

Reyrolle
Protection
Devices

High Impedance Restricted Earth Fault Protection

Technical Guidance Notes

Answers for energy

SIEMENS

Issue History

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Nomenclature

β =	Metrosil constant
C =	Metrosil constant
I_F =	Maximum through fault current corresponding to the rated stability limit (primary Amps)
I_{Fint} =	Maximum prospective internal fault current (primary Amps)
I_{MAG} =	Secondary magnetising (exciting) current of current transformer at V_s volts.
I_{NLR} =	Non-linear resistor (Metrosil) current.
I_{rated} =	Rated current
I_s =	Relay setting current
I_{shunt} =	Shunt setting resistor current
NER =	Neutral earthing resistor
NLR =	Non-linear resistor (Metrosil)
P_{1SEC} =	1 second power rating
P_{CONT} =	Continuous power rating
POC =	Primary operate current (fault setting)
POC_{prov} =	Provisional primary operate current (fault setting)
R_{CT} =	Resistance of CT secondary winding.
R_L =	Resistance of CT connection leads
R_{shunt} =	Resistance of shunt setting resistor
R_{stab} =	Resistance of stabilising resistor
T =	Turns ratio of all current transformers (Primary turns / Secondary turns)
V_{Fint} =	Maximum secondary internal fault voltage
V_k =	Kneepoint voltage of the CT
V_s =	Relay circuit setting voltage
V_{sprov} =	Provisional relay circuit setting voltage
Z_{pu} =	Per unit impedance

1. Introduction

High impedance restricted earth fault relays can be used to detect earth faults on transformer windings, reactor windings or the stator windings of machines.

Typical transformer restricted earth fault protection arrangements are shown in section 2.1. The term 'Balanced Earth Fault' is sometimes used where the REF relay is connected to the three line CTs only see Figure 2-1.

This document outlines general principles of restricted earth fault protection and includes worked examples for establishing the relay settings and specification of external components i.e. resistors and non-linear resistors (where required).

Although operation of relays with current settings and those with voltage settings is fundamentally the same there is a slightly different approach to the settings calculations procedures. The use of the 7SR (current operated) and 7PG23 (voltage operated) is considered.

2. Theory of REF schemes

2.1 Scheme Arrangements

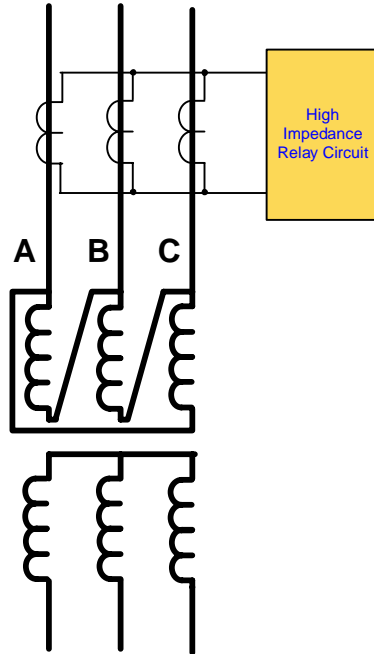


Figure 2-1 AC Connections – Restricted (Balanced) Earth Fault) 3 Wire, 3 CTs

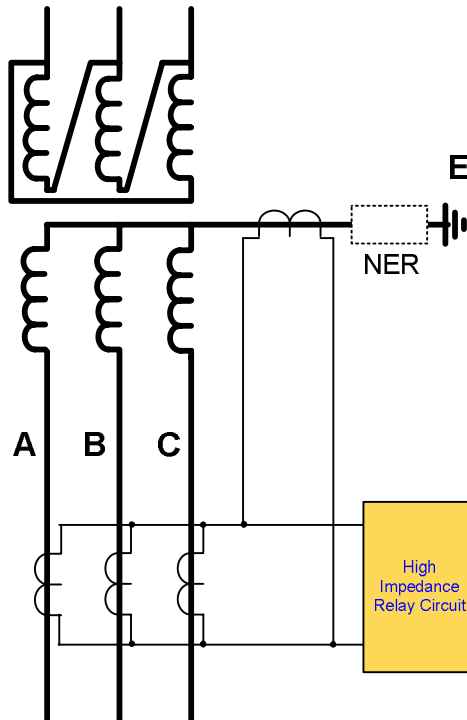


Figure 2-2 AC Connections – REF: 3 Wire + Earth, 4 CTs

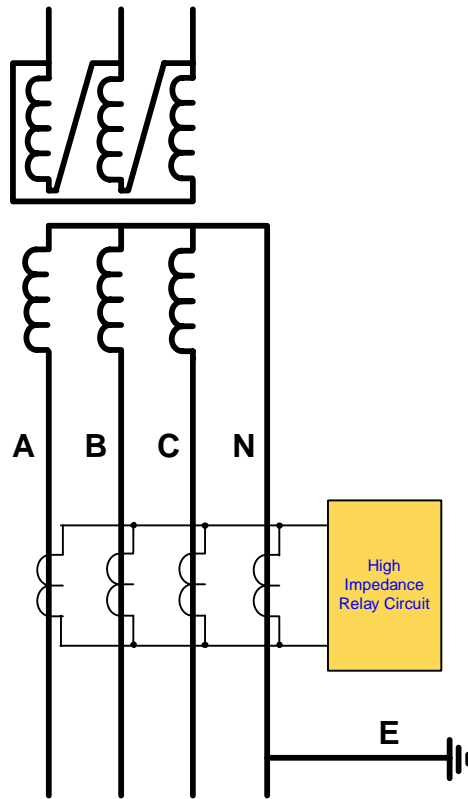


Figure 2-3 AC Connections – REF: 4 Wire + Earth, 4 CTs

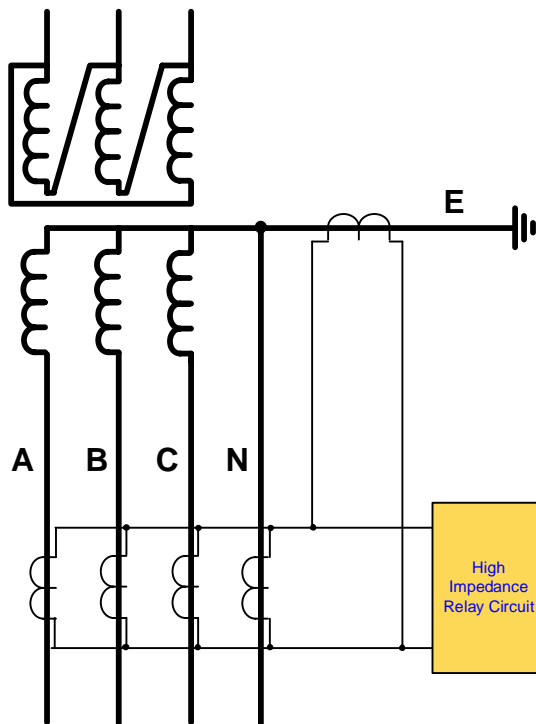


Figure 2-4 AC Connections – REF: 4 Wire + Earth, 5 CTs

2.2 Basic Principles

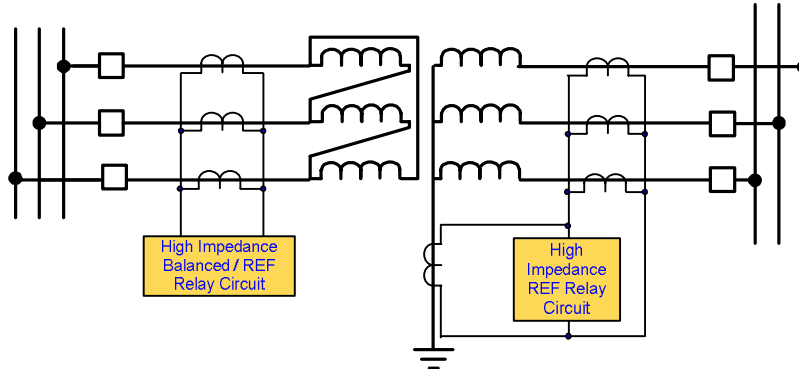


Figure 2-5 AC Connections – Balanced/Restricted Earth Fault Protection

The limit of the Restricted Earth Fault (REF) protection zone is defined by the location of the CTs.

The relay is connected to the current transformers in such a way as to measure the difference in earth fault current 'entering' the protected zone with that 'leaving' the protected zone. Where no internal earth fault occurs and the CTs transform perfectly the differential current is zero.

High impedance differential protection must:-

- 1) Guarantee stability for all load and through fault conditions. Note that due to transient CT errors (e.g. CT saturation) the CTs may not transform perfectly.

Stability of the protection is achieved by using a relay operating voltage that is greater than the maximum voltage which can appear across the relay under given through fault conditions.

- 2) Guarantee operation for internal fault conditions. The minimum primary operate current is defined as the 'fault setting'.

The relay fault setting is calculated taking into account: the required operate level for in-zone earth faults.

A non-linear resistor is wired into the relay circuit to limit circuit over-voltages.

