7SJ61
as High Impedance Relay

Type Test and Application Notes
Annex 1: Input Filter Tests

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reviewed and released

Editor

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1 Introduction

This test report verifies the performance of the 7SJ61 for application as high impedance restricted earth fault protection (REF) and high impedance bus duct protection. It describes the test setup and discusses the simulation results and provides also some application notes.

2 General test set up

2.1 Test set up

The concept of simulations and tests was developed in the way that on the one hand it has provided a good consistency with real situations and on the other hand it has offered the flexibility needed to carry out comprehensive studies (Figure 2.1). Thereby, power system and high impedance circuit were modeled in Power System Simulator PSS^{TM}NETOMAC. Then, the current flowing through the stabilizing resistance branch was saved at each studied case as a Comtrade-file. Consequently, the data was exported via Omicron Test Universe Software to the amplifier that generated the test signals to the relay. Finally, the fault record of the relay was read and evaluated with DIGSI/SIGRA. Such a construction allows studying the protection system's behavior by wide range of settings and different values of external components, like stabilizing resistor and MOV (varistor).

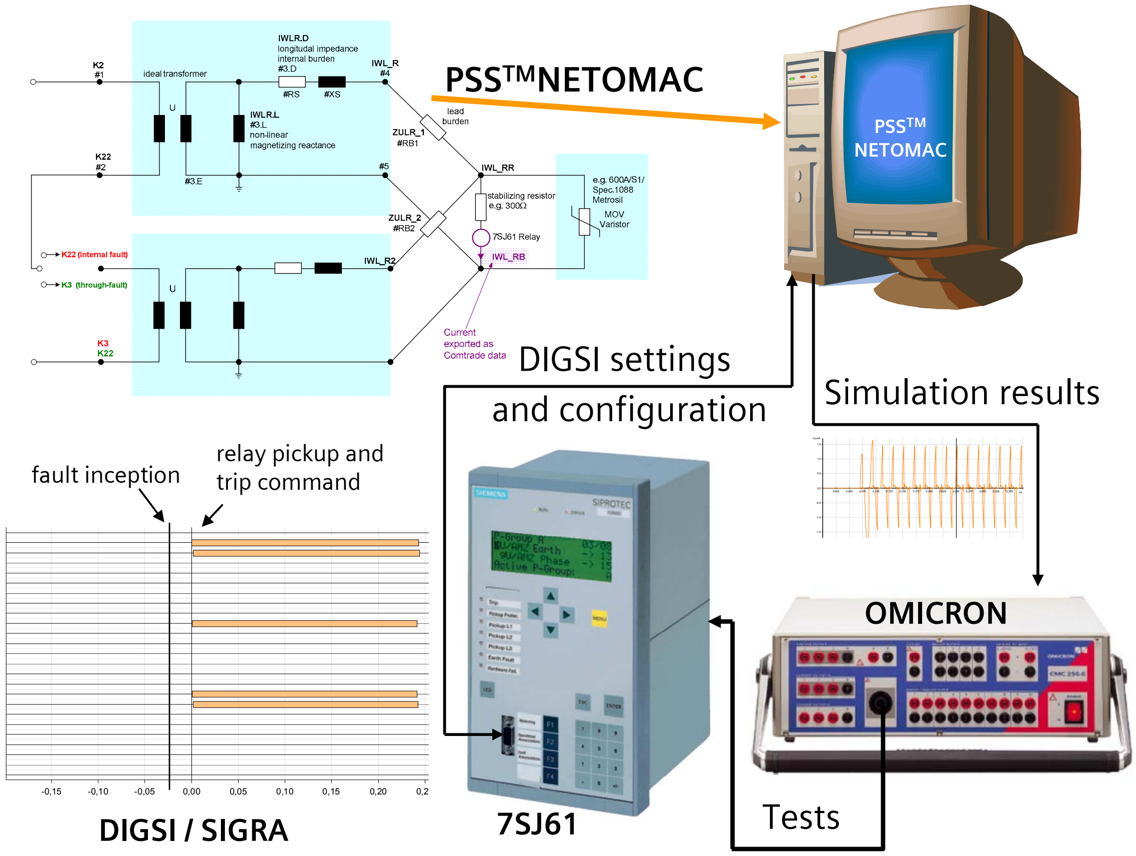

Figure 2.1 Test set up

2.1.1 Test object

Test object: **SIEMENS relay type 7SJ61, Order No. 7SJ6122-5EB90-1FB0/EE L0S**

Thereby, for REF the sensitive current input (Q7-Q8) was used and for bus duct the three standard current inputs were used, respectively.

2.1.2 CT and MOV models

Dedicated macros were developed to simulate the non-linear characteristic of CT-core and of the MOV. Moreover, such models enable one to simulate different types of CTs and switching between available MOV types. An example MOV characteristic of type Metrosil 600A/S1/Spec.1088 used in tests is shown in Figure 2.2.

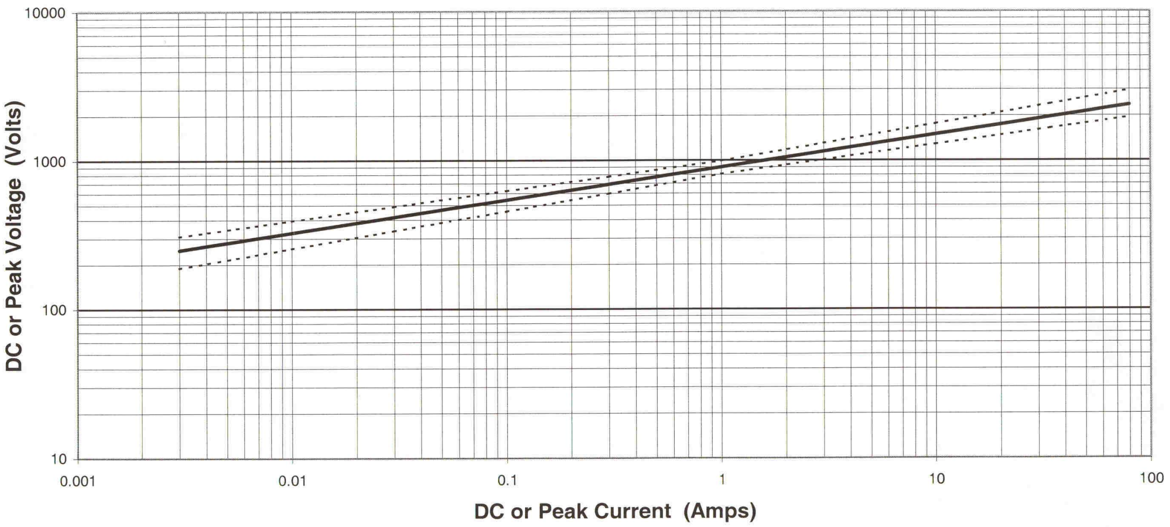

Figure 2.2 Voltage vs. Current characteristic of the MOV type Metrosil 600A/S1/Spec.1088 used in simulations

2.1.3 REF protection set up

Figure 2.3 shows the simplified connection diagram of the circuit together with the concept of the PSS^{TM}NETOMAC-project structure. The simulated circuit encloses four CTs connected to the network in which different types of faults can be simulated.
Thereby, the amplitude of the fault current, the fault inception angle and the network time constant can be changed, as well.

Due to changing of the fault location both the internal and through-faults were simulated as three-pole and single-pole faults.

