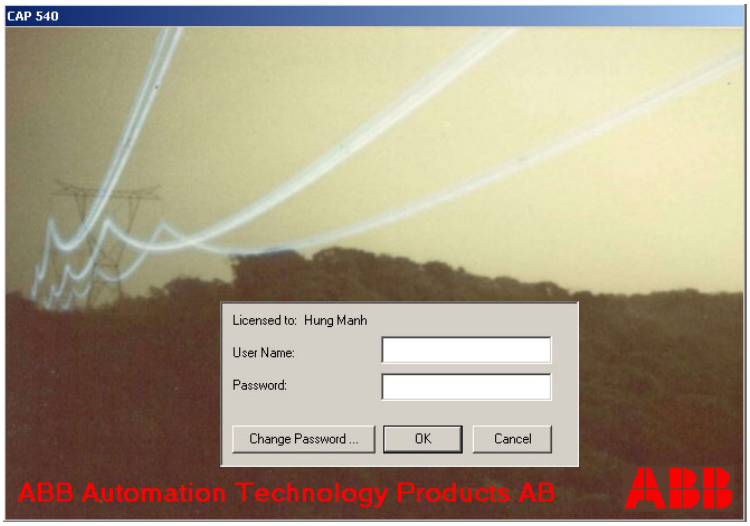
If the upper row in the window indicates 'Fail' instead of 'Ready' and the green LED is flashing, an internal failure in the terminal has been detected. Refer to the Self-supervision function in the Installation and Commissioning manual pages 40 – 42 to investigate the fault.

For a successful start-up the appearance of the local HMI should be as shown in the figure below:



2 Log on and build a new project tree

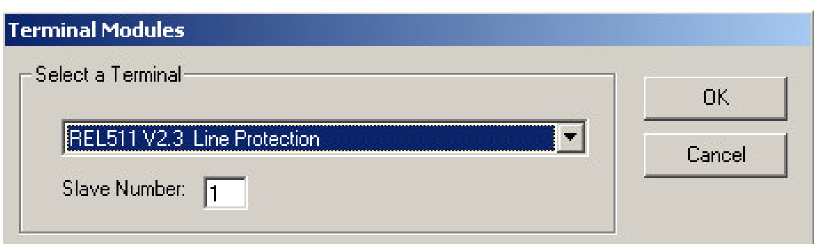
When starting CAP 540 the following dialog appears:



You should fill in User Name and Password and click OK as follows:
User Name: systemadministrator
Password: a10

When you have logged on, you can create a new project tree by selecting **File/New Project.** After **t**yping the file name in the New Project dialog box and clicking OK, a project structure down to Bay level will be created with default names. Right click on the nodes and select Add to add more nodes to your project.

The last level is the Terminal level. Right click on a Bay and select Add. In the Terminal Modules dialog select REL 511 V2.3 Line Protection.



Type in a vacant slave number (it must be unique for each terminal that belongs to the same SPA loop) and click OK. In our case, we use the number 30.

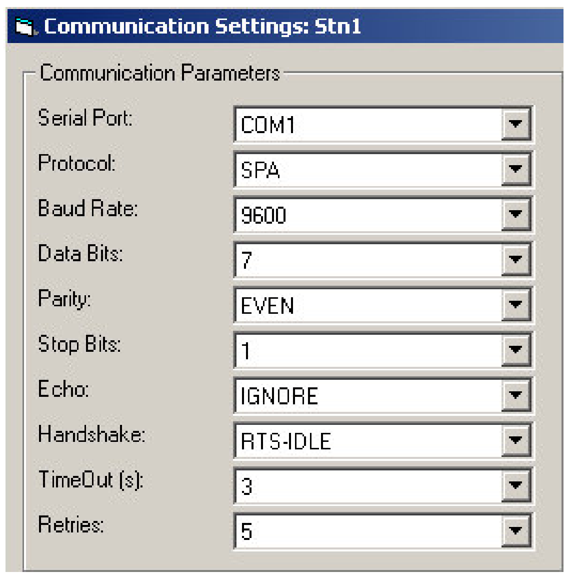
3 Setting and configuring the terminal

The specific values for each setting parameter and the configuration file have to be available before the terminal can be set and configured.

Each function included in the terminal has several setting parameters that have to be set in order to make the terminal behave as intended. The setting file can be prepared using the parameter setting (PST), which is available in the CAP 540. All settings can be entered manually through the local HMI or downloaded from a PC. Front port communication has to be established before the settings can be downloaded. The configuration can only be downloaded through the front connector on the local HMI.

4 Communication settings.

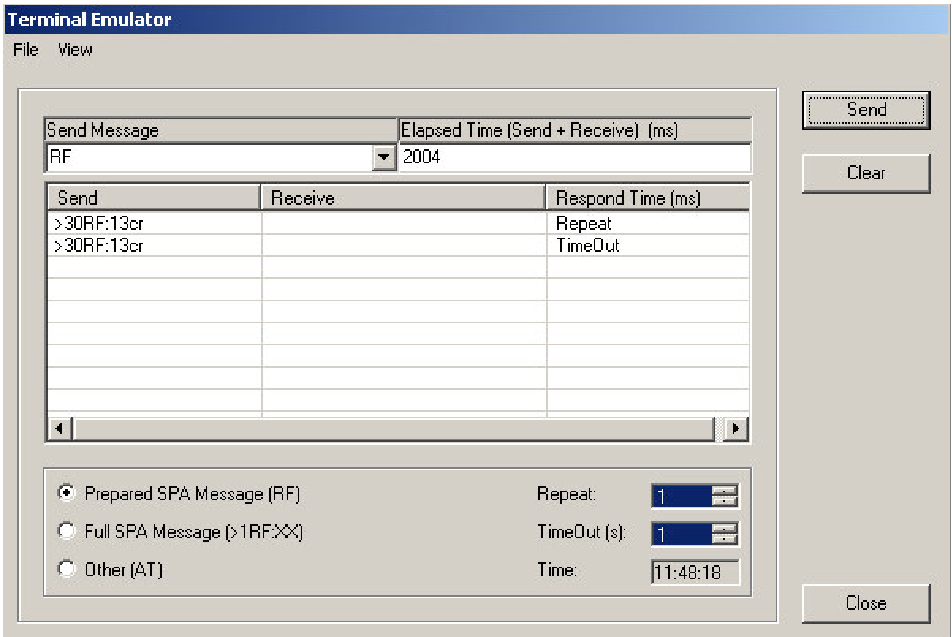
Click on Settings menu or right click on a station node and select **Communication Settings.** The dialog can only be opened if a station node is selected.



The Serial Port number depends on the configuration of the PC. The Baud Rate must be 9600 so that it corresponds to the setting of the front port of the terminal.