2.2.1 Stability Requirement

All CTs must have the same ratio.

The use of class PX CTs (IEC60044) is recommended and ensures steady state CT errors are minimised. A class PX CT has a defined secondary excitation characteristic and secondary winding resistance, this is sufficient to allow an assessment of its transient performance. Transient CT errors are caused by CT saturation e.g. due to high currents flowing at times of through faults. Where CT saturation conditions are different in each CT this will cause differential current to flow in the CT secondary circuit wiring. The highest level of differential current will flow when one set of CTs is fully saturated, providing zero output and all other CTs transform normally.

When fully saturated the CT secondary provides no current and it behaves as a resistance in the secondary circuit. Differential current in the secondary circuit will flow either through this 'resistance' or through the relay. A 'stabilising' resistance is added in series with the relay input to ensure that the operate voltage at the current setting is greater than the maximum voltage which can appear across the element/stabilising resistor during the maximum assigned through fault current. It is assumed that any earthing resistor can become short-circuit.

The maximum assigned through fault current for transformer REF protection is typically 16 x rated current of the protected winding. Other values used for assigning a value of through fault current for all plant types are:

- Impedance of the protected plant e.g. $I_F = 1/Z_{pu} \times I_{rated}$,
or
- Switchgear short circuit rating

The maximum voltage that can appear across the relay circuit can be determined by a simple calculation which makes the following assumptions:

One current transformer is fully saturated making its excitation current negligible.

The remaining current transformers maintain their ratio.

The resistance of the secondary winding of the saturated CT together with the leads connecting it to the relay circuit terminals constitute the only burden in parallel with the relay.

The minimum required relay operate voltage setting (V_s) is given by:

$$V_s \geq I_F (R_{CT} + R_L) \times T \quad (1)$$

To ensure high speed relay operation the relay circuit operating voltage should be selected in accordance with the stability requirement above (equation 1), also, the operate voltage should not exceed 0.5 x CT knee point voltage (V_k).

$$V_s \leq \frac{V_k}{2} \quad (2)$$

2.2.2 Operation Requirement

For internal faults the relay will operate at the calculated 'Voltage Setting' V_s . This operating voltage will also be applied across the CT secondary windings of all the CT secondaries connected in parallel with the relay. This voltage will drive a magnetising current in each of the CT secondary windings and this must be added to the relay operate current when calculating the operate current of the high impedance protection scheme.

$$\text{In general: P.O.C.} = (I_s + I_{NLR} + \sum I_{MAG})/T \quad (3)$$

2.2.3 Relay Types

2.2.3.1 7SR Relay

The REF function of the 7SR series relays is a current operated device typically with a setting range of 0.005 to $2.0 \times I_n$ ($I_n = 1A$ or $5A$). Typical installations require the addition of an external series stabilising resistor (R_{stab}) and a voltage limiting resistor (Metrosil).

The relay burden need not be considered as it is effectively negligible relative to the burden of the stabilising resistor. The setting (operate) voltage (V_s) across the Relay and Stabilising Resistor at the Relay operating current (I_s):

$$V_s = I_s \times R_{stab} \tag{4}$$

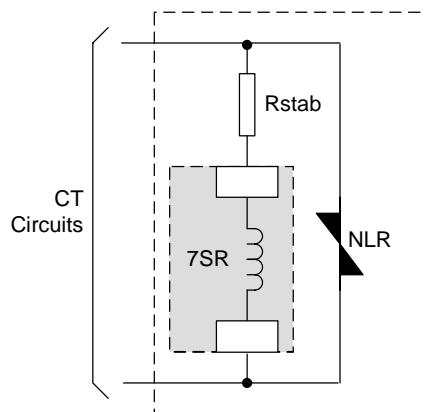


Figure 2-6 Typical Connections for 7SR Relay REF protection

2.2.3.2 7PG23 (5B3) Relay

The 7PG23 Restricted Earth fault protection relay is a voltage operated device with a setting range of 15V to 270V. The 7PG23 has an integral 75mm Metrosil with a constant 'C' value = 1000 and thermal rating of 8kJ. Where a thermal rating of greater than 8kJ is required an external 150mm Metrosil can be connected in parallel. The 'C' value of this additional Metrosil is chosen <1000 to ensure that current flows through the external device.

The relay has an operate current (I_s) of 20mA. The operate current can be increased where necessary by the addition of a shunt setting resistor (R_{shunt}). The total operate current at setting V_s is calculated from:

$$I_{total} = I_s + I_{shunt}$$

$$I_{total} = 0.02 + V_s/R_{shunt} \tag{5}$$

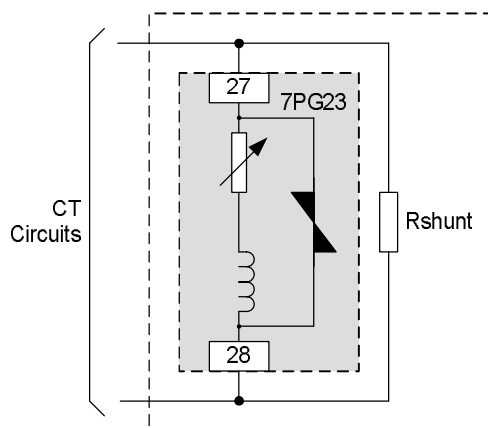


Figure 2-7 Typical Connections for 7PG23 Relay REF protection

2.2.4 Voltage Limiting Non-Linear Resistors (Metrosils)

When the relay circuit operates for an internal fault the circuit breakers are opened and the flow of fault current ceases.

Where a CB fails to trip then fault current will flow in the high impedance circuit until the fault is cleared by the operation of CB failure or back up protection. The fault clearance time for failed CB conditions should be considered when specifying the thermal rating of the relay circuit components.

Alternatively the high impedance circuit can be arranged to short circuit the external components after operation.

Non-linear resistors are connected in parallel with the relay circuit to limit the peak voltage developed across the high impedance components during internal faults to a 'safe' level below 3kV peak. Where a Metrosil is not connected in circuit the peak voltage can be calculated from:

$$V_{PK} = 2 \times \sqrt{2 \times V_K \times ((I_{Fint} \times R_{stab}) - V_K)} \quad (6)$$

Notwithstanding the above calculation it is recommended that a Metrosil is always fitted in the high impedance relay circuit.

The use of non-linear resistors manufactured by Metrosil is recommended. The operate characteristic is defined by:-

$$\text{Voltage characteristic: } V = C \cdot I^\beta \quad \text{For dc or instantaneous values.} \quad (7)$$

$$I_{rms} = 0.52 \left(\frac{V_{rms} \sqrt{2}}{C} \right)^\beta \quad \text{For applied sinusoidal voltages} \quad (8)$$

$$V_{peak} = 1.09C(I_{rms})^\beta \quad \text{For applied sinusoidal currents} \quad (9)$$

Where: C and β are Metrosil constants

Where an external Metrosil is used a single pole 7XG14 can be specified. Metrosils can be specified with a diameter of 75mm or 150mm and 'C' values of 450, 900 or 1000. Metrosils of diameter 75mm have a thermal rating of 8kJ. Where a higher thermal rating is required Metrosils of 150mm diameter with a thermal rating of 33kJ should be used.

The 7SG23 relay has an integral 75mm Metrosil with a constant 'C' value = 1000.

All Metrosils have a β value = 0.22 to 0.25

The chosen Metrosil 'C' value must;

- 1) Ensure negligible current flows through the Metrosil at relay operate voltage (V_s), and,
- 2) Limit over-voltages for operational and safety reasons i.e. $1.09C(I_{Fint}^\beta) < 3kV$

A 'C' value of 450 can be used where the relay operate voltage is less than 100V, a 'C' value of 1000 is recommended for settings above 100V. These values have a negligible effect on the relay circuit operate current.

Metrosil short time power rating must;

Be sufficient to dissipate the heat created by the flow of maximum secondary internal fault current. The Metrosil is chosen so that it can withstand I_{Fint} for the maximum fault clearance time. For a failed circuit breaker condition the back up protection clearance time must be considered – typically a one second rating is sufficient.

$$P_{1SEC} \geq \frac{4}{\pi} \times I_F \times T \times V_K \quad (10)$$

2.2.5 Resistors

When the relay circuit operates for an internal fault the circuit breakers are opened and the flow of fault current ceases. Where a CB fails to trip then fault current will flow in the high impedance circuit until the fault is cleared by the operation of CB fail or back up protection. The fault clearance time for failed CB conditions should be considered when specifying the thermal rating of the relay circuit components.

Alternatively the high impedance circuit can be arranged to short circuit the external components after operation.

The resistor continuous power rating must:

Be sufficient for continuous operation at the circuit operate voltage (Vs) and/or operate setting:

$$P_{\text{CONT}} \geq I^2 \times R \quad \text{or} \quad P_{\text{CONT}} \geq V_s^2/R$$

Short time rated to withstand I_{Fint} for the maximum fault clearance time. For a failed circuit breaker condition the back up protection clearance time is considered – typically a one second rating is sufficient.

$$P_{1\text{SEC}} \geq \frac{V_{\text{Fint}}^2}{R} \quad \text{Where: } V_{\text{Fint}} \geq \sqrt[4]{(V_K^3 \times R \times I_{\text{Fint}})} \times 1.3 \quad (11)$$

Where I_{Fint} is not known, the breaking capacity current of the Circuit Breaker can be used.