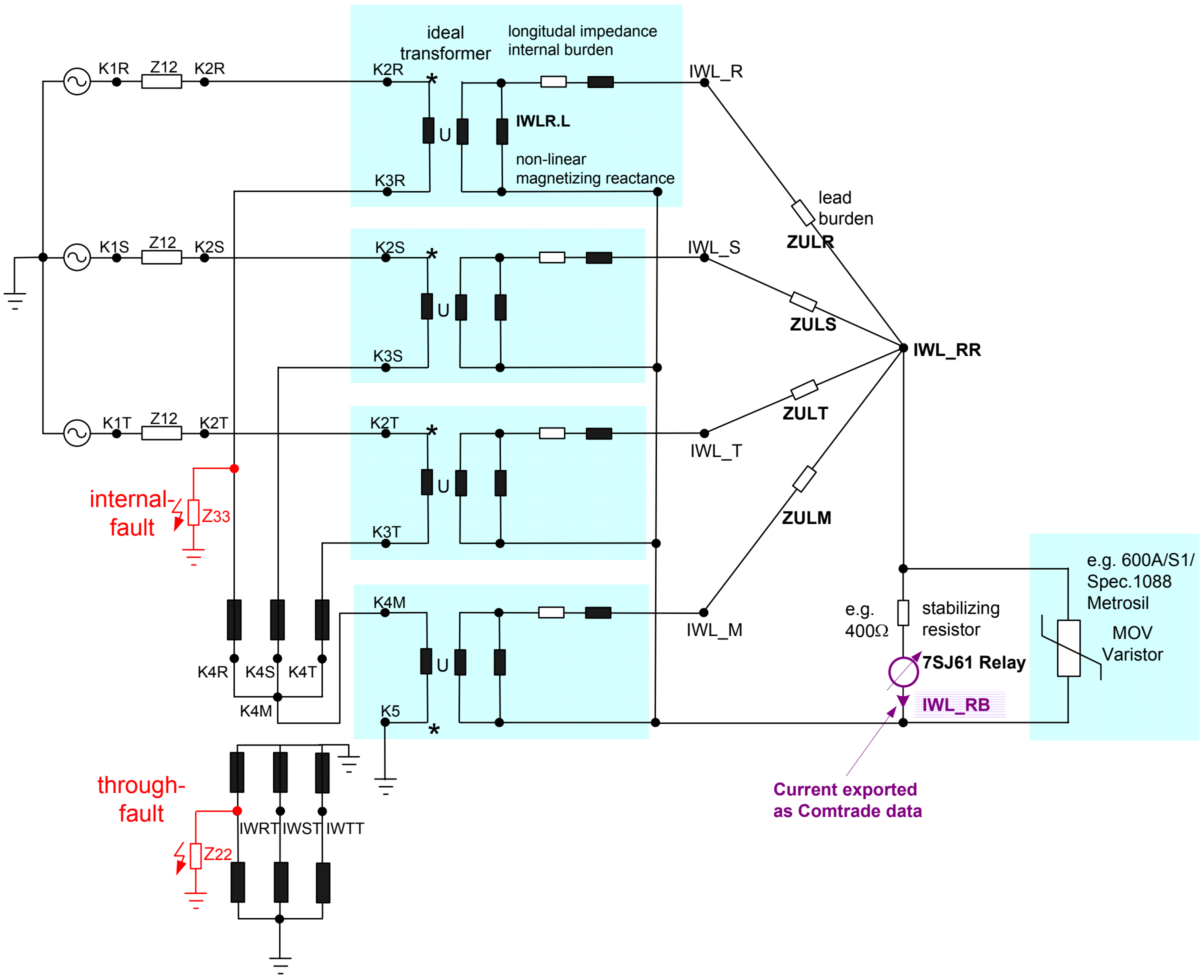

Figure 2.3 Structure of PSS^{TM}NETOMAC simulation project for REF protection tests

2.1.4 Bus duct protection set up

Figure 2.4 shows the circuit diagram together with the concept of the PSS^{TM}NETOMAC structure. The simulated circuit encloses two CTs connected to the system in which different types of faults can be simulated. Thereby the fault current, the fault inception angle and the system time-constant can be changed.

Due to a simple changeover of the CT primary connections (in Figure 2.4 on the left side) both, internal faults and through-faults can be simulated. The values of the stabilizing resistor and of the lead burden can also be varied.

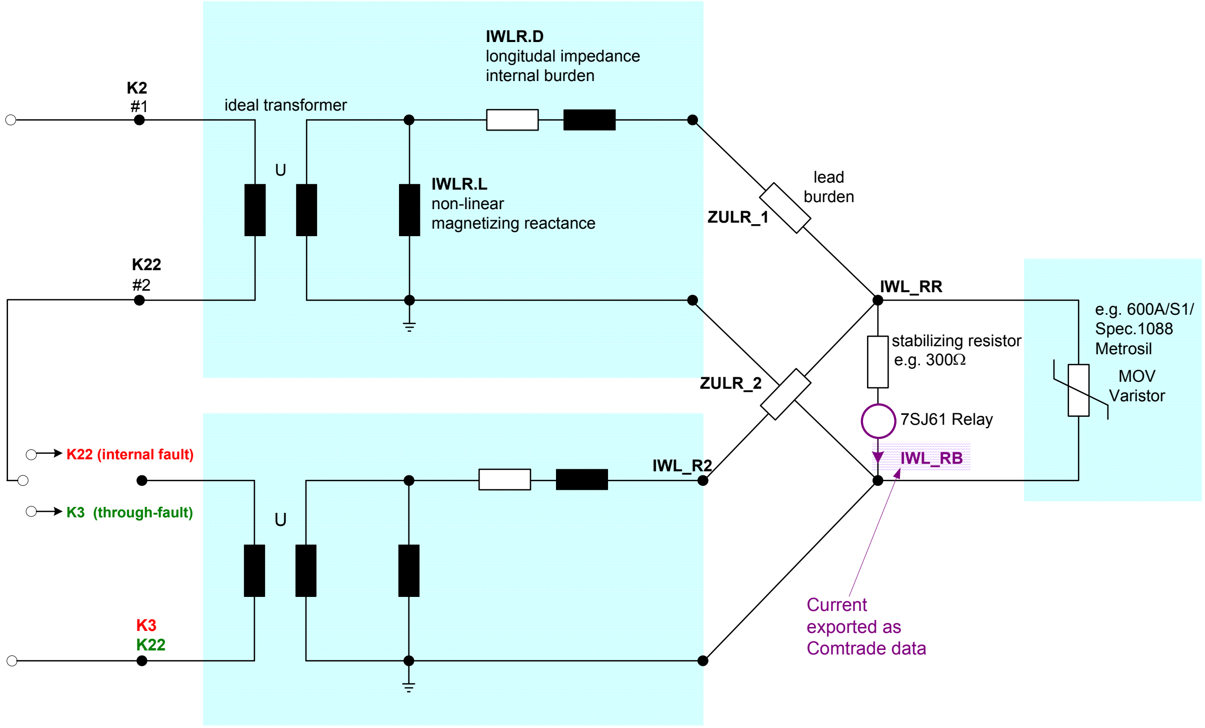

Figure 2.4 Structure of PSS^{TM}NETOMAC simulation project for busbar protection tests

3 REF protection tests

3.1 Test set up and parameters

For the simulations following assumptions have been made:

1. faults duration of 450 ms with inception angle (0^0 for L1, i.e. at voltage zero-crossing) were simulated in a network with time-constant of 150 ms,
2. four 800/1 IEC Class PX CTs were chosen and dimensioned with U_{knee} = 360 V and I_{knee} = 30 mA, internal burden of 3 Ω each,
3. a typical MOV was simulated of type: Metrosil 600A/S1/Spec.1088.

The calculation for the corresponding restricted earth fault protection scheme is attached to the report in appendix (p. 6.1).

Below, the summarized data are presented in concise form:

General system/ protected object data:	
Frequency	50 Hz
Network time-constant:	150 ms
Rated I_k''of the equipment:	63 kA
Protected object:	(Star connected) Winding of a power transformer power
Rated current I_r of the protected object	722A (calculated for: 500MVA at 400kV)
Maximum through fault current	=11.5 kA (calculated as 16 x I_r)
Fault setting for REF protection (primary value)	striven for 15% of I_r, i.e. ~110A
Setting set (secondary value):	0.15A (120A primary, 16.6% of I_r)
CT/ protection scheme data:	
Number of CTs connected in parallel	4
Type:	IEC Class PX
CT Ratio:	800 A/ 1 A
Knee point voltage U_{knee}:	360 V
Magnetizing current I_{knee} at knee point voltage:	0.03 A
Internal burden R_{CT} at 75^0C:	2 Ω
Length /cross section of the secondary lead:	180 m /4mm^2
Resulting lead burden (loop resistance) at 75^0C	1.98 Ω
Stabilizing resistor used:	400 Ω
MOV:	Metrosil 600A/S1/Spec.1088
Relay used:	sensitive earth fault input IEE (Q7, Q8) used
Setting range:	3mA to 1.5A in 1mA steps
Relay burden:	50 mΩ

Simulation framework

Fault duration simulated	450 ms
Fault inception angle:	0° referred to the phase L1
Short circuit type	three-pole and single-pole
Short circuit current value	simulated as internal and external with variable range (from zero to 63kA)

According to the dimensioning report (p. 6.1) a voltage stability setting of **60 V** is used to ensure stability with external faults. Considering the striven fault setting for REF a current setting of **0.15A** was used. This leads to the stabilizing resistance of **400 Ω**.

$$R_{stab} = \frac{U_{s,set}}{I_{set}} = \frac{60\text{V}}{0.15\text{A}} = 400\ \Omega$$

Therefore, the following was set to the tested relay **7SJ61:**

2703	**high-set inst. pickup IEE>>**	**= 0.15A**
2704	**high-set inst. time delay t>>**	**= 0s**

3.2 REF Protection –test results

Consecutively the following cases have been carried out:

A. RELAY SENSITIVITY with **internal single-pole faults**

B. RELAY STABILITY with following fault types:

   a. **through-faults** (single- and three-pole),

   b. **three-pole internal faults**.

The results of the tests are shown in following, structured in tables with exemplary waveforms. The current values given in tables below are short-circuit-current values referred to the fault current at the fault location.

3.2.1 Sensitivity with internal single-pole faults

Table 3.1 Sensitivity with internal single-pole faults

Speed for internal fault scenario with Uk = 360 V, Us = 60 V, Rstab=400Ohm, Metrosil 1088 Setting Is,set: IEE>> = 0.15A (120 A primary)												
Fault current: Ikint [A]	84	96	108	120	132	180	240	600	1200	2400	6000	63000
Ratio: Ikint /Is,set	0.7	0.8	0.9	1	1.1	1.5	2	5	10	20	50	525
trip time: trelay[ms]	**N**	**N**	**N**	**45**	**40**	**37**	**28**	**22**	**22**	**21**	**21**	**20**

In Figure 3.1 the behavior of the relay on internal single-pole short-circuit-current can be seen. The current flowing through the differential branch and its rms value, as calculated by SIGRA, are presented, as well.