The Slave Number and the Baud Rate settings must be equal in the PC program and the terminal. The Slave Number and the Baud Rate settings in the terminal are done on the local HMI at: **Configuration / TerminalCom / SPACom / Front**

Before start communicating to a terminal, make sure the communication setup in CAP 540 is correct. Terminal Emulator is used for fault tracing. Start the Terminal Emulator by selecting a terminal in the project structure and then select Terminal Emulator in the Tools menu.



If “Repeat” and TimeOut” appear in the Respond Time field after clicking Send as shown in the above figure, the communication set up is incorrect and it should be checked again.

5 Upload configuration

The entire configuration is stored in the terminal and it can be upload to the PC. For back-up purposes and off-line engineering, a copy of the terminal configuration should be kept on the PC system. Start the Upload Configuration by selecting the terminal in the project tree and then select Upload Configuration in the On-line menu.

6 Download the configuration

To download the configuration to the terminal:

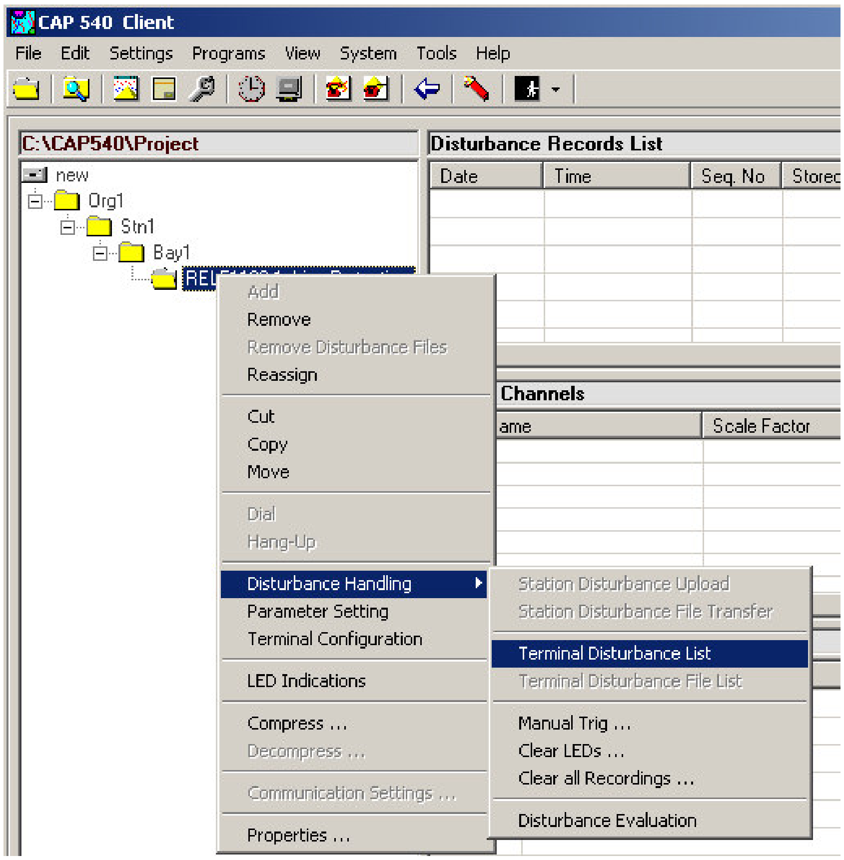
- Select the terminal that you want to download in the Project Tree.
- Select Download Configuration in the On-line menu, and the Download configuration dialog appears.
- Select Download PST configuration if relevant, click Yes, and downloading starts by uploading the list of available functions.

The Compare Configuration function starts automatically. If the downloading has been successful and there are no differences between the function libraries in the terminal and in the configuration, no differences will be detected in the comparison process. If differences appear in the comparison list, then start the downloading procedure again.

7 Disturbance handling

The disturbance report stored in the terminal provides the network operator with proper information about disturbance in the primary network. To upload the disturbance report to the PC:

- Select the Terminal level and right click.
- Continue with Disturbance Handling and with Terminal Disturbance List.



Appendix C

Relay configuration

1 2 3 4 5 6

A

Configuration for laboratory exercise using numerical relay REL511-2.3

Work sheet name	Description	Sheet
OVERVIEW	List of content	1
IMP_PROT	Distance protection functions	2
CUR_PRO	Current functions	3-4
VOL_PROT	Voltage functions	5
TRIP	Trip logic	6
INT	Internal signals	7
I_O	Binary inputs and outputs	8-9
HMI_LED	Indications on local HMI LED	10-11
DRP	Disturbance report	12
EV	Events for SCS	13-14