As stated in section 2.2.3 the 7SR relays have a stabilising resistor connected in series with the REF current input. 7PG23 relays use a shunt connected resistor to increase the operate current where required.

3. 7SR Relays: Example Calculations

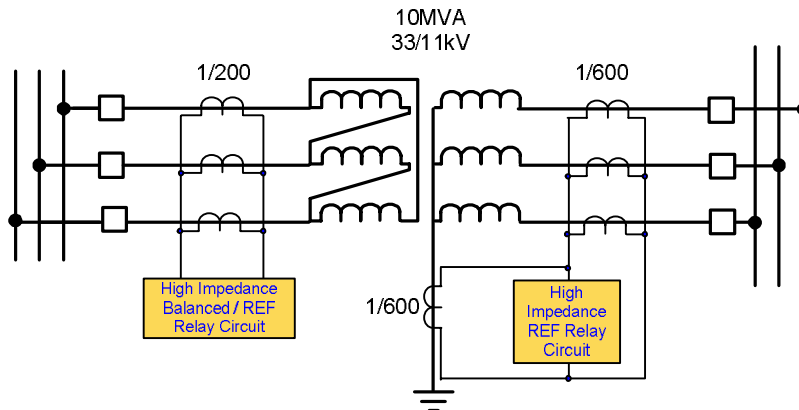


Figure 3-1 AC Connections – Balanced/Restricted Earth Fault Protection

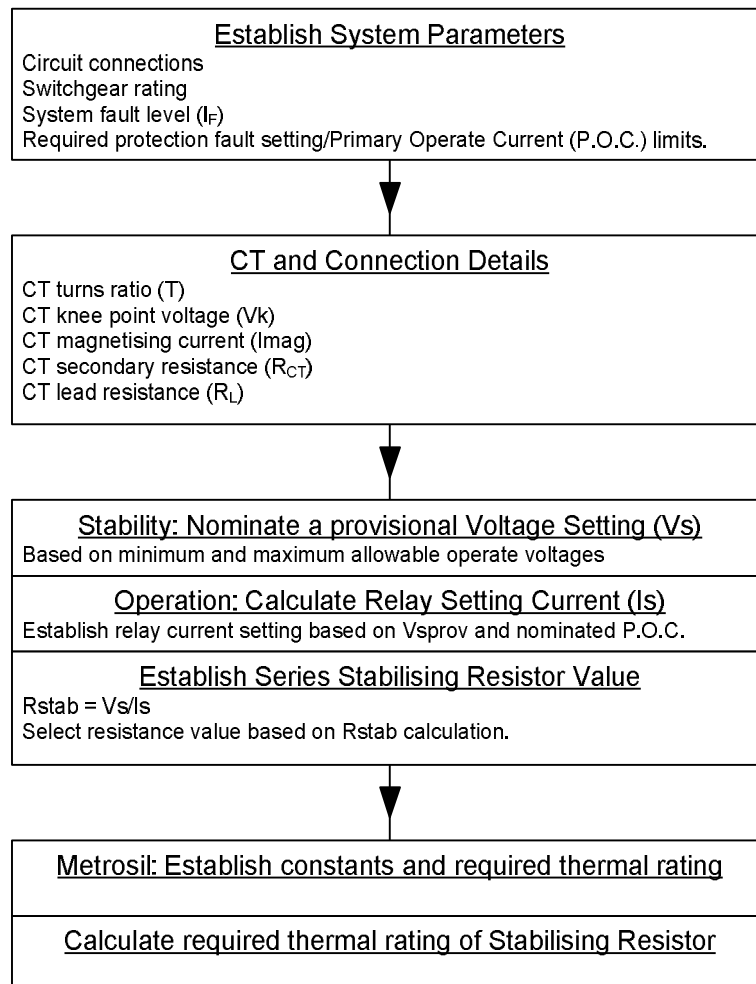


Figure 3-2 Calculation Procedure – 7SR Series Relay

3.1 7SR Relay: Balanced EF Protection - 3 Wire System

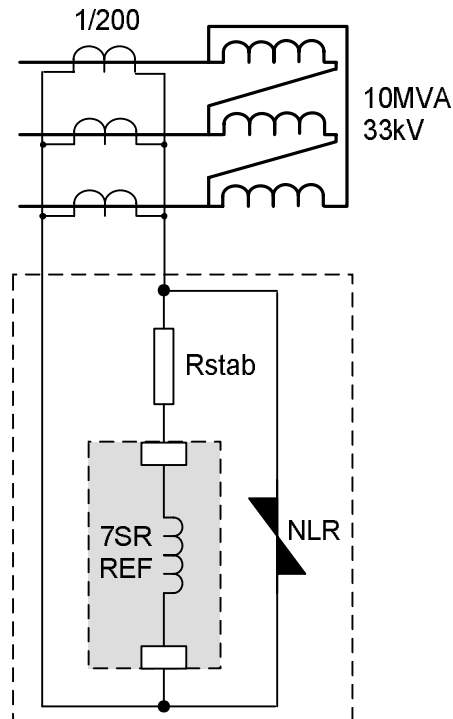


Figure 3-3 Example System – Balanced Earth Fault Protection

Line CT (LCT) and Connection Details

Turns ratio (T)	1/200
Voltage Knee Point (V_K)	120V
Magnetising Current (I_{mag}) @ V_K	30mA
CT secondary resistance (R_{CT})	2.5 Ohms
CT lead loop resistance (R_L)	0.15 Ohms max.

Settings Requirements

Rated current = $VA / (\sqrt{3} \times V_L)$

Rated current = $10 \times 10^6 / (\sqrt{3} \times 33000) = 175A$

Assigned through fault current (rated stability limit) = $16 \times$ rated current = 2.8kA. See section 2.2.1

Required Primary Operate Current

Typically 10 – 25% of protected winding rated current (I_{rated}), or as specified by the user.

POCprov (10 – 25% of I_{rated}) = 17.5 – 43.8A. Say 20A. (0.1A secondary). See section 2.2.2

Calculation of Required Stability Voltage Limits

The assigned through fault current is 2800A.

With reference to section 2.2.1

$$V_s \geq I_F (R_{CT} + R_L) \times T = \frac{2800}{200} \times (2.5 + 0.15) = 37.1V$$

$$V_s \leq \frac{V_k}{2} = \frac{120}{2} = 60V$$

$$\therefore 37.1 < V_s < 60$$

Calculation of Stabilising Resistor Value

The required relay setting (Is) can be calculated from:

$$POC = (3(I_{MAGLCT}) + I_s) / T$$

$$\text{Therefore: } I_s = POC \times T - 3(I_{MAGLCT}) = 20/200 - 3(I_{MAGLCT})$$

$$I_s = 0.1 - 3(I_{MAGLCT})$$

Say $V_{sprov} = 50V$ (from requirement $37.1 < V_s < 60$)

From CT magnetising curve (see appendix) : At 50V $I_{MAGLCT} = 8mA$

$$I_s = 0.1 - 3(0.008) = 0.076A \text{ say } 0.08A$$

$$R_{stab} = 50/0.08 = 625 \text{ Ohms (Say } 600 \text{ Ohms giving } V_s = 600 \times 0.08 = 48V)$$

Metrosil Specification

With reference to section 2.2.4

'C' Value

$V_s = 48V$ (i.e. $< 100V$) so a 'C' value of 450 is chosen

Short Time Power Rating

From equation 10:

$$P_{1SEC} \geq \frac{4}{\pi} \times I_F \times T \times V_k$$

$$P_{1SEC} \geq \frac{4}{\pi} \times 2800 \times \frac{1}{200} \times 120 = 2139W$$

For values $< 8kW/s$ a 75mm Metrosil is used.