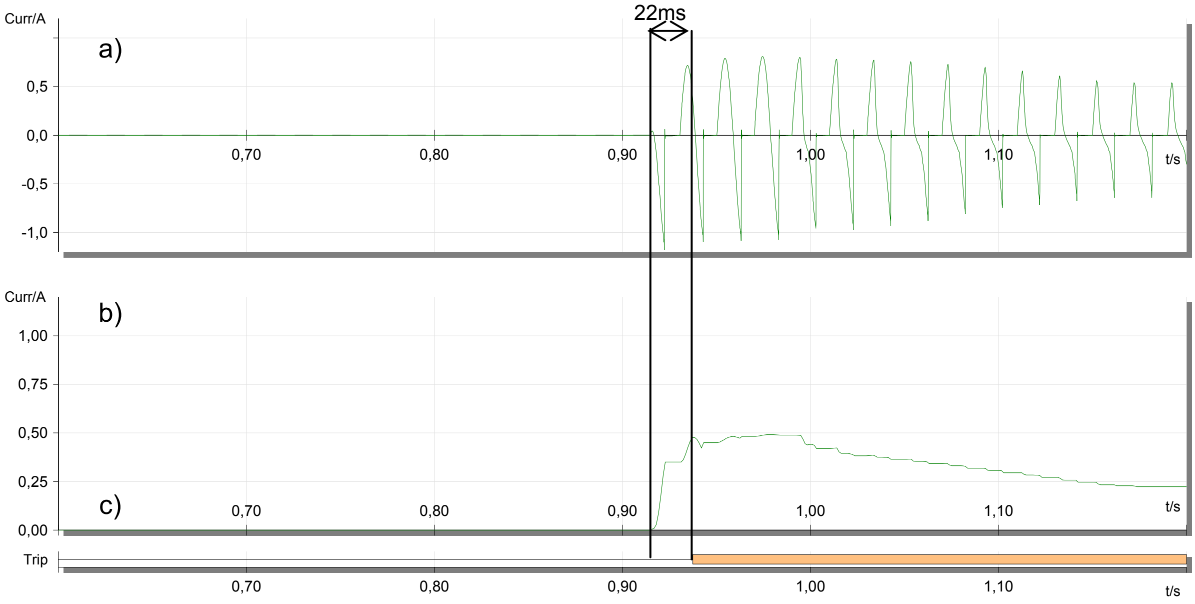

Figure 3.1 Instantaneous current (a) and its rms value (b) flowing through the differential branch by an internal single-pole fault current of 600 A. Relay trip command (c)

3.2.2 Stability with through-faults

Table 3.2 summarizes the results of the stability tests with external faults.

Table 3.2 Stability with through-faults (N means no trip)

Stability for external fault scenarios with Uk = 360 V, Us = 60 V, Rstab=400Ohm, Metrosil 1088
Setting Is,set: IEE>> = 0.15A (120 A primary)

Fault current: Ikint [A]	6400	12800	19200	25600	27200	28800	30400	31200	32000
Ratio: Ikint /Is,set	8	16	24	32	34	36	38	39	40
trip time: trelay[ms]	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**34.6**

It can be seen in Table 3.2 that the relay remains stable over the whole range of fault currents, to which it was dimensioned (i.e. 11.5kA – 16 times the rated current of the protected object in this case). It fulfills herewith the requirement for stability at through-faults.

Moreover, some more tests were made in order to test at which value of the theoretical through fault current the relay trips, if the dimensioning criteria remain the same. One can observe (Table 3.2) that it happens not before 32kA short circuit current (40-times the rated current of the protected object in this case). Such through fault current can never be reached practically, since the impedance of the protected object will never be so low to allow for such current. In Figure 3.2 the current flowing through the differential branch is presented for an exemplary 25.6 kA external three-pole fault .

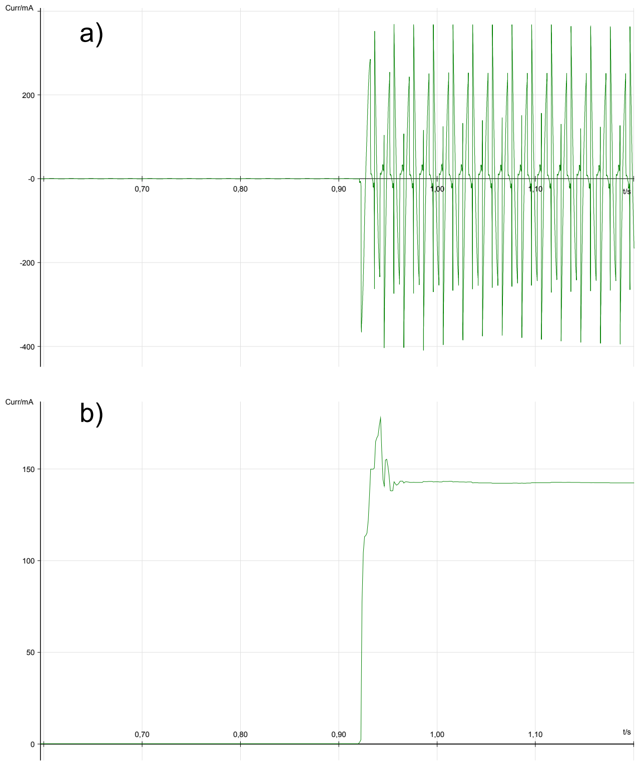

Figure 3.2 Instantaneous current (a) and its rms value (b) flowing through the differential branch by an external three-pole fault of 25.6 kA

3.3 Discussion of test results for REF

The tests have verified the relay sensitivity with internal single-pole faults. The calculated reduced sensitivity of ca. 18 % of the primary rated current of the protected object (i.e. about 130 A) has been achieved. The tests have been carried out point on wave at voltage zero-crossing to represent the worst case to CTs. As far as the sensitivity is concerned, it can be stated that the relay correctly trips with all applied fault currents (Table 3.1)

The stability with the through-faults can be verified by calculation of the CT requirements. Starting from the calculated through-fault current of 11.5 kA that was used for the calculation of the stabilizing voltage setting (60V – see p.6.1) the relay was tested for stability on through faults. One can observe that the relay remains stable for all calculated through faults. Even when the through-fault currents are of range up to 30 kA the relay remains stable (Table 3.2). One can observe (Table 3.2) the relay remains stable up to short circuit current that is 40-times the rated current of the protected object in this case 32kA), which is well above the calculated stability limit of the protection scheme (11.5 kA in this case). On can state that also such through fault current can never be reached practically within the REF scheme, since the impedance of the protected object will never be so low to allow for such a current.

Summarizing, it can be said that the relay maintains its stability in accordance to the boundary conditions that have been determined during the CT dimensioning.

4 Bus duct protection

4.1 Test set up and parameters

For the simulations of the bus duct differential protection using high impedance scheme (Figure 2.4) the following assumptions have been made:

4. faults duration of 450 ms with inception angle (0^0 for L1, i.e. at voltage zero-crossing) were simulated in a network with time-constant of 150 ms,
5. two 2000/1 IEC Class PX CTs (per phase) were chosen and dimensioned with U_{knee} = 1600 V and I_{knee} = 20 mA, internal burden of 6 Ω each,
6. a typical MOV was simulated of type: Metrosil 600A/S1/Spec.1088.

The calculation for the corresponding protection scheme is attached to the report in appendix (p.6.2).

Below, the summarized data are presented in concise form:

General system/ protected object data:

Frequency	50 Hz
Network time-constant:	150 ms
Rated I_k''of the equipment:	63 kA
Protected object:	Bus duct
Rated current I_r of the protected object	2000A (as the rated current of the feeder)
Maximum through fault current	=63 kA
Fault setting for protection (primary value)	striven for 100% i.e. ~2000A
Setting set (secondary value):	1.0A

CT/ protection scheme data:

Number of CTs connected in parallel	2 (per phase)
Type:	IEC Class PX
CT Ratio:	2000 A/ 1 A
Knee point voltage U_{knee}:	1600 V
Magnetizing current I_{knee} at knee point voltage:	0.02 A
Internal burden R_{CT} at 75^0C:	6 Ω
Length /cross section of the secondary lead:	180 m /4mm^2
Resulting lead burden (loop resistance) at 75^0C	1.98 Ω
Stabilizing resistor used:	260 Ω
MOV:	Metrosil 600A/S1/Spec.1088
Relay used:	phase input I (Q1...Q6) used
Setting range:	0.1A to 35A in 0.01A steps
Relay burden:	50 mΩ

Simulation framework

Fault duration simulated	450 ms
Fault inception angle:	0° referred to the phase L1
Short circuit type	three-pole and single-pole
Short circuit current value	simulated as internal and external with variable range (from zero to 63kA)

According to the dimensioning report (p. 6.2) a voltage stability setting of **260 V** is used to ensure stability with external faults. Considering the striven fault setting for bus duct protection a current setting of **1.0A** was used. This leads to the stabilizing resistance of **260 Ω**:

$$R_{stab} = \frac{U_{s,set}}{I_{set}} = \frac{260V}{1A} = 260\ \Omega\,.$$

Therefore, the following was set to the tested relay **7SJ61:**

1202	**high-set inst. pickup I>>**	**= 1.0A**
1203	**high-set inst. time delay t>>**	**= 0s**

4.2 Bus duct protection –test results

At these conditions the following tests have been carried out:

- RELAY **SENSITIVITY with internal faults**
- RELAY **STABILITY with through-faults**,

Additionally, stability tests were performed for the case that one set of CTs lies closely to the protection cubicle (5m), while the other one is 180m far away. Moreover one set of CT have reduced knee-point voltage (from 1600V to 500V) The Summarizing, the following tests were carried out.

A. RELAY STABILITY with **through-faults**, for different lead burden
B. RELAY STABILITY with **through-faults**, when one CT saturates earlier
C. RELAY STABILITY with **through-faults**, (cases C+ D together)

The summarized results of the tests are shown in following, structured in tables with exemplary waveforms. The currents mentioned there are internal or external fault short-circuit-currents referred to the fault current at the fault location, respectively. Thereby, the time between the fault inception and relay trip is given in milliseconds.

4.2.1 Sensitivity with internal faults

To check the sensitivity of the dimensioned system (see p. 6.2) several **internal faults** were simulated starting from switchgear rated value of 63 kA and reducing the fault current so that the relay does not trip. The results of the simulations are expressed in Table 4.1.