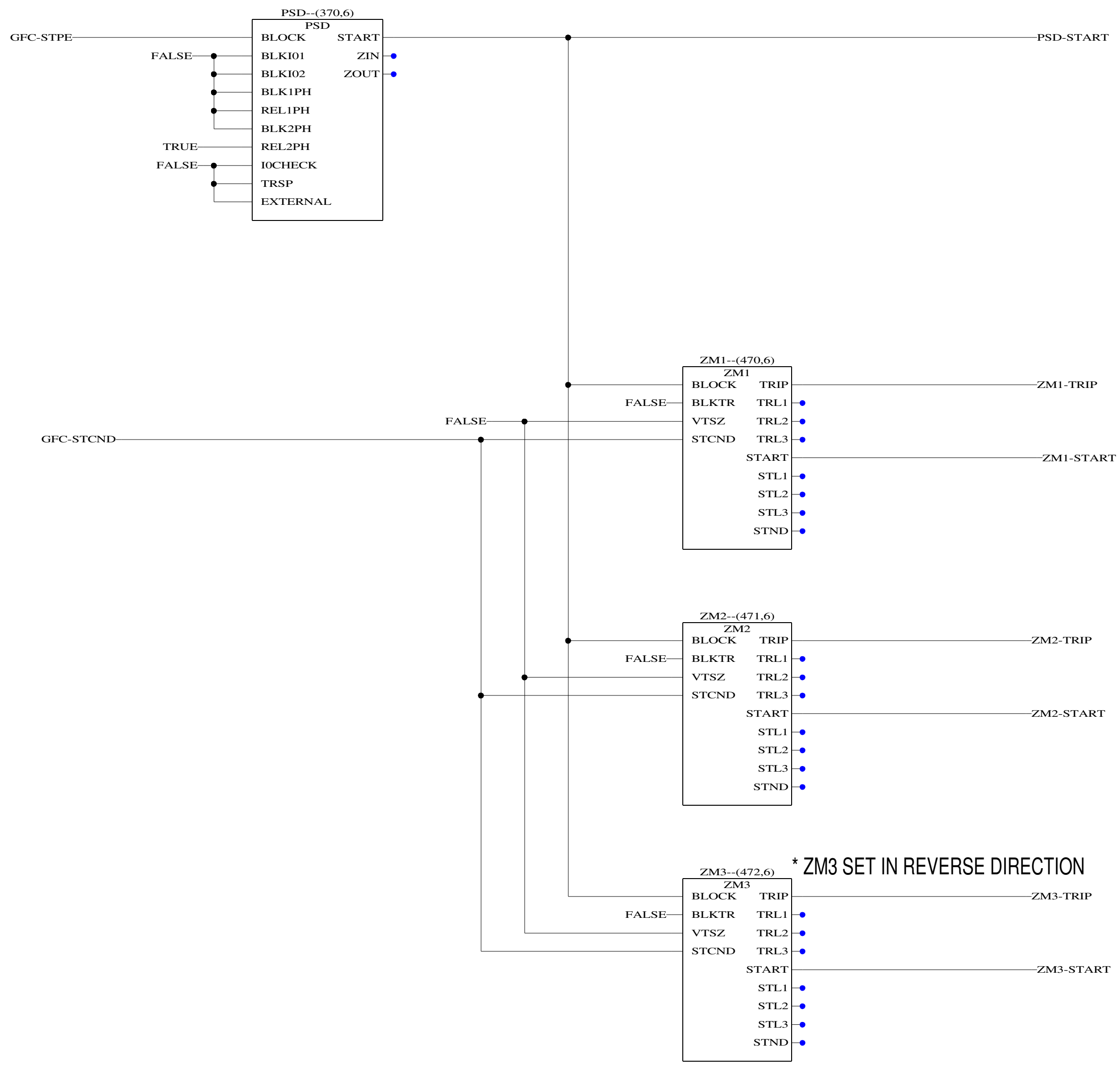
B

C

D

Rev Ind	Reg nr	Prepared T.M.Hung, H. Akyea 20/09/05	Configuration diagram REL 511*2.3	Resp dep	OVERVIEW
Based on	Pcl	Approved Daniel Karlsson 28/09/05	Chalmers University of Technology	Rev Ind	Sheet 1/14
		Power System Protection		Laboratory exercise	

1 2 3 4 5 6



Prepared T.M.Hung, H. Akyea 20/09/05	Configuration diagram REL 511*2.3		IMP_PROT
Approved Daniel Karlsson 28/09/05		Resp dep	Rev Ind
Rev Ind / Reg nr	Power System Protection	Chalmers University of Technology	Laboratory exercise	Sheet 2/14
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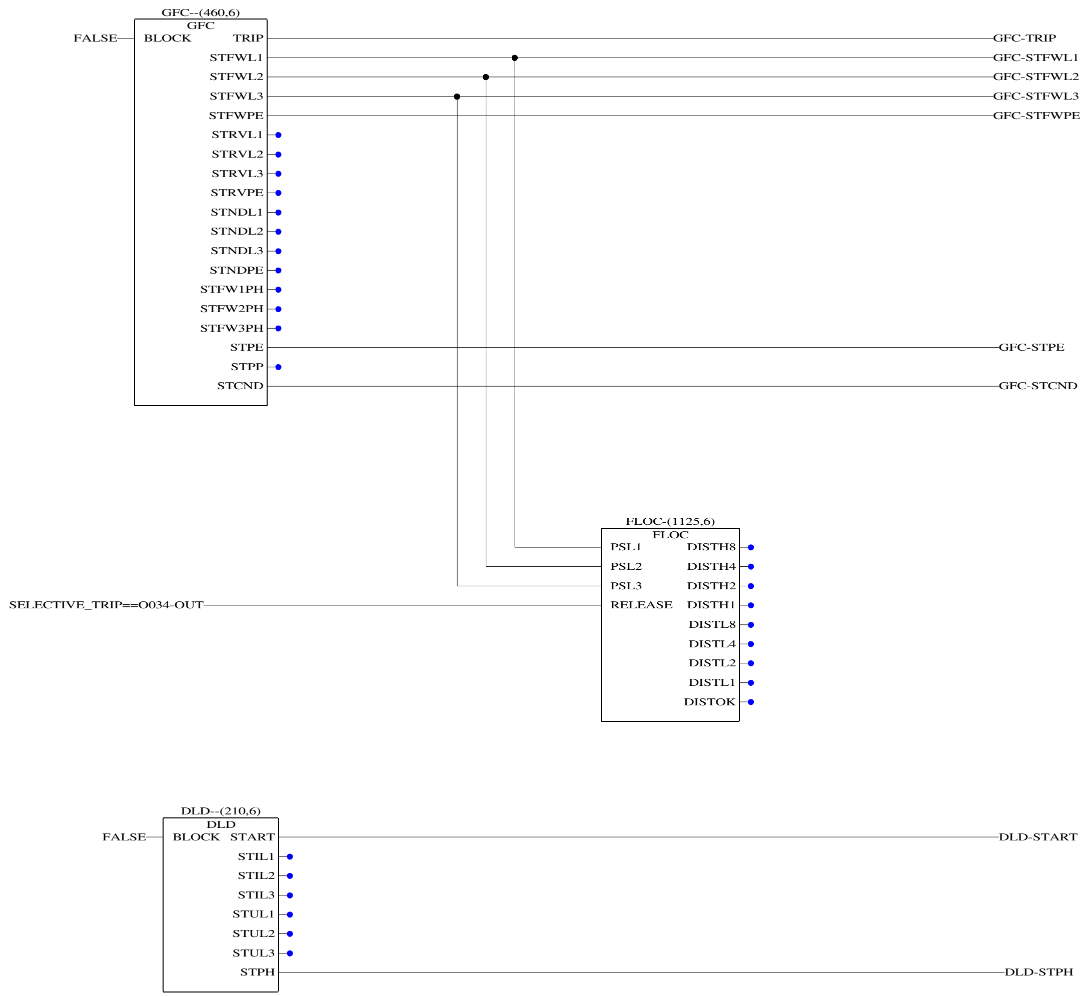