Stabilising Resistor Specification

With reference to section 2.2.5

Continuous Power Rating

$$P_{CONT} \geq I_s^2 \times R_{stab}$$

$$P_{CONT} \geq 0.08^2 \times 600$$

$$P_{CONT} \geq 3.8W$$

Short Time Power Rating

$$P_{1SEC} \geq \frac{V_{Fint}^2}{R_{stab}} \quad \text{Where: } V_{Fint} \geq \sqrt[4]{(V_K^3 \times R_{stab} \times I_{Fint})} \times 1.3$$

$$I_{Fint} = \frac{2800}{200} = 14A$$

$$V_{Fint} \geq \sqrt[4]{(V_K^3 \times R_{stab} \times I_{Fint})} \times 1.3$$

$$V_{Fint} \geq \sqrt[4]{(120^3 \times 600 \times 14 \times 1.3)} = 451V$$

$$P_{1SEC} \geq \frac{451^2}{600} = 339W$$

Summary of Relay Settings and Components

REF Element = Enabled

REF Setting (Is) = 0.08A

REF Delay = 0s

Rstab = 600 Ohms, 30W continuous (typical manufacturers data)

Metrosil: diameter = 75mm, 'C' value = 450

POC (Fault Setting) = (3(I_{MAGLCT}) + Is) / T

POC = (3(0.008) + 0.08) x 200 = 20.8A

3.2 7SR Relay: Restricted Earth Fault Protection - 3 Wire + Earth System

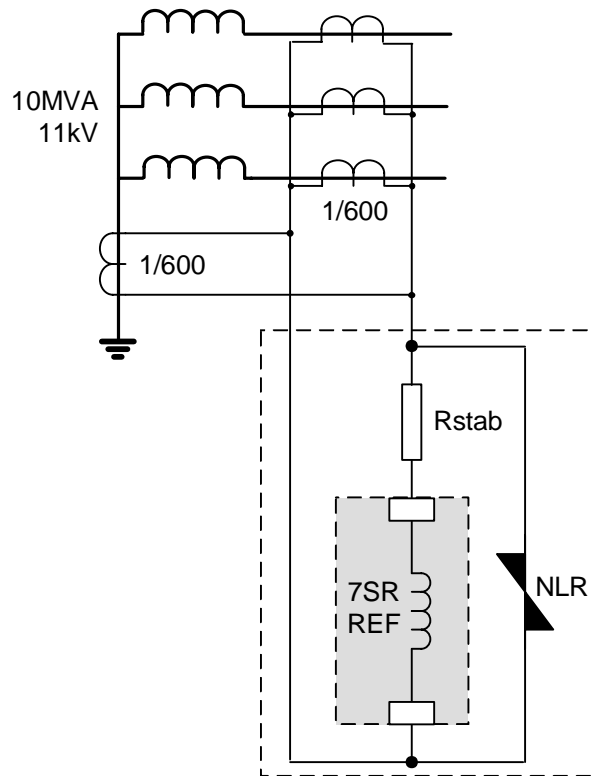


Figure 3-4 Example System – 3 Wire + Earth REF Protection

CT and Connection Details

	Line CT (LCT)	Earth CT (ECT)
Turns ratio (T)	1/600	1/600
Voltage Knee Point (V_K)	360V	300V
Magnetising Current (I_{mag}) @ V_K	30mA	40mA
CT secondary resistance (R_{CT})	7.5Ω	6.0Ω
CT lead loop resistance (R_L)	0.15Ω	0.2Ω

Settings Requirements

Rated current = $VA / (\sqrt{3} \times V_L)$

Rated current = $10 \times 10^6 / (\sqrt{3} \times 11000) = 525A$

Assigned through fault current (rated stability limit) = $16 \times$ rated current = 8.4kA. See section 2.2.1

Required Primary Operate Current (Fault Setting)

10 – 25% of protected winding rated current, or as specified by the user.

POCprov (10 – 25% of I_{rated}) = 52.5 - 131A. Say 60A. (0.1A secondary). See section 2.2.2

Calculation of Required Stability Voltage Limits

The assigned through fault current is 8400A.

With reference to section 2.2.1

$$V_s \geq I_F (R_{CT} + R_L) \times T$$

$$V_s \geq \frac{8400}{600} \times (7.5 + 0.15) = 107.1V$$

$$V_s \geq \frac{8400}{600} \times (6 + 0.2) = 86.8V$$

$$V_s \leq \frac{V_{KMIN}}{2} = \frac{300}{2} = 150V$$

∴ 107.1 < Vs < 150

Calculation of Stabilising Resistor Value

The required relay setting Is can be calculated from:

$$POC = (3(I_{MAGLCT}) + I_{MAGECT} + I_s) / T$$

Therefore: $I_s = POC \times T - (3(I_{MAGLCT}) + I_{MAGECT}) = 60/600 - (3(I_{MAGLCT}) + I_{MAGECT})$

$$= 0.1 - (3(I_{MAGLCT}) + I_{MAGECT})$$

Say Vsprov = 120V (from requirement 107.1 < Vs < 150)

From CT magnetising curve: At 120V $I_{MAGLCT} = 7mA$ and $I_{MAGECT} = 9mA$

$$I_s = 0.1 - (3(0.007) + 0.009) = 0.07A$$

$$R_{stab} = V_s / I_s = 120 / 0.07 = 1714 \text{ Ohms (Say 1800 Ohms giving } V_s = 1800 \times 0.07 = 126V)$$

Metrosil Specification

With reference to section 2.2.4

'C' Value

$V_s = 126V$ (i.e. > 100V) so a 'C' value of 1000 is chosen

Short Time Power Rating

From equation 10:

$$P_{1SEC} \geq \frac{4}{\pi} \times I_F \times T \times V_k$$

$$P_{1SEC} \geq \frac{4}{\pi} \times 8400 \times \frac{1}{600} \times 360 = 6417W$$

For values < 8kW/s a 75mm Metrosil is used.

Stabilising Resistor Specification

With reference to section 2.2.5

Continuous Power Rating

$$P_{CONT} \geq I_s^2 \times R_{stab}$$

$$P_{CONT} \geq 0.07^2 \times 1800$$

$$P_{CONT} \geq 8.82W$$

Short Time Power Rating

$$P_{1SEC} \geq \frac{V_{Fint}^2}{R_{stab}} \quad \text{Where: } V_{Fint} \geq \sqrt[4]{(V_k^3 \times R_{stab} \times I_{Fint})} \times 1.3$$

$$I_{Fint} = \frac{8400}{600} = 14A$$

$$V_{Fint} \geq \sqrt[4]{(V_k^3 \times R_{stab} \times I_{Fint})} \times 1.3$$

$$V_{Fint} \geq \sqrt[4]{(360^3 \times 1800 \times 14 \times 1.3)} = 1354V$$

$$P_{1SEC} \geq \frac{1354^2}{1800} = 1018W$$

Summary of Relay Settings and Components

REF Element = Enabled

REF Setting (Is) = 0.07A

REF Delay = 0s

Rstab = 1800 Ohms, 45W continuous (typical manufacturers data)

Metrosil: diameter = 75mm, 'C' value = 1000

POC (Fault Setting) = (3(I_{MAGLCT}) + I_{MAGECT} + Is) / T

POC = (3(0.007) + 0.009 + 0.07) x 600 = 60A

3.3 7SR Relay: Restricted Earth Fault Protection - 4 Wire 4CT

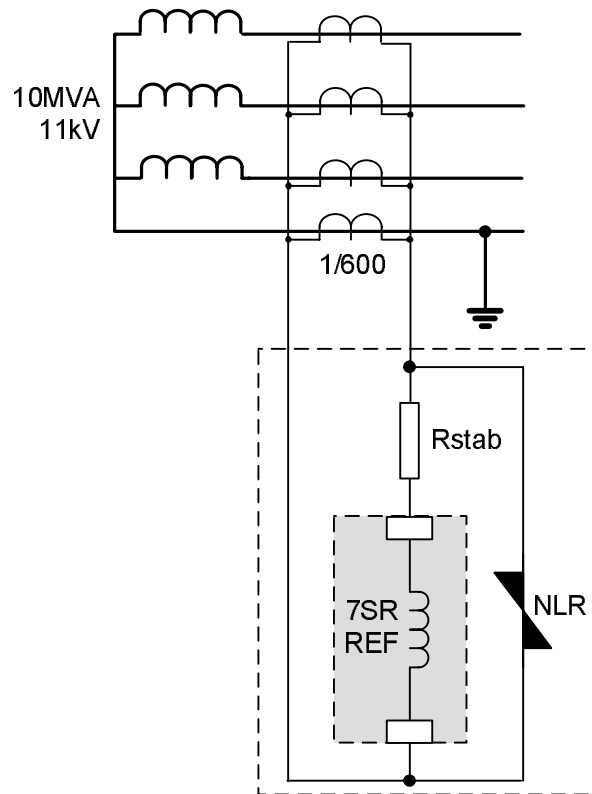


Figure 3-5 Example System – 4 Wire REF Protection

CT and Connection Details

	Line CT (LCT)	Neutral CT (NCT)
Turns ratio (T)	1/600	1/600
Voltage Knee Point (V_K)	360V	450V
Magnetising Current (I_{mag}) @ V_K	30mA	20mA
CT secondary resistance (R_{CT})	7.5Ω	4.5Ω
CT lead loop resistance (R_L)	0.15Ω	0.5Ω

Settings Requirements

Rated current = $VA / (\sqrt{3} \times V_L)$

Rated current = $10 \times 10^6 / (\sqrt{3} \times 11000) = 525A$

Assigned through fault current (rated stability limit) = $16 \times$ rated current = 8.4kA. See section 2.2.1

Required Primary Operate Current (Fault Setting)

10 – 25% of protected winding rated current, or as specified by the user.

POCprov (10 – 25% of Irated) = 52.5 - 131A. Say 60A. (0.1A secondary). See section 2.2.2

Calculation of Required Stability Voltage Limits

The assigned through fault current is 8400A.