Table 4.1 Sensitivity with internal faults (N means no trip)

Speed for internal fault scenario with **Uk = 1600 V, Us = 260 V, Im = 20 mA,** Rstab=260 Ohm, Metrosil 1088 Setting Is,set: I >> = 1.00 A (2000 A primary)														
Fault current: Ikint [A]	1400	1600	1800	2000	2200	3000	3200	3400	3600	3800	4000	10000	20000	63000
Ratio: Ikint /Is,set	0.7	0.8	0.9	1	1.1	1.5	1.6	1.7	1.8	1.9	2	5	10	31.5
trip time: trelay[ms]	**N**	**N**	**N**	**N**	**31.5**	**31.5**	**31.5**	**31**	**31**	**30.4**	**30.9**	**30.8**	**29.3**	**30.1**

In the following figures the behavior of the relay can be compared for different internal short-circuit-currents. The currents flowing through the differential branch and its rms value, as calculated by SIGRA, are presented, as well.

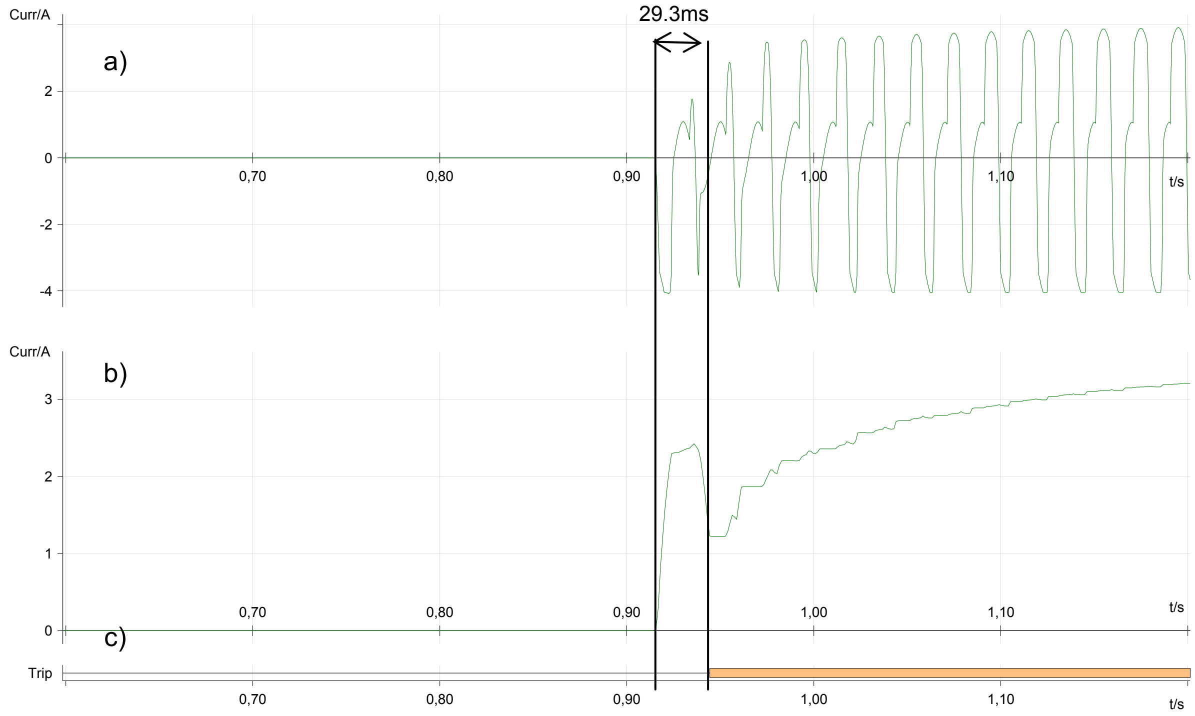

Figure 4.1 Instantaneous current (a) and its rms value (b) flowing through the differential branch by an internal fault current of 20 kA. Relay trip command (c)

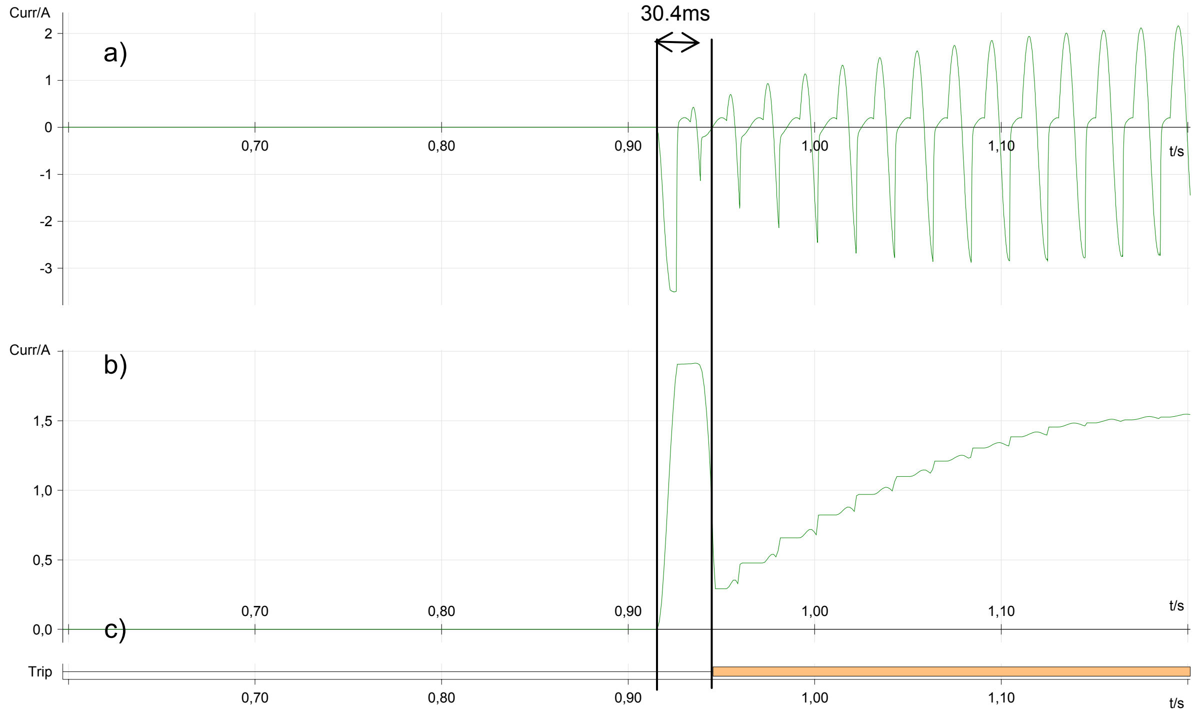

Figure 4.2 Instantaneous current (a) and its rms value (b) flowing through the differential branch by an internal fault current of 3800 A. Relay trip command (c);

4.2.2 Stability with through-faults

To check the stability of the dimensioned system (see p. 6.2) several **external (through-flowing) faults** were simulated starting from the rated current of the bus duct (in this case 2kA) and increasing it up to a short circuit current value of 70 kA. The results of the simulations are expressed in Table 4.2.

Table 4.2 Stability with external faults (N means no trip)

Stability for internal fault scenario with **Uk = 1600 V, Us = 260 V, Im = 20 mA,** Rstab=260 Ohm, Metrosil 1088			
Setting Is,set: I >> = 1.00 A (2000 A primary)			
Fault current: Ikint [A]	2000	63000	70000
Ratio: Ikint /Is,set	1	31.5	35
trip time: trelay[ms]	**N**	**N**	**N**

Additionally, to check the relay stability in non-ideal conditions, **through-faults** were simulated for the following cases:

- **Case A**. Different lead burden (180 m; 5 m):

  RESULTS: Current values till 70 kA were tested with no reaction of the relay.

- **Case B**. Different CTs; The first CT was correctly dimensioned (as in the example), the second one has the knee voltage at 86 V, with the current at knee point voltage being equal to 10 mA:

  RESULTS: Current values till 70 kA were tested with no reaction of the relay.

- **Case C**. Different lead burden (180 m; 5 m) and different CTs; The first CT was correctly dimensioned, the second one has knee voltage at 86 V with the current at knee point voltage being equal to 10 mA (type 1) or 20 mA (type 2):

  RESULTS: Current values till 70 kA were tested. The relay remains stable.

Case A: Stability; different lead burden

The case was tested for different lead burden. The results are summarized in Table 4.3. The currents in the three tables below are through-fault short-circuit-current values referred to the fault current at the fault location.

Table 4.3 Stability with through-faults Stability at different lead burden (N means no trip)

Stability for internal fault scenario with **Uk = 1600 V, Us = 260 V, Im = 20 mA,** Rstab=260 Ohm, Metrosil 1088, **Rwire1=2 Ohm, Rwire1 =0.1 Ohm**			
Setting Is,set: I >> = 1.00 A (2000 A primary)			
Fault current: Ikint [A]	2000	63000	70000
Ratio: Ikint /Is,set	1	31.5	35
trip time: trelay[ms]	**N**	**N**	**N**

Case B: Stability; different CTs

The case was tested for different CT parameters. The first CT was dimensioned as in the basic example (see p. 6.2); the second one has knee voltage reduced to 500 V while the current at knee point voltage being equal to 20 mA. The results are summarized in Table 4.4.

Table 4.4 Stability with through-faults: Stability at different CT' knee point voltage (N means no trip)

Stability for internal fault scenario with **Uk1 = 1600 V, Uk2 = 500 V Us = 260 V, Im = 20 mA,** Rstab=260 Ohm, Metrosil 1088, Rwire=2 Ohm,			
Setting Is,set: I >> = 1.00 A (2000 A primary)			
Fault current: Ikint [A]	2000	63000	70000
Ratio: Ikint /Is,set	1	31.5	35
trip time: trelay[ms]	**N**	**N**	**N**

Case C: Stability; worst case

These tests were carried out for the case that combines different lead burden with different CTs. The parameters of the respective elements being identical to those described in case A and B, respectively. The results are summarized in Table 4.5.