Prepared	T.M.Hung, H. Akyea	20/09/05
Approved	Daniel Karlsson	28/09/05

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CUR_PROT

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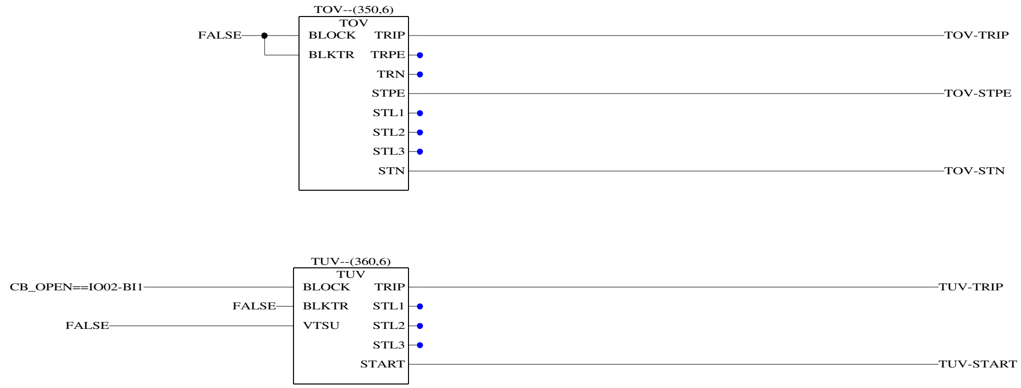
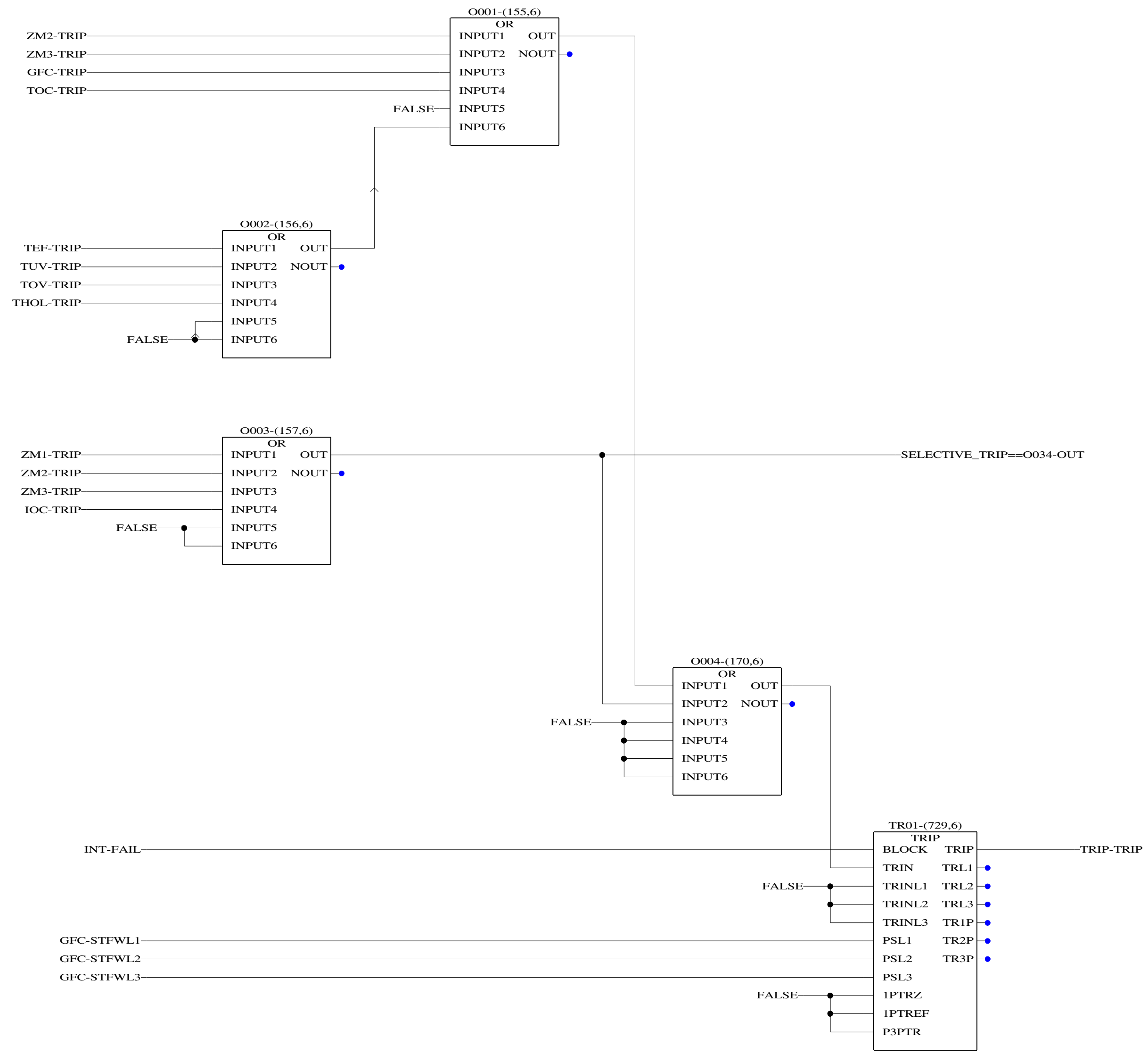
Prepared	T.M.Hung, H. Akyea	20/09/05	Configuration diagram REL 511*2.3
Approved	Daniel Karlsson	28/09/05	
Rev Ind	Reg nr	Power System Protection	Chalmers University of Technology
Based on	Pcl		

		CUR_PROT
Resp dep	Rev Ind	
Laboratory exercise		Sheet 4/14



Prepared T.M.Hung, H. Akyea 20/09/05	Configuration diagram REL 511*2.3		VOL_PROT
Approved Daniel Karlsson 28/09/05		Resp dep	Rev Ind
Rev Ind / Reg nr / Based on / Pcl	Power System Protection	Chalmers University of Technology	Laboratory exercise
			Sheet 5/14



Prepared	T.M.Hung, H. Akyea	20/09/05
Approved	Daniel Karlsson	28/09/05

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TRIP

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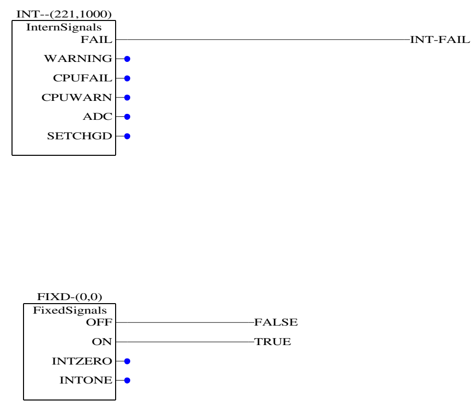
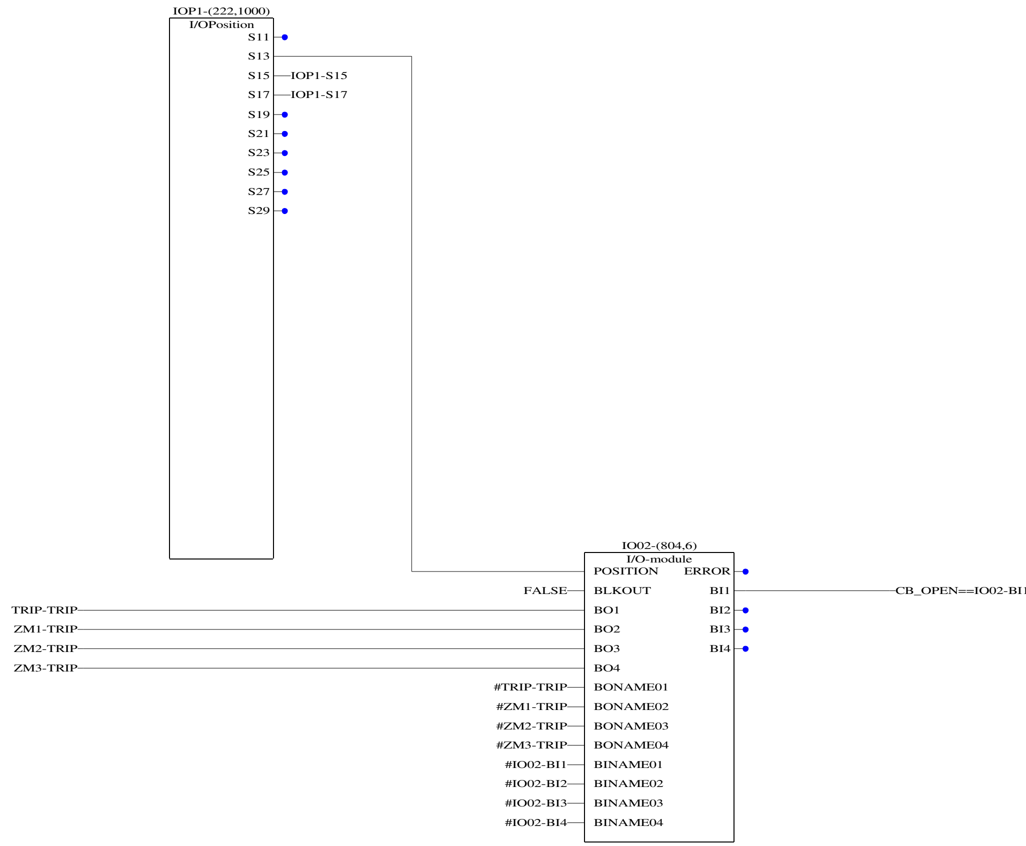