With reference to section 2.2.1

$$V_s \geq I_F(R_{CT} + R_L) \times T$$

$$V_s \geq \frac{8400}{600} \times (7.5 + 0.15) = 107.1V$$

$$V_s \geq \frac{8400}{600} \times (4.5 + 0.5) = 70V$$

$$V_s \leq \frac{V_{KMIN}}{2} = \frac{360}{2} = 180V$$

$\therefore 107.1 < V_s < 180$

Calculation of Stabilising Resistor Value

The required relay setting (Is) can be calculated from:

$$POC = 3(I_{MAGLCT}) + I_{MAGNCT} + I_s / T$$

Therefore: $I_s = POC \times T - (3(I_{MAGLCT}) + I_{MAGNCT}) = 60/600 - (3(I_{MAGLCT}) + I_{MAGNCT})$

$$= 0.1 - (3(I_{MAGLCT}) + I_{MAGNCT})$$

Say $V_{sprov} = 120V$ (from requirement $107.1 < V_s < 180$)

From CT magnetising curve: At 120V $I_{MAGLCT} = 7mA$ and $I_{MAGNCT} = 4mA$

$$I_s = 0.1 - (3(0.007) + 0.004) = 0.075A$$

$$R_{stab} = V_s/I_s = 120/0.075 = 1600 \text{ Ohms}$$

Metrosil Specification

With reference to section 2.2.4

'C' Value

$V_s = 120V$ (i.e. $> 100V$) so a 'C' value of 1000 is chosen

Short Time Power Rating

From equation 10:

$$P_{1SEC} \geq \frac{4}{\pi} \times I_F \times T \times V_K$$

$$P_{1SEC} \geq \frac{4}{\pi} \times 8400 \times \frac{1}{600} \times 450 = 8kW$$

For values $< 8kW/s$ a 75mm Metrosil is used.

Stabilising Resistor Specification

With reference to section 2.2.5

Continuous Power Rating

$$P_{CONT} \geq I_s^2 \times R_{stab}$$

$$P_{CONT} \geq 0.075^2 \times 1600$$

$$P_{CONT} \geq 9W$$

Short Time Power Rating

$$P_{1SEC} \geq \frac{V_{Fint}^2}{R_{stab}} \quad \text{Where: } V_{Fint} \geq \sqrt[4]{(V_k^3 \times R_{stab} \times I_{Fint})} \times 1.3$$

$$I_{Fint} = \frac{8400}{600} = 14A$$

$$V_{Fint} \geq \sqrt[4]{(V_k^3 \times R_{stab} \times I_{Fint})} \times 1.3$$

$$V_{Fint} \geq \sqrt[4]{(450^3 \times 1600 \times 14 \times 1.3)} = 1554V$$

$$P_{1SEC} \geq \frac{1554^2}{1600} = 1509W$$

Summary of Relay Settings and Components

REF Element = Enabled

REF Setting (Is) = 0.075A

REF Delay = 0s

Rstab = 1600 Ohms, 60W continuous (typical manufacturers data)

Metrosil: diameter = 75mm, 'C' value = 1000

POC (Fault Setting) = (3(I_{MAGLCT}) + I_{MAGNCT} + Is) / T

POC = (3(0.007) + 0.004 + .075) x 600 = 60A

3.4 7SR Relay: Restricted Earth Fault Protection - 4 Wire 5CT

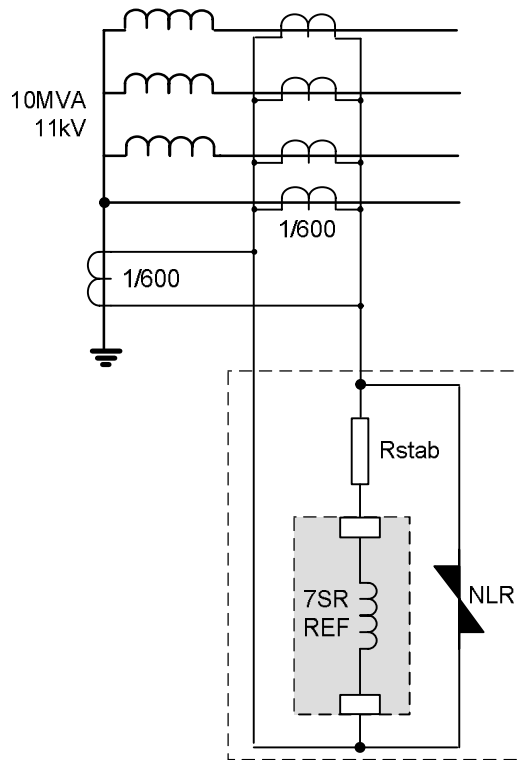


Figure 3-6 Example System – 4 Wire + Earth REF Protection

CT and Connection Details

	Line CT (LCT)	Neutral CT (NCT)	Earth CT (ECT)
Turns ratio (T)	1/600	1/600	1/600
Voltage Knee Point (V_K)	360V	450V	300V
Magnetising Current (I_{mag}) @ V_K	30mA	20mA	40mA
CT secondary resistance (R_{CT})	7.5Ω	4.5Ω	6.0Ω
CT lead loop resistance (R_L)	0.15Ω	0.5Ω	0.2Ω

Settings Requirements

Rated current = $VA / (\sqrt{3} \times V_L)$

Rated current = $10 \times 10^6 / (\sqrt{3} \times 11000) = 525A$

Assigned through fault current (rated stability limit) = $16 \times$ rated current = 8.4kA. See section 2.2.1

Required Primary Operate Current (Fault Setting)

10 – 25% of protected winding rated current, or as specified by the user.

POCprov (10 – 25% of Irated) = 52.5 - 131A. Say 60A. (0.1A secondary). See section 2.2.2

Calculation of Required Stability Voltage Limits

The assigned through fault current is 8400A.

With reference to section 2.2.1

$$V_s \geq I_F(R_{CT} + R_L) \times T$$

$$V_s \geq \frac{8400}{600} \times (7.5 + 0.15) = 107.1V$$

$$V_s \geq \frac{8400}{600} \times (6 + 0.2) = 86.6V$$

$$V_s \geq \frac{8400}{600} \times (4.5 + 0.5) = 70V$$

$$V_s \leq \frac{V_{KMIN}}{2} = \frac{300}{2} = 150V$$

∴ 107.1 < Vs < 150V

Calculation of Stabilising Resistor Value

The required relay setting Is can be calculated from:

$$POC = (3(I_{MAGLCT}) + I_{MAGNCT} + I_{MAGECT} + I_s) / T$$

$$I_s = POC \times T - (3(I_{MAGLCT}) + I_{MAGNCT} + I_{MAGECT}) = 60/600 - (3(I_{MAGLCT}) + I_{MAGNCT} + I_{MAGECT})$$

$$= 0.1 - (3(I_{MAGLCT}) + I_{MAGNCT} + I_{MAGECT})$$

Say Vsprov = 120V (from requirement 107.1 < Vs < 180)

From CT magnetising curve: At 120V I_{MAGLCT} = 7mA , I_{MAGNCT} = 4mA and I_{MAGECT} = 9mA

$$I_s = 0.1 - (3(0.007) + 0.004 + 0.009) = 0.066A \text{ say } 0.065A$$

$$R_{stab} = V_s/I_s = 120/0.065 = 1846 \text{ Ohms (Say } 1800 \text{ Ohms giving } V_s = 1800 \times 0.065 = 117V)$$

Metrosil Specification

'C' Value

Vs = 117V (i.e. > 100V) so a 'C' value of 1000 is chosen

Short Time Power Rating

Using the empirical formula

$$P_{1SEC} \geq \frac{4}{\pi} \times I_F \times T \times V_K$$

$$P_{1SEC} \geq \frac{4}{\pi} \times 8400 \times \frac{1}{600} \times 450 = 8kW$$

For values < 8kW/s a 75mm Metrosil is used.