Table 4.5 Stability with through-faults: Stability at different values of different lead burden and different CT's knee point voltage (N means no trip)

Stability for internal fault scenario with **Uk1 = 1600 V, Uk2 = 500 V** Us = 260 V, Im = 20 mA, Rstab=260 Ohm, Metrosil 1088, **Rwire1=2 Ohm, Rwire1 =0.1 Ohm**			
Setting Is,set: I >> = 1.00 A (2000 A primary)			
Fault current: Ikint [A]	2000	63000	70000
Ratio: Ikint /Is,set	1	31.5	35
trip time: trelay[ms]	**N**	**N**	**N**

It can be seen that the relay remained stable for all performed through-faults. Even if high fault currents result in a small current flowing through the differential branch, and thus through the relay input circuits..

4.3 Discussion of test results for Bus duct protection

Sensitivity test of the dimensioned system has verified correct relay performance and calculations as per section 4.1. The estimated sensitivity of slightly above 2000 A (primary) was confirmed in the tests (Table 4.1). For fault currents higher than 10 kA the operating time of the relay remains below 30ms. (Figure 4.1). For smaller short-circuit currents the operating time slightly increases (Figure 4.2) until the desired sensitivity limit is reached (Table 4.1).

Analyzing the results of the stability tests it can be seen that the results are satisfactory (Table 4.2 to Table 4.5). For all test relay stability was maintained also by extremely high theoretical through-fault current values.

5 Conclusions

The tests results verify the correct operation of the 7SJ61 relay applied as high impedance relay. All three I>> inputs are suitable for bus duct protection and the IEE>> input for restricted earth fault protection.

The relay remained stable with through fault and sensitive as per specification with performed tests.

6 Appendices

6.1 Restricted Earth Fault Protection CT Dimensioning - report

A. System Information:

As a exemplary protected object is 400-kV winding of a 500MVA transformer (rated current I_r=722A). Type of protection: Restricted Earth Fault.

- Maximum through fault current for external faults $I_{k,max,thr}$ (typically considered as I_r/uk or calculated as per ESI standard as 16 times rated current I_r of the protected winding)
  = here taken as 16 x 722A = 11.5kA
- Maximum internal fault current $I_{k,max,int}$ (according to the rated short circuit current level of the S/S)
  = here taken as 63kA,
- Minimum internal fault current to be detected $I_{k,min,int}$ = here striven for 15% of the rated current of the protected winding, i.e. ~110 A

B. Current Transformer Information

All CTs used in this type of scheme must have the same turns ratio ($K_n=I_{pn}/I_{sn}$). They should be of high accuracy and low leakage reactance type, as well (IEC Class 5P or IEC Class PX). Here IEC standard Class PX is considered.

- Turns Ratio K_n = 800/1
- Secondary resistance R_{ct} = 2 Ohm
- Knee-point voltage U_{knee} = 360V
- Magnetizing current at knee-point voltage I_{knee} = 30mA
- CT lead loop resistance R_{wire} ~ 2 Ohm (assumed 180m distance between CT and the Relay with 4mm^2 copper wire)

C. Protection Relay Information

- **7SJ612 (MLFB- 7SJ6122-5EB90-1FB0/EE L0S)** digital overcurrent relay with 50 1ph(I >>) and input signals at Q7 and Q8 is used.
- Operating current or current setting range I_{set} = 0.003 A to 1.5 A in steps of 0.001 A.
- Relay burden R_{relay} = 50mΩ

D. CT requirements

DATA OF CT 1 ACCORDING IEC PX:

CT type:	IEC class PX
Transformation ratio:	800 A / 1 A
Kneepoint voltage Uknee:	360 V
Mag. current Iknee at Uknee:	0.03 A
Internal resistance Rct:	2 Ω
Remark:	400-kV Transformer winding

RELAY DATA:

Manufacturer:	SIEMENS	
Type:	7SJ612 (REF)	
Internal burden:	0.05	VA (sensitive earth fault detection input)
Remark:		

CT REQUIREMENTS FOR 7SJ612(REF):

All CTs must have the same transformation ratio. To prevent maloperation of the relay during saturation of the CTs on an external fault, the actual stability voltage U_S must be at least the voltage $U_{S,min}$ produced by the maximum secondary through fault current, flowing through the cable resistance and the CTs' internal resistance:

$$U_s \geq U_{s,\min}$$

where

$$U_{s,\min} = I_{k,\,max,\,thr} \frac{I_{sn}}{I_{pn}} \left(R_{ct} + R_{wire}\right)$$

In addition to this, the kneepoint voltage must be higher than twice the actual stability voltage:

$$U_{knee} \geq 2 \cdot U_s \qquad \text{(Requirement 1)}$$

where :

U_S : actual stability voltage
$U_{S,min}$: minimum stability voltage
U_{knee} : kneepoint voltage of CT
$I_{k,max,thr}$: max. symmetrical short-circuit current for external faults
I_{pn} : CT primary nominal current
I_{sn} : CT secondary nominal current
R_{ct} : internal burden of CT
R_{wire} : cable burden

E. Cable burden

The cable burden is calculated by the single length, the cross section, the specific resistivity for copper and an effective factor for the wire length.

This factor k_{wire} is 2 if the return wire is to be considered.

Length:	l_{wire} = 180 m
Cross section:	a_{wire} = 4 mm^2
Spec. resisitivity (Cu):	ρ_{cu} = 0.022 Ω mm^2/m at 75 °C
Eff. wire length in p.u.:	k_{wire} = 2
$R_{wire} = \frac{k_{wire} \cdot \rho_{Cu} \cdot l_{wire}}{a_{wire}}$	= 1.98 Ω

F. Calculation of stability voltage:

The minimum stability voltage of 7SJ602 (REF) to ensure stability on external faults:

$$U_{s,\min} = I_{k,\,max,\,thr} \frac{I_{sn}}{I_{pn}} \left(R_{ct} + R_{wire}\right) \qquad = 56.838 \text{ V}$$

where:

$U_{s,min}$:	minimum stability voltage	
$I_{k,max,thr}$:	max. symmetrical short-circuit current for external faults	11.5 kA
I_{pn} :	CT primary nominal current	800 A
I_{sn} :	CT secondary nominal current	1 A
R_{ct} :	internal burden of CT	2 Ω
R_{wire} :	cable burden	1,98 Ω

The actual stability voltage U_S should be set to at least $U_{s,min}$.. Therefore the following can be set:

U_S	**= 60 V**	**(Uknee ≥ 2Us)**

G. Calculation of maximum sensitivity:

According to the actual stability voltage and considering that the relay has a variable a.c. current setting on the 1 A tap of 0.003 A to 1.5 A in 0.001 A steps, the maximum primary current sensitivity I_p can be obtained:

$$I_p = \frac{I_{pn}}{I_{sn}} \left(I_{s,\min} + N \cdot I_{knee} \cdot \frac{U_s}{U_{knee}} \right) \qquad = 18.4 \text{ A}$$

where:

Ip :	maximum primary current sensitivity	
$I_{s,min}$:	minimum relay current setting	0.003 A
N :	number of CTs in parallel with relay	4
I_{knee} :	mag. current I_{knee} at U_{knee}	0.03 A
U_S :	actual stability voltage	60 V
U_{knee} :	kneepoint voltage of CT	360 V

Acc. to sensitivity of 2.3 % of nominal primary current In. This corresponds to sensitivity of 2.5 % of nominal current of the object Ir= 722 A.

H. Fault setting calculation:

For a desired decreased sensitivity of 15 % of Ir a corresponding relay current setting can be calculated:

$$I_s = I_{p,des} \cdot \frac{I_{sn}}{I_{pn}} - N \cdot I_{knee} \cdot \frac{U_s}{U_{knee}} \qquad = 0.115\ \text{A}$$

where:

I_S :	secondary relay current setting to reach the desired sensitivity	
N :	number of CTs in parallel with relay	4
I_{knee} :	mag. Current I_{knee} at U_{knee}	0.03 A
Ip,des :	desired current sensitivity of object	108.3 A
Us :	actual stability voltage	60 V
U_{knee} :	kneepoint voltage of CT	360 V

Considering the setting range of the relay on the IEE 1A tap of 0.003A to 1.5A in 0.001A steps the pickup current can be chosen: $I_{S,set}$ = 0.15 A

Therefore:

2703	**high-set inst. pickup IEE>>**	**= 0.15A**
2704	**high-set inst. time delay t>>**	**= 0s**

I. Effective fault sensitivity calculation:

The effective sensitivity on the secondary side can be calculated as follows:

$$I_{eff\_sens} = \left(I_{s,set} + N \cdot I_{knee} \cdot \frac{U_s}{U_{knee}} \right) \qquad = 0.17\ \text{A}$$

where:

I_{eff_sens}:	effective current sensitivity (secondary)	
$I_{S,set}$:	relay current setting	0.15 A
N:	number of CTs in parallel with relay	4
I_{knee}:	mag. current I_{knee} at U_{knee}	0.03 A
U_S :	actual stability voltage	60 V
U_{knee} :	kneepoint voltage of CT	360 V

This corresponds to a sensitivity of 136 A on primary side or 17 % In. This corresponds to a sensitivity of 18.8 % of rated current of the protected object Ir= 722 A.