	Prepared T.M.Hung, H. Akyea 20/09/05	Configuration diagram REL 511*2.3		INT
	Approved Daniel Karlsson 28/09/05			
Rev Ind / Reg nr	Power System Protection		Resp dep / Rev Ind	
Based on / Pcl		Chalmers University of Technology	Laboratory exercise	Sheet 7/14



Prepared T.M.Hung, H. Akyea 20/09/05
Approved Daniel Karlsson 28/09/05

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REL 511*2.3

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I_O

Resp dep | Rev Ind

Laboratory exercise

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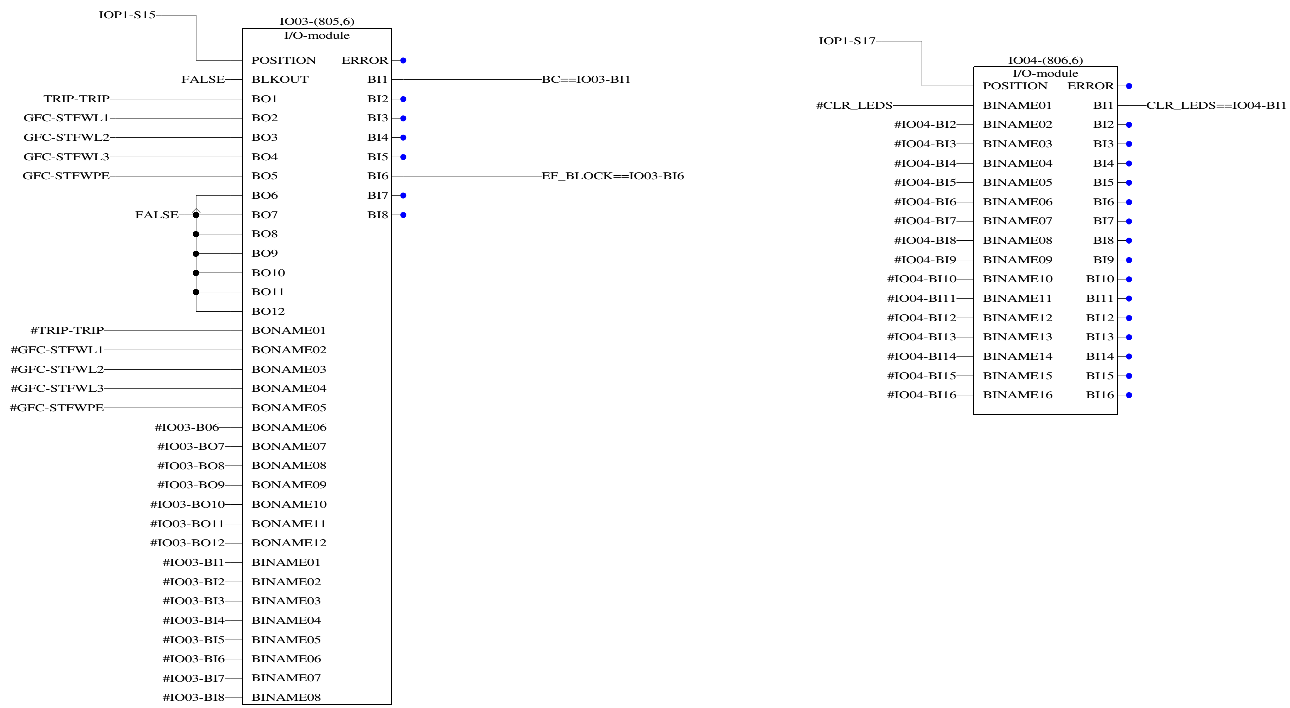

Prepared T.M.Hung, H. Akyea 20/09/05
Approved Daniel Karlsson 28/09/05

Configuration diagram
REL 511*2.3

I_O

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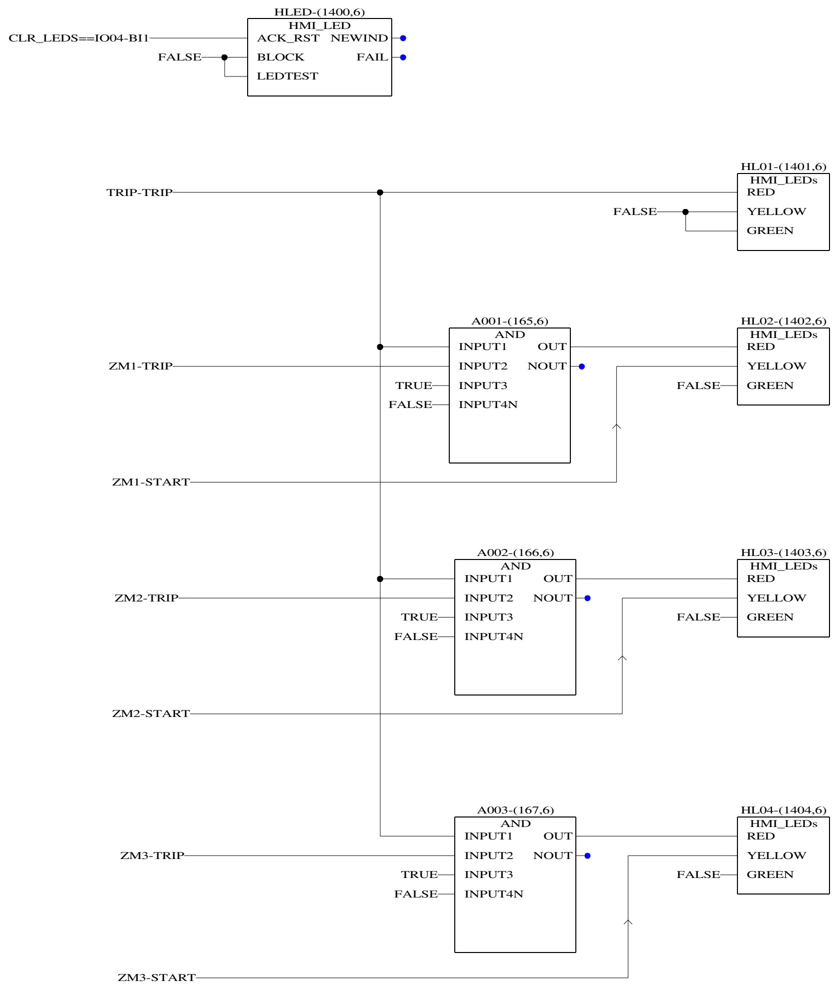