Stabilising Resistor Specification

Continuous Power Rating

$$P_{CONT} \geq I_s^2 \times R_{stab}$$

$$P_{CONT} \geq 0.065^2 \times 1800$$

$$P_{CONT} \geq 7.6W$$

Short Time Power Rating

$$P_{1SEC} \geq \frac{V_{Fint}^2}{R_{stab}} \quad \text{Where: } V_{Fint} \geq \sqrt[4]{(V_K^3 \times R_{stab} \times I_{Fint})} \times 1.3$$

$$I_{Fint} = \frac{8400}{600} = 14A$$

$$V_{Fint} \geq \sqrt[4]{(V_K^3 \times R_{stab} \times I_{Fint})} \times 1.3$$

$$V_{Fint} \geq \sqrt[4]{450^3 \times 1800 \times 14} \times 1.3 = 1600V$$

$$P_{1SEC} \geq \frac{1600^2}{1800} = 1422W$$

Summary of Relay Settings and Components

REF Element = Enabled

REF Setting = 0.065A

REF Delay = 0s

Rstab = 1800 Ohms, 60W continuous (typical manufacturers data)

Metrosil: diameter = 75mm, 'C' value = 1000

POC (Fault Setting) = (3(I_{MAGLCT}) + I_{MAGNCT} + I_{MAGECT} + I_s) / T

POC = (3(0.007) + 0.004 + 0.009 + 0.065) x 600 = 59.4A

4. 7PG23 (5B3) Relay: Example Calculations

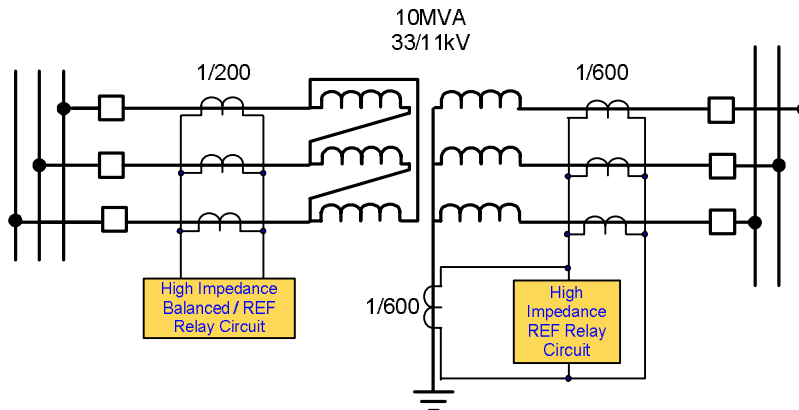


Figure 4-1 AC Connections – Balanced/Restricted Earth Fault Protection

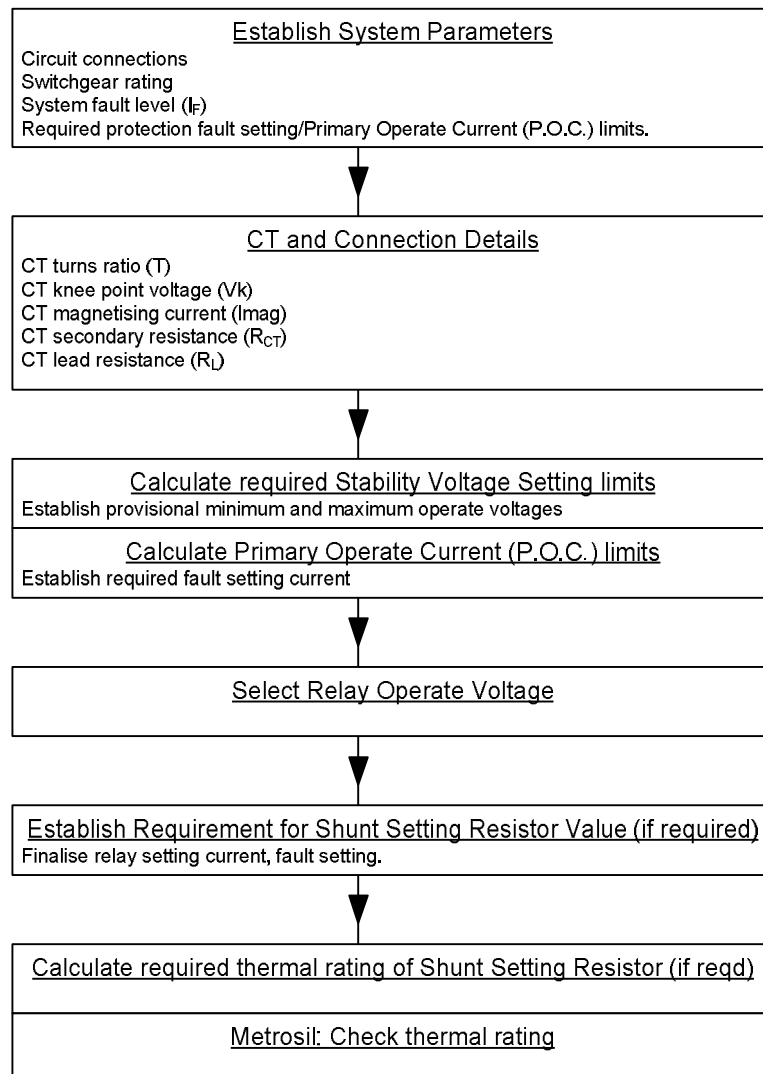


Figure 4-2 Calculation Procedure – 7PG23 (5B3) Series Relay

4.1 7PG23 Relay: Balanced EF Protection - 3 Wire System

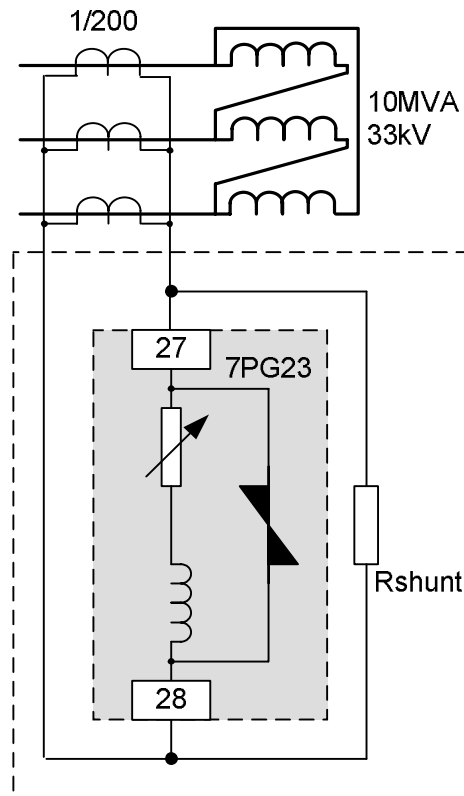


Figure 4-3 Example System – Balanced Earth Fault Protection

Line CT (LCT) and Connection Details

Turns ratio (T)	1/200
Voltage Knee Point (V_K)	120V
Magnetising Current (I_{mag}) @ V_K	30mA
CT secondary resistance (R_{CT})	2.5 Ohms
CT lead loop resistance (R_L)	0.15 Ohms max.

Settings Requirements

$$\text{Rated current} = VA / (\sqrt{3} \times V_L)$$

$$\text{Rated current} = 10 \times 10^6 / (\sqrt{3} \times 33000) = 175A$$

Assigned through fault current (rated stability limit) = 16 x rated current = 2.8kA. See section 2.2.1

Required Primary Operate Current

Typically 10 – 25% of protected winding rated current (I_{rated}), or as specified by the user.

POCprov (10 – 25% of I_{rated}) = 17.5 – 43.8A. Say 20A. (0.1A secondary). See section 2.2.2

Calculation of Required Stability Voltage Limits

The assigned through fault current is 2800A.

With reference to section 2.2.1

$$V_s \geq I_F(R_{CT} + R_L) \times T = \frac{2800}{200} \times (2.5 + 0.15) = 37.1V$$

$$V_s \leq \frac{V_k}{2} = \frac{120}{2} = 60V$$

$$\therefore 37.1 < V_s < 60$$

Calculation of Shunt Setting Resistor Value

The required for the value of operate current to flow through the shunt setting resistor (Rstab) can be calculated from:

$$POC = (3(I_{MAGLCT}) + I_s + I_{shunt}) / T$$

$$I_{shunt} = POC \times T - (3(I_{MAGLCT}) + I_s)$$

$$= 0.1 - (3(I_{MAGLCT}) + 0.02)$$

Say Vsprov = 50V (from requirement 37.1 < Vs < 60)

From CT magnetising curve (see appendix) : At 50V I_{MAGLCT} = 8mA

$$I_{shunt} = 0.1 - (3(0.008) + 0.02) = 0.056A$$

$$R_{shunt} = V_s / I_{shunt} = 50 / 0.056 = 892 \text{ Ohms (Say 820 Ohms giving } I_{shunt} = 50 / 820 = 0.061A)$$

Metrosil Specification

Short Time Power Rating

Using the empirical formula

$$P_{1SEC} \geq \frac{4}{\pi} \times I_F \times T \times V_k$$

$$P_{1SEC} \geq \frac{4}{\pi} \times 2800 \times \frac{1}{200} \times 120 = 2139W$$

For values < 8kW/s the integral 75mm Metrosil is suitably rated.