J. Calculation of stabilizing resistor:

The proper value of stabilizing resistor R_{stab} is required to ensure stability during through-faults and is calculated by using the actual stability voltage = 60 V and the pickup current setting of the relay $I_{s,set}$ = 0.15 A (please refer to above).

$$R_{stab} = \frac{U_s}{I_{s,set}} - R_{relay} \qquad = 400\ \Omega$$

where the relay burden: R_{relay} = 0.05 Ω was neglected

The stabilizing resistor R_{stab} can be chosen with a necessary minimum power rating P_{stab} of:

$$P_{stab} = 4\frac{U_s^{\ 2}}{R_{stab}} \qquad = 36\ \mathrm{W}$$

Therefore, take typical adjustable resistor and adjust:

R_{stab} = 400 Ω, with power rating of 40 W

K. Calculation of max. voltage at relay terminal:

The relay should normally be applied with an external varistor which should be connected across the relay and stabilizing resistor input terminals. The varistor limits the voltage across the terminals under maximum internal fault conditions. The theoretical voltage which may occur at the terminals is:

$$U_{k,\max int} = I_{k,\max int}\frac{I_{sn}}{I_{pn}}\left(R_{ct} + R_{wire} + R_{stab}\right) \qquad = 31813\ \mathrm{V}$$

$$U_{max,relay} = 2\sqrt{2U_{knee}(U_{k,max,int} - U_{knee})} \qquad = 9518\ \mathrm{V}$$

where:

$I_{k,\ max,\ int}$:	max. symmetrical short-circuit current of internal faults	= 63 kA

A varistor is required if:

$U_{max,relay} \geq$ 1500 V

In this case:

$U_{max,relay} \geq$ 9518 V

Therefore:

Varistor	**= required**

E.g. a METROSIL of type 600A/S1/Spec.1088 can be used.

6.2 Bus duct Protection CT Dimensioning - report

A. System Information:

As a exemplary protected object is bus duct with rated current of the following feeder of I_r=2000A.. Type of protection: High Impedance Busbar protection.

- Maximum through fault current for external faults $I_{k,max,thr}$
  Rated short circuit withstand current of the busbar
  = here taken as 63kA
- Maximum internal fault current $I_{k,max,int}$ (according to the rated short circuit withstand current of busbar)
  = here taken as 63kA,
- Minimum internal fault current to be detected $I_{k,min,int}$ = here striven for 100% of the rated current of the feeder 2000 A 8practicalyy setting of 1.2 ..1.3 times the rated current is recommended. Here, for simplicity setting 1.0 is used.

B. Current Transformer Information

All CTs used in this type of scheme must have the same turns ratio ($K_n=I_{pn}/I_{sn}$). They should be of high accuracy and low leakage reactance type, as well. Here IEC standard Class PX is considered.

- Turns Ratio K_n = 2000/1
- Secondary resistance R_{ct} = 6 Ohm
- Knee-point voltage U_{knee} = 1600V
- Magnetizing current at knee-point voltage I_{knee} = 20mA
- CT lead loop resistance R_{wire} ~ 2 Ohm (assumed 180m distance between CT and the Relay with 4mm^2 copper wire)

C. Protection Relay Information

- **7SJ612 (MLFB- 7SJ6122-5EB90-1FB0/EE L0S)** digital overcurrent relay with 50/51 (I>, I >>) and input signals at Q1 to Q6 are used.
- Operating current or current setting range I_{set} = 0.1 A to 35 A in steps of 0.01 A.
- Relay burden R_{relay} = 50mΩ

D. CT requirements

DATA OF CT 1 ACCORDING IEC PX:

CT type:	IEC class PX	
Transformation ratio:	2000 A / 1 A	
Kneepoint voltage Uknee:	1600	V
Mag. current Iknee at Uknee:	0.02	A
Internal resistance Rct:	6	Ω
Remark:	Bus duct	

RELAY DATA:

Manufacturer:	SIEMENS	
Type:	7SJ612 (BB)	
Internal burden:	0.05	VA
Remark:		

CT REQUIREMENTS FOR 7SJ612(REF):

All CTs must have the same transformation ratio. To prevent maloperation of the relay during saturation of the CTs on an external fault, the actual stability voltage U_S must be at least the voltage $U_{S,min}$ produced by the maximum secondary through fault current, flowing through the cable resistance and the CTs' internal resistance:

$$U_s \geq U_{s,\min}$$

where

$$U_{s,\min} = I_{k,\,max,\,thr} \frac{I_{sn}}{I_{pn}} \left(R_{ct} + R_{wire} \right)$$

In addition to this, the kneepoint voltage must be higher than twice the actual stability voltage:

$$U_{knee} \geq 2 \cdot U_s \qquad \text{(Requirement 1)}$$

where :

U_S : actual stability voltage
$U_{S,min}$: minimum stability voltage
U_{knee} : kneepoint voltage of CT
$I_{k,max,thr}$: max. symmetrical short-circuit current for external faults
I_{pn} : CT primary nominal current
I_{sn} : CT secondary nominal current
R_{ct} : internal burden of CT
R_{wire} : cable burden

E. Cable burden

The cable burden is calculated by the single length, the cross section, the specific resistivity for copper and an effective factor for the wire length.

This factor k_{wire} is 2 if the return wire is to be considered.

Length: $l_{wire} = 180$ m
Cross section: $a_{wire} = 4$ mm^2
Spec. resisitivity (Cu): $\rho_{cu} = 0.022\ \Omega$ mm^2/m at 75 °C
Eff. wire length in p.u.: $k_{wire} = 2$

$$R_{wire} = \frac{k_{wire} \cdot \rho_{Cu} \cdot l_{wire}}{a_{wire}} \qquad = 1.98\ \Omega$$

F. Calculation of stability voltage:

The minimum stability voltage of 7SJ602 (REF) to ensure stability on external faults:

$$U_{s,\min} = I_{k,\,max,\,thr} \frac{I_{sn}}{I_{pn}} \left(R_{ct} + R_{wire} \right) \qquad = 250.55\ \text{V}$$

where:

$U_{s,min}$:	minimum stability voltage	
$I_{k,max,thr}$:	max. symmetrical short-circuit current for external faults	63 kA
I_{pn} :	CT primary nominal current	2000 A
I_{sn} :	CT secondary nominal current	1 A
R_{ct} :	internal burden of CT	6 Ω
R_{wire} :	cable burden	1.98 Ω

The actual stability voltage U_S should be set to at least $U_{s,min}$.. Therefore the following can be set:

U_S	**= 260 V**	**(Uknee ≥ 2Us)**

G. Calculation of maximum sensitivity:

According to the actual stability voltage and considering that the relay has a variable a.c. current setting on the 1 A tap of 0.1 A to 35 A in 0.01 A steps, the maximum primary current sensitivity I_p can be obtained:

$$I_p = \frac{I_{pn}}{I_{sn}} \left(I_{s,\min} + N \cdot I_{knee} \cdot \frac{U_s}{U_{knee}} \right) \qquad = 213\ \text{A}$$

where:

Ip :	maximum primary current sensitivity	
$I_{s,min}$:	minimum relay current setting	0.1 A
N :	number of CTs in parallel with relay	2
I_{knee} :	mag. current I_{knee} at U_{knee}	0.02 A
U_S :	actual stability voltage	260 V
U_{knee} :	kneepoint voltage of CT	1600 V

Acc. to sensitivity of 10.6 % of nominal primary current In. This corresponds to sensitivity of 10.6 % of nominal current of the object Ir= 2000 A.

H. Fault setting calculation:

For a desired decreased sensitivity of 100 % of Ir a corresponding relay current setting can be calculated:

$$I_s = I_{p,des} \cdot \frac{I_{sn}}{I_{pn}} - N \cdot I_{knee} \cdot \frac{U_s}{U_{knee}} \qquad = 0.994 \text{ A}$$

where:

I_S :	secondary relay current setting to reach the desired sensitivity	
N :	number of CTs in parallel with relay	2
I_{knee} :	mag. Current I_{knee} at U_{knee}	0.02 A
Ip,des :	desired current sensitivity of object	2000 A
Us :	actual stability voltage	260 V
U_{knee} :	kneepoint voltage of CT	1600 V

Considering the setting range of the relay on the 1A tap of 0.1A to 35A in 0.01A steps the pickup current can be chosen: $I_{S,set}$ = 1.0 A

Therefore:

1202	**high-set inst. pickup I>>**	**= 1.0A**
1203	**high-set inst. time delay t>>**	**= 0s**

I. Effective fault sensitivity calculation:

The effective sensitivity on the secondary side can be calculated as follows:

$$I_{eff\_sens} = \left(I_{s,set} + N \cdot I_{knee} \cdot \frac{U_s}{U_{knee}} \right) \qquad = 1.01 \text{ A}$$

where:

I_{eff_sens}:	effective current sensitivity (secondary)	
$I_{S,set}$:	relay current setting	1.0 A
N:	number of CTs in parallel with relay	2
I_{knee}:	mag. current I_{knee} at U_{knee}	0.02 A
U_S :	actual stability voltage	260 V
U_{knee} :	kneepoint voltage of CT	1600 V

This corresponds to a sensitivity of 2013 A on primary side or 100.6 % In. This corresponds to a sensitivity of 100.6 % % of rated current of the protected object Ir= 2000 A.

J. Calculation of stabilizing resistor:

The proper value of stabilizing resistor R_{stab} is required to ensure stability during through-faults and is calculated by using the actual stability voltage = 260 V and the pickup current setting of the relay $I_{s,set}$ = 1.0 A (please refer to above).

$$R_{stab} = \frac{U_s}{I_{s,set}} - R_{relay} \qquad = 260\ \Omega$$

where the relay burden: R_{relay} = 0.05 Ω was neglected.