Prepared T.M.Hung, H. Akyea 20/09/05	Configuration diagram REL 511*2.3		HMI_LED
Approved Daniel Karlsson 28/09/05		Resp dep	Rev Ind
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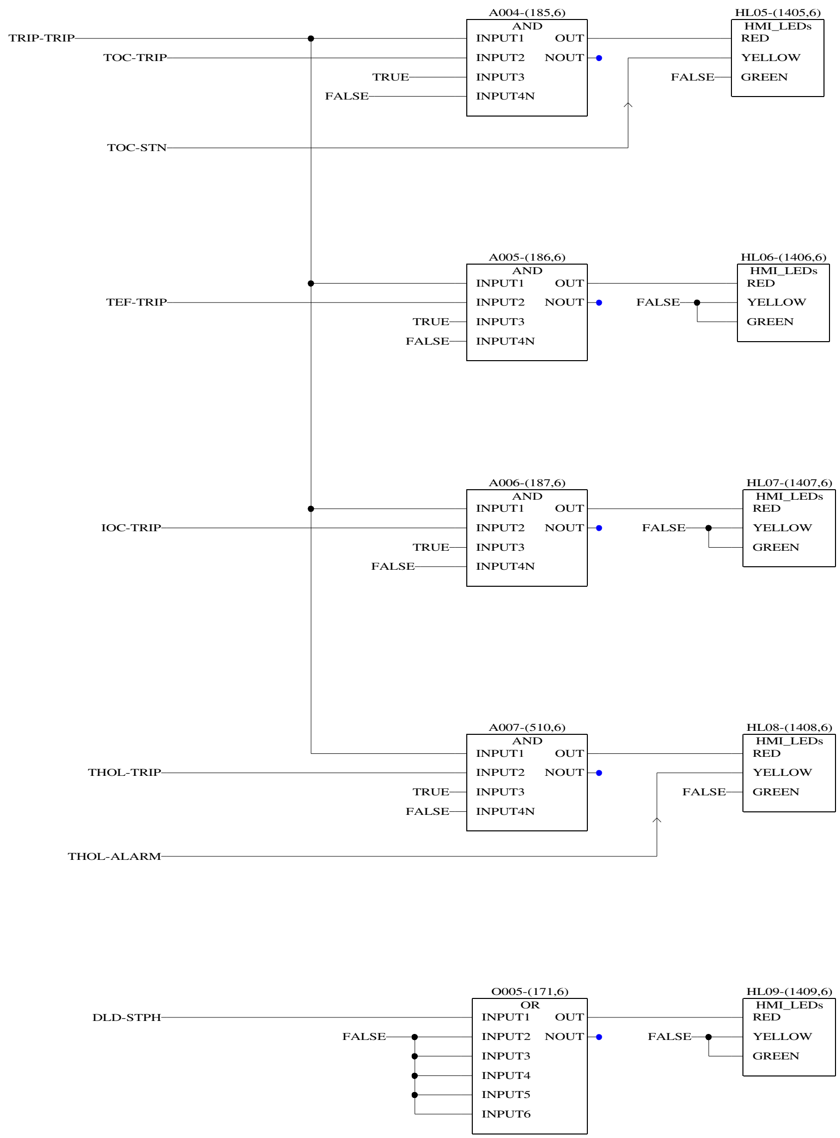

Prepared	T.M.Hung, H. Akyea	20/09/05	Configuration diagram REL 511*2.3		HMI_LED
Approved	Daniel Karlsson	28/09/05		Resp dep	Rev Ind
Rev Ind	Reg nr	Power System Protection	Chalmers University of Technology	Laboratory exercise	Sheet 11/14
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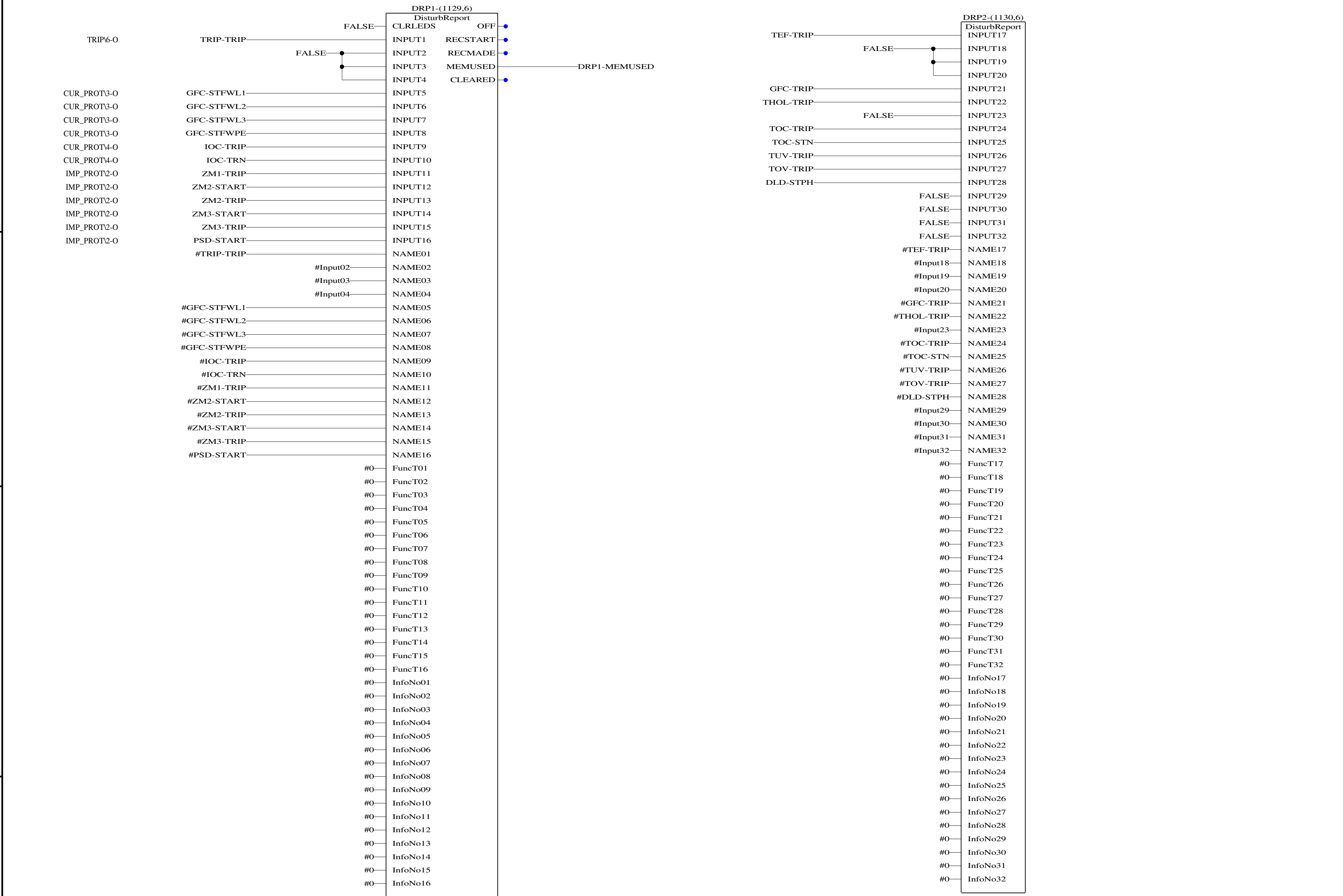