Shunt Resistor Specification

With reference to section 2.2.5

Continuous Power Rating

$$P_{CONT} \geq V_s^2 / R_{shunt}$$

$$P_{CONT} \geq 50^2 / 820$$

$$P_{CONT} \geq 3.0W$$

Short Time Power Rating

$$P_{1SEC} \geq \frac{V_{Fint}^2}{R_{stab}} \quad \text{Where: } V_{Fint} \geq \sqrt[4]{(V_K^3 \times R_{shunt} \times I_{Fint})} \times 1.3$$

$$I_{Fint} = \frac{2800}{200} = 14A$$

$$V_{Fint} \geq \sqrt[4]{(V_K^3 \times R_{shunt} \times I_{Fint})} \times 1.3$$

$$V_{Fint} \geq \sqrt[4]{(120^3 \times 820 \times 14 \times 1.3)} = 488V$$

$$P_{1SEC} \geq \frac{488^2}{820} = 290W$$

Summary of Relay Settings and Components

$$V_s = 50V$$

$$R_{shunt} = 820 \text{ Ohms, } 20W \text{ continuous (typical manufacturers data)}$$

Additional external Metrosil – not required.

$$POC \text{ (Fault Setting)} = (3(I_{MAGLCT}) + I_s + I_{shunt}) / T$$

$$POC = (3(0.008) + 0.02 + 0.061) \times 200 = 21A$$

4.2 7PG23 Relay: Restricted Earth Fault Protection - 3 Wire + Earth System

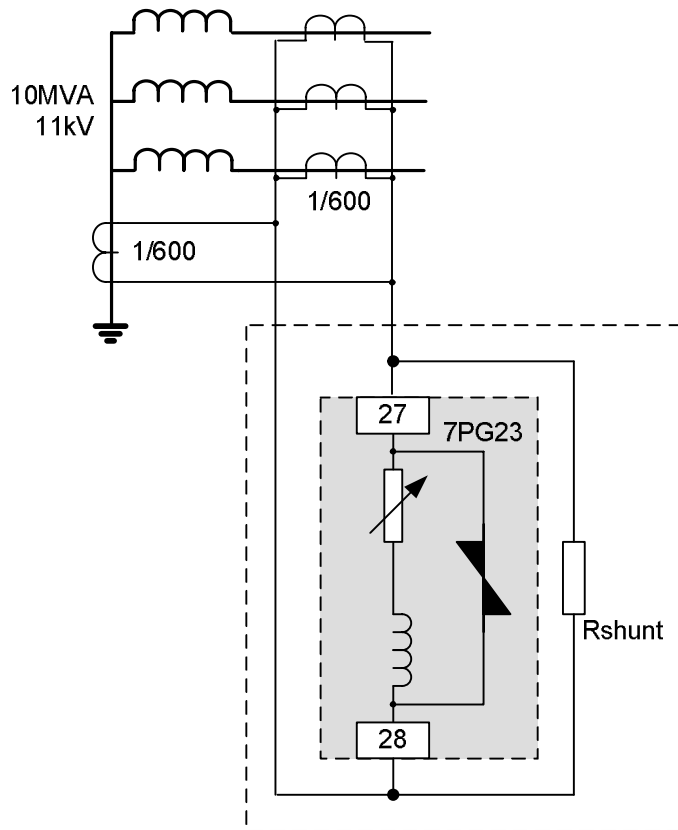


Figure 4-4 Example System – 3 Wire + Earth REF Protection

CT and Connection Details

	Line CT (LCT)	Earth CT (ECT)
Turns ratio (T)	1/600	1/600
Voltage Knee Point (V_K)	360V	300V
Magnetising Current (I_{mag}) @ V_K	30mA	40mA
CT secondary resistance (R_{CT})	7.5Ω	6.0Ω
CT lead loop resistance (R_L)	0.15Ω	0.2Ω

Settings Requirements

Rated current = $VA / (\sqrt{3} \times V_L)$

Rated current = $10 \times 10^6 / (\sqrt{3} \times 11000) = 525A$

Assigned through fault current (rated stability limit) = $16 \times$ rated current = 8.4kA. See section 2.2.1

Required Primary Operate Current (Fault Setting)

10 – 25% of protected winding rated current, or as specified by the user.

POCprov (10 – 25% of I_{rated}) = 52.5 - 131A. Say 60A. (0.1A secondary). See section 2.2.2

Calculation of Required Stability Voltage Limits

The assigned through fault current is 8400A.

With reference to section 2.2.1

$$V_s \geq I_F(R_{CT} + R_L) \times T$$

$$V_s \geq \frac{8400}{600} \times (7.5 + 0.15) = 107.1V$$

$$V_s \geq \frac{8400}{600} \times (6 + 0.2) = 86.8V$$

$$V_s \leq \frac{V_{KMIN}}{2} = \frac{300}{2} = 150V$$

$$\therefore 107.1 < V_s < 150$$

Calculation of Shunt Setting Resistor Value

The required for the value of operate current to flow through the shunt setting resistor (Rstab) can be calculated from:

$$POC = (3(I_{MAGLCT}) + I_{MAGECT} + I_s + I_{shunt}) / T$$

$$I_{shunt} = POC \times T - (3(I_{MAGLCT}) + I_{MAGECT} + I_s)$$

$$= 0.1 - (3(I_{MAGLCT}) + I_{MAGECT} + 0.02)$$

Say $V_{sprov} = 120V$ (from requirement $107.1 < V_s < 150$)

From CT magnetising curve: At 120V $I_{MAGLCT} = 7mA$ and $I_{MAGECT} = 9mA$

$$I_{shunt} = 0.1 - (3(0.007) + 0.009 + 0.02) = 0.05A$$

$$R_{shunt} = V_s / I_{shunt} = 120 / 0.05 = 2400 \text{ Ohms}$$

Metrosil Specification

Short Time Power Rating

Using the empirical formula

$$P_{1SEC} \geq \frac{4}{\pi} \times I_F \times T \times V_K$$

$$P_{1SEC} \geq \frac{4}{\pi} \times 8400 \times \frac{1}{600} \times 360 = 6417W$$

For values < 8kW/s the integral 75mm Metrosil is suitably rated.

Shunt Resistor Specification

Continuous Power Rating

$$P_{\text{CONT}} \geq V_s^2 / R_{\text{shunt}}$$

$$P_{\text{CONT}} \geq 120^2 / 2400$$

$$P_{\text{CONT}} \geq 6.0\text{W}$$

Short Time Power Rating

$$P_{1\text{SEC}} \geq \frac{V_{\text{Fint}}^2}{R_{\text{stab}}} \quad \text{Where: } V_{\text{Fint}} \geq \sqrt[4]{(V_K^3 \times R_{\text{shunt}} \times I_{\text{Fint}})} \times 1.3$$

$$I_{\text{Fint}} = \frac{2800}{200} = 14\text{A}$$

$$V_{\text{Fint}} \geq \sqrt[4]{(V_K^3 \times R_{\text{shunt}} \times I_{\text{Fint}})} \times 1.3$$

$$V_{\text{Fint}} \geq \sqrt[4]{(360^3 \times 2400 \times 14 \times 1.3)} = 1455\text{V}$$

$$P_{1\text{SEC}} \geq \frac{1455^2}{2400} = 882\text{W}$$

Summary of Relay Settings and Components

$$V_s = 120\text{V}$$

Rshunt = 2400 Ohms, 40W continuous (typical manufacturers data)

Additional external Metrosil – not required.

$$\text{POC (Fault Setting)} = (3(I_{\text{MAGLCT}}) + I_{\text{MAGECT}} + I_s + I_{\text{shunt}}) / T$$

$$\text{POC} = (3(0.007) + 0.009 + 0.02 + 0.05) \times 600 = 60\text{A}$$

4.3 7PG23 Relay: Restricted Earth Fault Protection - 4 Wire 4CT

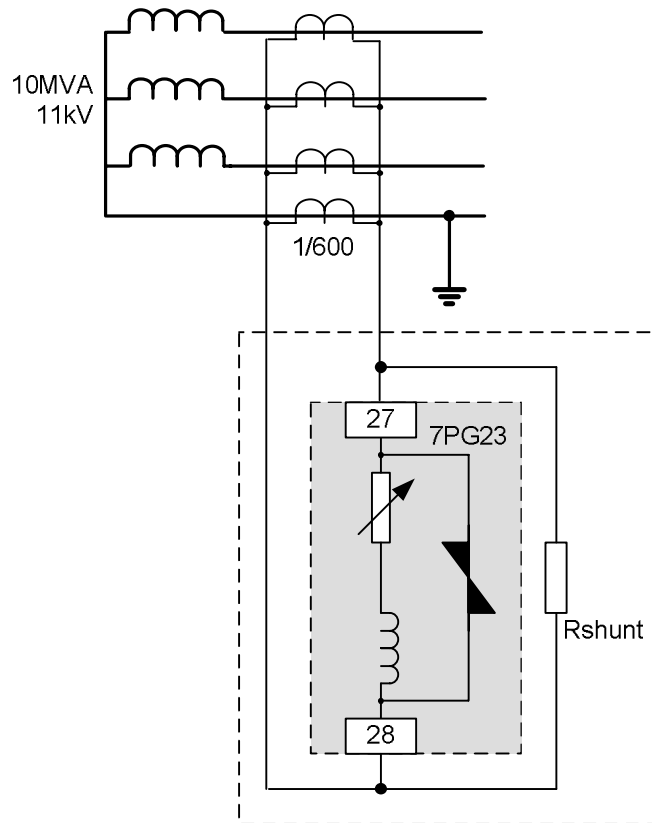


Figure 4-5 Example System – 4 Wire REF Protection

CT and Connection Details

	Line CT (LCT)	Neutral CT (NCT)
Turns ratio (T)	1/600	1/600
Voltage Knee Point (V_K)	360V	450V
Magnetising Current (I_{mag}) @ V_K	30mA	20mA
CT secondary resistance (R_{CT})	7.5 Ω	4.5 Ω
CT lead loop resistance (R_L)	0.15 Ω	0.5 Ω

Settings Requirements

Rated current = $VA / (\sqrt{3} \times V_L)$

Rated current = $10 \times 10^6 / (\sqrt{3} \times 11000) = 525A$

Assigned through fault current (rated stability limit) = $16 \times$ load current = 8.4kA. See section 2.2.1

Required Primary Operate Current (Fault Setting)

10 – 25% of protected winding rated current, or as specified by the user.