The stabilizing resistor R_{stab} can be chosen with a necessary minimum power rating P_{stab} of:

$$P_{stab} = 4\frac{U_s}{R_{stab}}^{2} \qquad = 1040.4\ \text{W}$$

Therefore, take typical adjustable resistor and adjust:

R_{stab} = 260 Ω, with power rating of 1000 W

K. Calculation of max. voltage at relay terminal:

The relay should normally be applied with an external varistor which should be connected across the relay and stabilizing resistor input terminals. The varistor limits the voltage across the terminals under maximum internal fault conditions. The theoretical voltage which may occur at the terminals is:

$$U_{k,\max int} = I_{k,max,int} \frac{I_{sn}}{I_{pn}} \left(R_{ct} + R_{wire} + R_{stab} \right) \qquad = 8441\ \text{V}$$

$$U_{max,relay} = 2\sqrt{2U_{knee}(U_{k,max,int} - U_{knee})} \qquad = 9357\ \text{V}$$

where:

$I_{k,\ max,\ int}$:	max. symmetrical short-circuit current of internal faults	= 63 kA

A varistor is required if:

$U_{max,relay} \geq$ 1500 V

In this case:

$U_{max,relay} \geq$ 9357 V

Therefore:

Varistor	**= required**

E.g. a METROSIL of type 600A/S1/Spec.1088 can be used.

7 Annex: Input Filter Tests

This annex to the report describes the verification of the input filter performance of the 7SJ61 device that will be used for the high impedance application. The tests were carried on to bring the evidence that the input circuit is tuned to fundamental frequency. This part of the report describes the test setup and discusses the results. The tests were carried on the same device as described in report, i.e.

Test object: **SIEMENS relay type 7SJ61, Order No. 7SJ6122-5EB90-1FB0/EE L0S**

Thereby, tests were performed on the three standard current inputs (Q1-Q6) and on the sensitive current input (Q7-Q8), respectively.

7.1 Test set up

In order to bring the evidence that the metering input circuit is filtered with a filter that is tuned to the current fundamental component of 50Hz (or 60Hz) and insensitive to harmonics and DC, the variable frequency source was simulated at the Real Time Digital Simulator (RTDS) Laboratory. Thereby, the source of fundamental harmonic and the source of the different non-fundamental frequencies were connected together within Real Time Digital Simulator (RTDS). Then, the signal generated by RTD was sent to the amplifier that generated the test signals to the relay. Finally, the trip signal from the relay was gathered by the data acquisition system. Such a setup allows studying the behavior of the input circuit of the relay in a comfortable way (Figure 7.1).

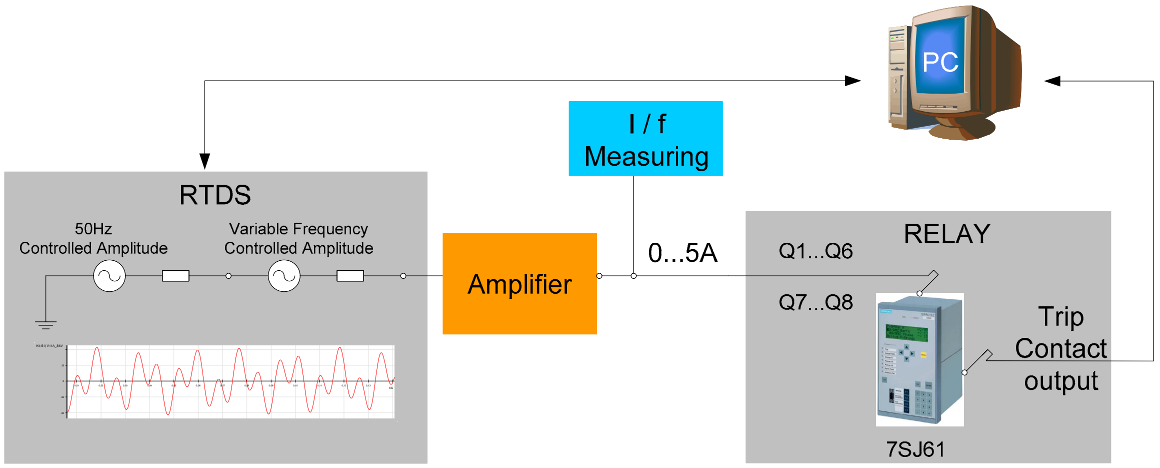

Figure 7.1 Test set-up for the relay input filter characteristic tests

7.2 Test procedure and results

In order to test the input filter characteristic the following theoretical background must be mentioned at first.

7.2.1 Transfer function of the input circuit of the overcurrent relay 7SJ61

For the 50-1,50N-1,51,51N Protection function of the over current protection relays 7SJ61-64 the effective values of the fundamental component of the measured quantity is calculated as shown in Figure 7.2 :

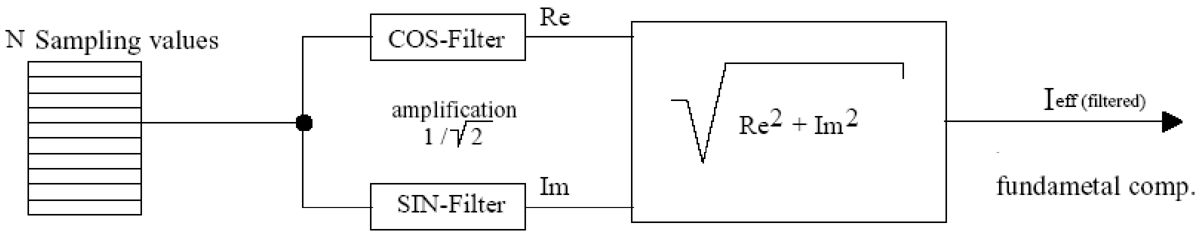

Figure 7.2 Calculation of the fundamental component of the measured quantity within 7SJ61-relay

The COS-Filter and SIN-Filter shown in Figure 7.2 are tuned to the fundamental frequency (50Hz or 60Hz). In other words the calculation of the threshold values for the DMT/IDMT protection function utilizes discrete Fourier transformation (DFT). Thereby, FIR-Filter (Finite Impulse Response) is used as Cosinus filter for the real component and Sinus filter for the imaginary component of the measuring value.

The fundamental component of the measuring quantity (e.g. current) is calculated then using this FIR-Filter. The length of the filter equals the length of the period. With 20 samples per period (sampling frequency of 1kHz) the filter order equals N=20.

Therefore it can be written:

$$\mathrm{Re}(I_n) = \sum_{k=0}^{N-1} a_k i_{n-k} \qquad a_k = \frac{2}{N}\cos(k\frac{2\pi}{N} + \frac{\pi}{N})$$

$$\mathrm{Im}(I_n) = \sum_{k=0}^{N-1} b_k i_{n-k} \qquad b_k = \frac{2}{N}\sin(k\frac{2\pi}{N} + \frac{\pi}{N}) \qquad \text{with } N = 20$$

The amplitude of the fundamental component of the signal at the time point n equals to:

$$B_n = \sqrt{\mathrm{Re}^2(I_n) + \mathrm{Im}^2(I_n)}$$

For the root mean square value it is then:

$$\mathrm{Eff}_n = \frac{1}{\sqrt{2}} \cdot B_n$$

Within a protection relay the root calculation is avoided due to the relatively long computation time. Instead of the root operation by the threshold monitoring the threshold values are then squared.

The theoretical transfer function (frequency response) of such Fourier filter is shown in Figure 7.3.

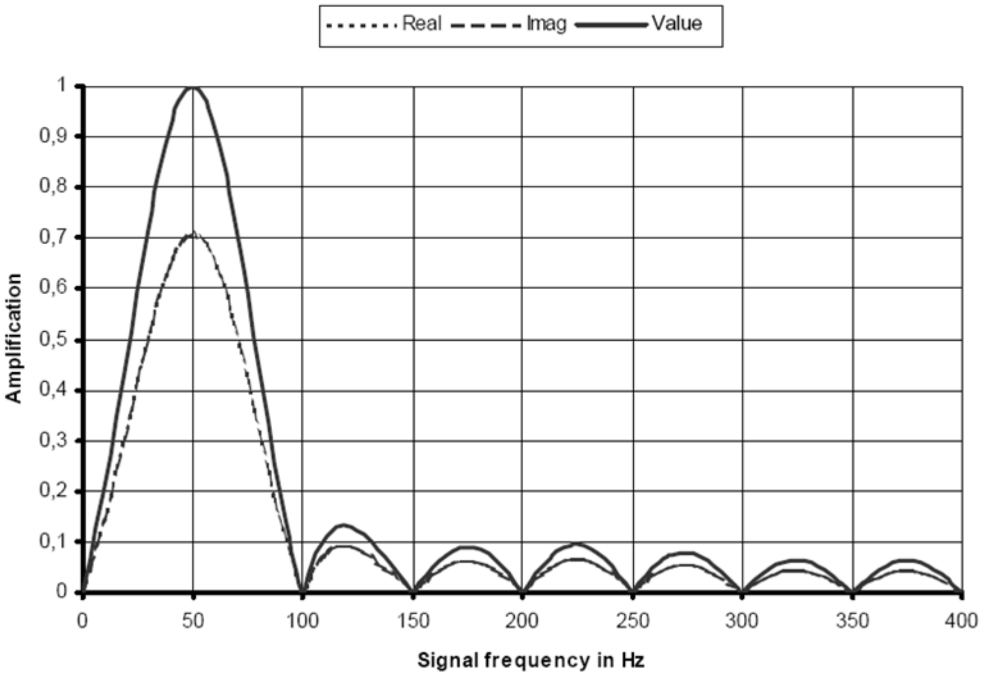

Figure 7.3 Relay input filter characteristic

7.2.2 Input filter testing procedure

For the tests of the relay input filtering characteristic the following has been fixed:

1. The setting of the relay was fixed at 0.2A for both phase and sensitive current inputs in order to obtain comparable results and to have enough amplification margin when applying other frequencies.
2. The CT setting describing the CT-Ratio was fixed at 1000/1 to obtain straightforward and easy readability of the measured values at the relay display.
3. The fundamental frequency was fixed at 50Hz.
4. Then, the rms value of the fundamental component (50Hz) of the current was obtained at which the relay trips.
5. After that, 90% of this value was fixed for the fundamental component source.
6. For different frequencies (up to 400Hz in variable steps 5Hz-10Hz) the amplitude of the current was increased up to the point that the relay trips.
7. This value of the non-fundamental frequency component was inversed and then plotted vs. frequency. In such way the measured input filter characteristic (transfer function) was obtained.