Prepared	T.M.Hung, H. Akyea	20/09/05	Configuration diagram REL 511*2.3
Approved	Daniel Karlsson	28/09/05	DRP
Rev Ind	Reg nr	Power System Protection	Resp dep / Rev Ind
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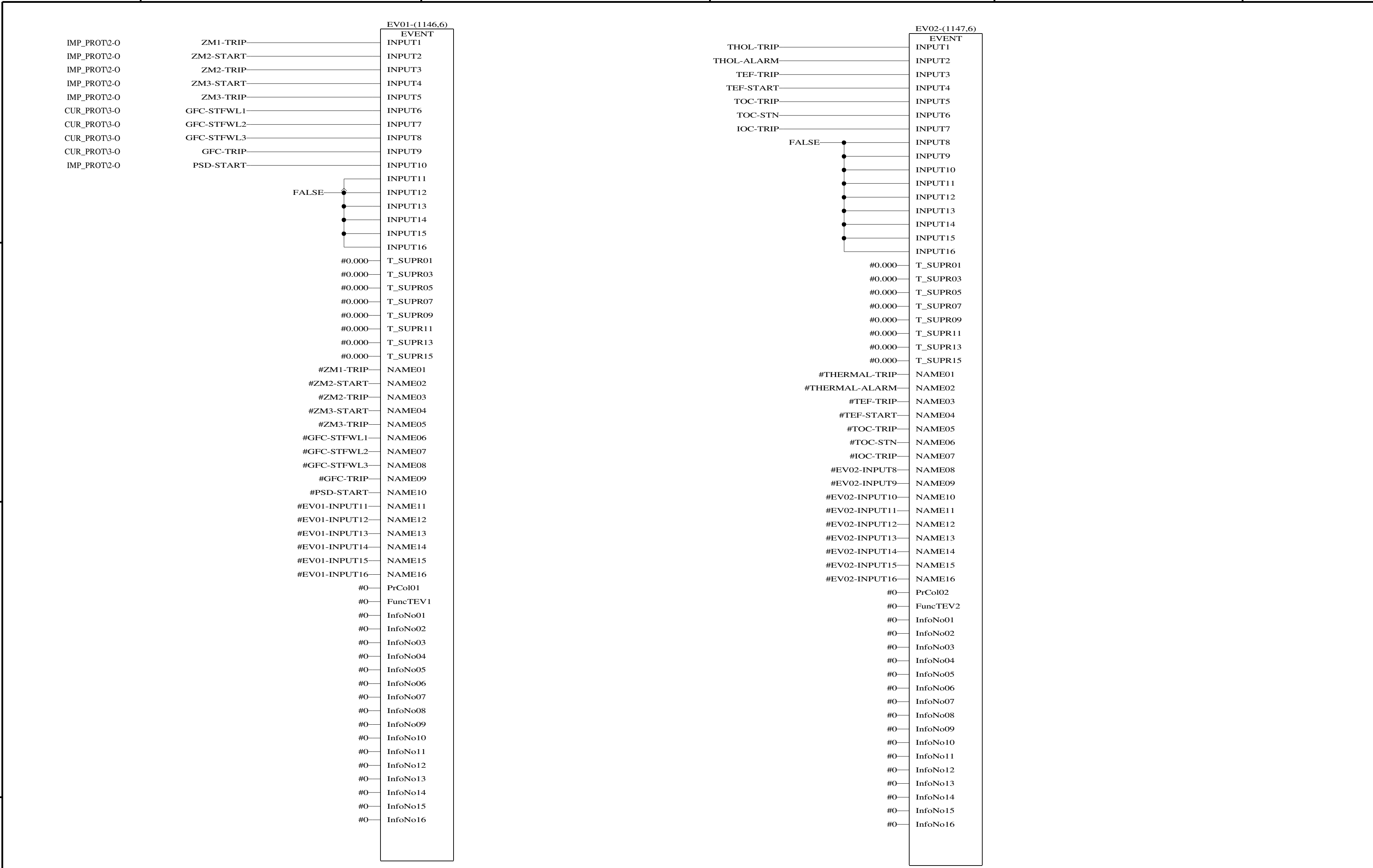

Prepared	T.M.Hung, H. Akyea	20/09/05	
Approved	Daniel Karlsson	28/09/05	
Rev Ind		Reg nr	
Based on		Pcl	

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Configuration diagram
REL 511*2.3