7.2.3 Test results of the standard current input (Q1-Q6)

The setting of the relevant parameter was made as follows:

1202	**high-set inst. pickup I>>**	**= 0.2A**
1203	**high-set inst. time delay t>>**	**= 0s**

The trip on fundamental component was achieved at 0.195A.

According to the test procedure, as described in p. 7.2.1 the following figure (Figure 7.4) presents the results of the input filter characteristic.

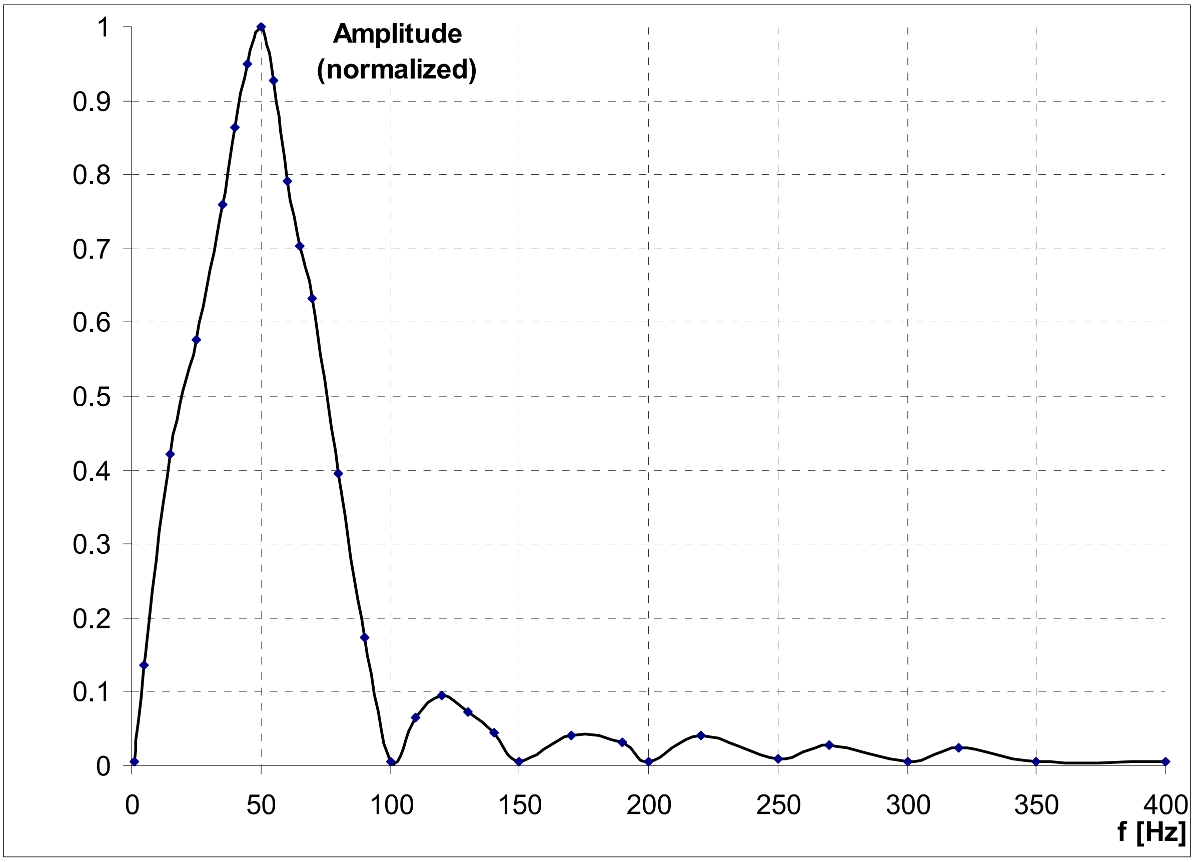

Figure 7.4 Measured filter characteristic for phase current input (Q1-Q6)

It can be clearly seen that the current measuring input of the 7SJ61 relay is tuned to the fundamental frequency and insensitive to harmonics (i.e. 100Hz, 150Hz, 200Hz, 250Hz, ..), as theoretically expected (see Figure 7.3). The measured characteristic of the input filter corresponds well to the theoretical one.

7.2.4 Test results of the sensitive current input (Q7-Q8)

The setting of the relevant parameter was made as follows:

2703	**high-set inst. pickup IEE>>**	**= 0.2A**
2704	**high-set inst. time delay t>>**	**= 0s**

The trip on fundamental component was achieved at 0.1995A.

According to the test procedure, as described in p. 7.2.1 the following figure (Figure 7.5) presents the results of the input filter characteristic.

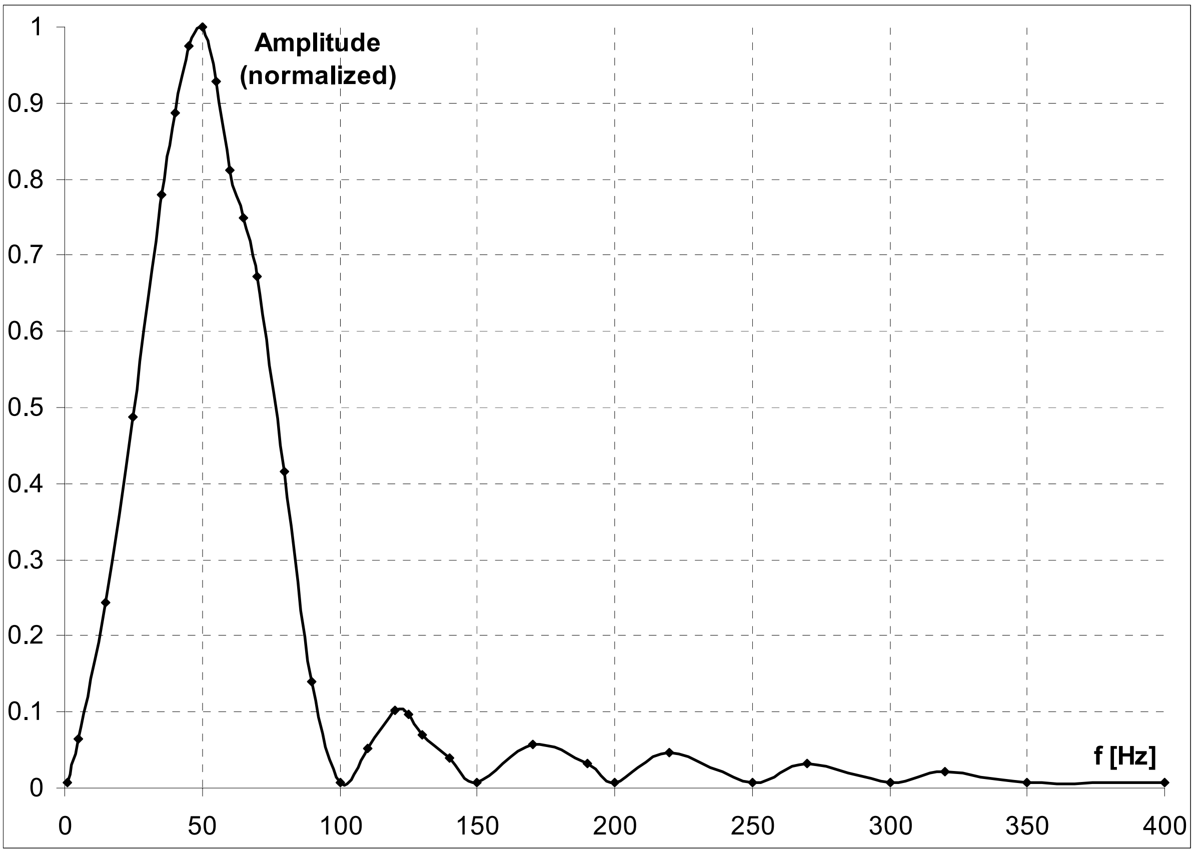

Figure 7.5 Measured filter characteristic for sensitive current input (Q7-Q8)

It can be clearly seen that the current measuring input (sensitive) of the 7SJ61 relay is tuned to the fundamental frequency as well and insensitive to harmonics (i.e. 100Hz, 150Hz, 200Hz, 250Hz, ..), as theoretically expected (see Figure 7.3). The measured characteristic of the input filter corresponds well to the theoretical one, too.

7.3 Discussion of test results and conclusion

It can be stated that the tests described in this chapter have verified that the relay input is tuned to fundamental component of the current and insensitive to harmonics and DC.

Summarizing, the tests results have verified the correct operation of the 7SJ61 relay applied as high impedance relay. All three I>> inputs are suitable for bus duct protection and the IEE>> input for restricted earth fault protection.

The relay remained stable with through fault and sensitive as per specification with performed tests. The filter characteristic is tuned to the fundamental component