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EV

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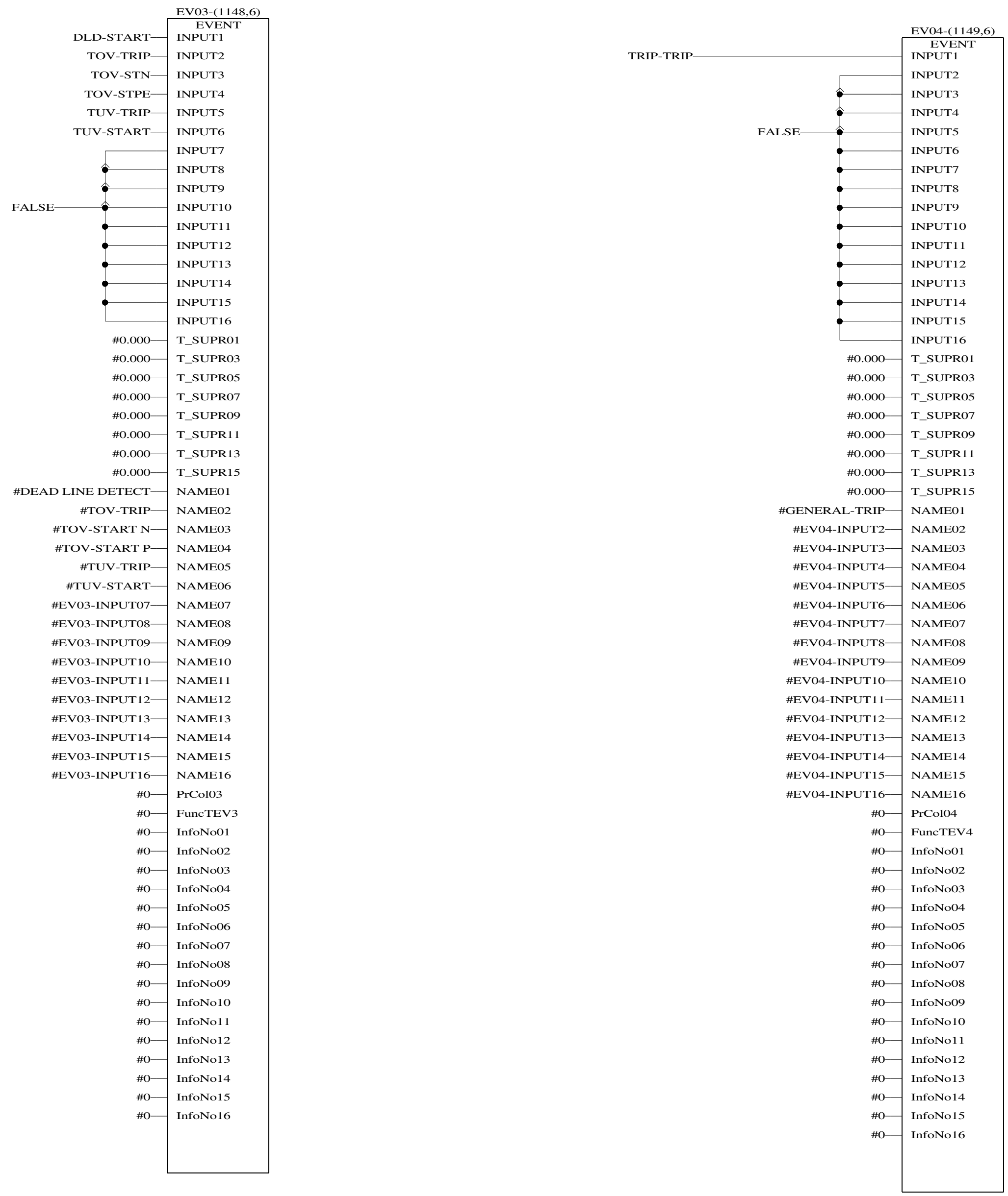

Prepared T.M.Hung, H. Akyea 20/09/05	Configuration diagram REL 511*2.3		EV
Approved Daniel Karlsson 28/09/05		Resp dep	Rev Ind
Rev Ind / Reg nr	Power System Protection	Chalmers University of Technology	Sheet 14/14
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BC==IO03-BI1	I_O\9-O
CB_OPEN==IO02-BI1	VOL_PROT\5-I
CLR_LEDS==IO04-BI1	I_O\9-O
DLD-START	EV\14-I
DLD-STPH	DRP\12-I
	HMI_LED\11-I
EF_BLOCK==IO03-BI6	I_O\9-O
GFC-STCND	IMP_PROT\2-I
GFC-STFWL1	DRP\12-I
	EV\13-I
	I_O\9-I
	TRIP\6-I
GFC-STFWL2	DRP\12-I
	EV\13-I
	I_O\9-I
	TRIP\6-I
GFC-STFWL3	DRP\12-I
	EV\13-I
	I_O\9-I
	TRIP\6-I
GFC-STFWPE	DRP\12-I
	I_O\9-I
GFC-STPE	IMP_PROT\2-I
GFC-TRIP	DRP\12-I
	EV\13-I
	TRIP\6-I
INT-FAIL	TRIP\6-I
IOC-TRIP	DRP\12-I
	EV\13-I
	HMI_LED\11-I
	TRIP\6-I
IOC-TRN	DRP\12-I
IOP1-S15	I_O\9-I
IOP1-S17	I_O\9-I
PSD-START	EV\13-I
	IMP_PROT\2-O
SELECTIVE_TRIP==O034-OUT	TRIP\6-O
TEF-START	EV\13-I
TEF-TRIP	DRP\12-I
	EV\13-I
	HMI_LED\11-I
	TRIP\6-I
THOL-ALARM	EV\13-I
	HMI_LED\11-I
THOL-TRIP	DRP\12-I
	EV\13-I
	HMI_LED\11-I
	TRIP\6-I
TOC-STN	DRP\12-I
	EV\13-I
	HMI_LED\11-I
TOC-TRIP	DRP\12-I
	EV\13-I
	HMI_LED\11-I
	TRIP\6-I
TOV-STN	VOL_PROT\5-O
TOV-STPE	VOL_PROT\5-O
TOV-TRIP	EV\14-I
	TRIP\6-I
	VOL_PROT\5-O
TRIP-TRIP	EV\14-I
	HMI_LED\10-I
	HMI_LED\11-I
	I_O\8-I
	I_O\9-I
	TRIP\6-O
TUV-START	VOL_PROT\5-O
TUV-TRIP	EV\14-I
	TRIP\6-I
	VOL_PROT\5-O
ZM1-START	IMP_PROT\2-O
ZM1-TRIP	EV\13-I
	HMI_LED\10-I
	I_O\8-I
	IMP_PROT\2-O
	TRIP\6-I
ZM2-START	EV\13-I
	HMI_LED\10-I
	IMP_PROT\2-O
ZM2-TRIP	EV\13-I
	HMI_LED\10-I
	I_O\8-I
	IMP_PROT\2-O
	TRIP\6-I (2)
ZM3-START	EV\13-I
	HMI_LED\10-I
	IMP_PROT\2-O
ZM3-TRIP	EV\13-I
	HMI_LED\10-I
	I_O\8-I
	IMP_PROT\2-O
	TRIP\6-I (2)

Prepared T.M.Hung, H. Akyea 20/09/05
Approved Daniel Karlsson 28/09/05

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Configuration diagram
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