POCprov (10 – 25% of Irated) = 52.5 - 131A. Say 60A. (0.1A secondary). See section 2.2.2

Calculation of Required Stability Voltage Limits

The assigned through fault current is 8400A.

With reference to section 2.2.1

$$V_s \geq I_F(R_{CT} + R_L) \times T$$

$$V_s \geq \frac{8400}{600} \times (7.5 + 0.15) = 107.1V$$

$$V_s \geq \frac{8400}{600} \times (4.5 + 0.5) = 70V$$

$$V_s \leq \frac{V_{KMIN}}{2} = \frac{360}{2} = 180V$$

$\therefore 107.1 < V_s < 180$

Calculation of Shunt Setting Resistor Value

The required relay setting Is can be calculated from:

$$POC = (3(I_{MAGLCT}) + I_{MAGNCT} + I_s + I_{shunt}) / T$$

$$I_{shunt} = POC \times T - 3(I_{MAGLCT}) - I_{MAGNCT} - I_s$$

$$= 0.1 - 3(I_{MAGLCT}) - I_{MAGNCT} - 0.02$$

Say Vsprov = 120V (from requirement 107.1 < Vs < 150)

From CT magnetising curve: At 120V I_{MAGLCT} = 7mA and I_{MAGNCT} = 4mA

$$I_{shunt} = 0.1 - 3(0.007) - 0.004 - 0.02 = 0.055A$$

$$R_{shunt} = V_s / I_{shunt} = 120 / 0.055 = 2182 \text{ Ohms (say 2200 Ohms)}$$

Metrosil Specification

Short Time Power Rating

Using the empirical formula

$$P_{1SEC} \geq \frac{4}{\pi} \times I_F \times T \times V_K$$

$$P_{1SEC} \geq \frac{4}{\pi} \times 8400 \times \frac{1}{600} \times 450 = 8kW$$

For values < 8kW/s the integral 75mm Metrosil is suitably rated.

Stabilising Resistor Specification

Continuous Power Rating

$$P_{CONT} \geq V_s^2 / R_{shunt}$$

$$P_{CONT} \geq 120^2 / 2200$$

$$P_{CONT} \geq 6.5W$$

Short Time Power Rating

$$P_{1SEC} \geq \frac{V_{Fint}^2}{R_{stab}} \quad \text{Where: } V_{Fint} \geq \sqrt[4]{(V_K^3 \times R_{shunt} \times I_{Fint})} \times 1.3$$

$$I_{Fint} = \frac{2800}{200} = 14A$$

$$V_{Fint} \geq \sqrt[4]{(V_K^3 \times R_{shunt} \times I_{Fint})} \times 1.3$$

$$V_{Fint} \geq \sqrt[4]{(450^3 \times 2200 \times 14 \times 1.3)} = 1683V$$

$$P_{1SEC} \geq \frac{1683^2}{2200} = 1287W$$

Summary of Relay Settings and Components

$$V_s = 120V$$

$$R_{shunt} = 2200 \text{ Ohms, } 45W \text{ continuous (typical manufacturers data)}$$

Additional external Metrosil – not required.

$$POC \text{ (Fault Setting)} = (3(I_{MAGLCT}) + I_{MAGNCT} + I_s + I_{shunt}) / T$$

$$POC = (3(0.007) + 0.004 + 0.02 + 0.055) \times 600 = 60A$$

4.4 7PG23 Relay: Restricted Earth Fault Protection - 4 Wire 5CT

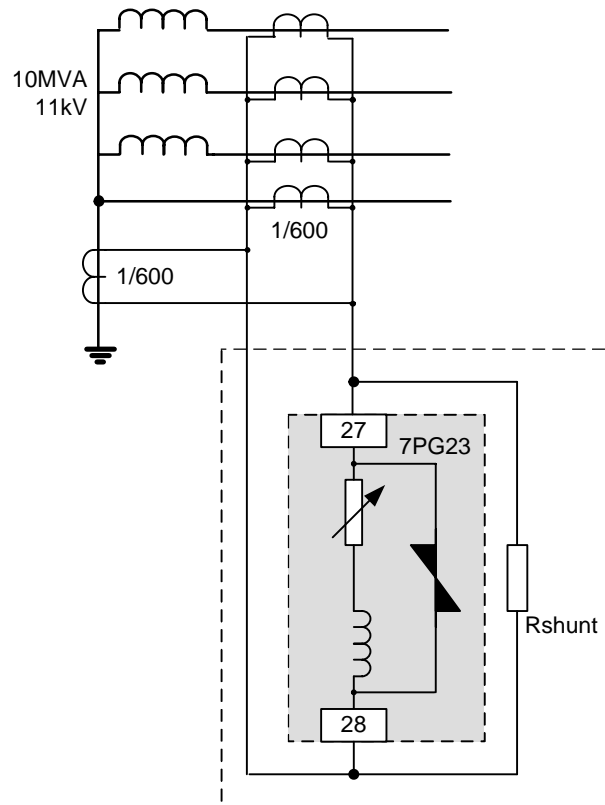


Figure 4-6 Example System – 4 Wire + Earth REF Protection

CT and Connection Details

	Line CT (LCT)	Neutral CT (NCT)	Earth CT (ECT)
Turns ratio (T)	1/600	1/600	1/600
Voltage Knee Point (V_K)	360V	450V	300V
Magnetising Current (I_{mag}) @ V_K	30mA	20mA	40mA
CT secondary resistance (R_{CT})	7.5Ω	4.5Ω	6.0Ω
CT lead loop resistance (R_L)	0.15Ω	0.5Ω	0.2Ω

Settings Requirements

$$\text{Rated current} = VA / (\sqrt{3} \times V_L)$$

$$\text{Rated current} = 10 \times 10^6 / (\sqrt{3} \times 11000) = 525A$$

Assigned through fault current (rated stability limit) = 16 x rated current = 8.4kA. See section 2.2.1

Required Primary Operate Current (Fault Setting)

10 – 25% of protected winding rated current, or as specified by the user.

POCprov (10 – 25% of Irated) = 52.5 - 131A. Say 60A. (0.1A secondary). See section 2.2.2

Calculation of Required Stability Voltage Limits

The assigned through fault current is 8400A.

With reference to section 2.2.1

$$V_s \geq I_F(R_{CT} + R_L) \times T$$

$$V_s \geq \frac{8400}{600} \times (7.5 + 0.15) = 107.1V$$

$$V_s \geq \frac{8400}{600} \times (6 + 0.2) = 86.6V$$

$$V_s \geq \frac{8400}{600} \times (4.5 + 0.5) = 70V$$

$$V_s \leq \frac{V_{KMIN}}{2} = \frac{300}{2} = 150V$$

∴ 107.1 < Vs < 150V

Calculation of Shunt Setting Resistor Value

The required relay setting Is can be calculated from:

$$POC = (3(I_{MAGLCT}) + I_{MAGNCT} + I_{MAGECT} + I_s + I_{shunt}) / T$$

$$I_{shunt} = POC \times T - (3(I_{MAGLCT}) + I_{MAGNCT} + I_{MAGECT} + I_s)$$

$$= 0.1 - (3(I_{MAGLCT}) + I_{MAGNCT} + I_{MAGECT} + 0.02)$$

Say Vsprov = 120V (from requirement 107.1 < Vs < 150)

From CT magnetising curve: At 120V I_{MAGLCT} = 7mA, I_{MAGNCT} = 4mA and I_{MAGECT} = 9mA

I_{shunt} = 0.1 - (3(0.007) + 0.004 + 0.009 + 0.02) = 0.046A

R_{shunt} = Vs/I_{shunt} = 120/0.046 = 2609 Ohms (Say 2700 Ohms giving I_{shunt} = 120/2700 = 0.044A)

Metrosil Specification

Short Time Power Rating

Using the empirical formula

$$P_{1SEC} \geq \frac{4}{\pi} \times I_F \times T \times V_K$$

$$P_{1SEC} \geq \frac{4}{\pi} \times 8400 \times \frac{1}{600} \times 450 = 8kW$$

For values < 8kW/s the integral 75mm Metrosil is suitably rated.

Stabilising Resistor Specification

Continuous Power Rating

$$P_{\text{CONT}} \geq V_s^2 / R_{\text{shunt}}$$

$$P_{\text{CONT}} \geq 120^2 / 2700$$

$$P_{\text{CONT}} \geq 5.3\text{W}$$

Short Time Power Rating

$$P_{1\text{SEC}} \geq \frac{V_{\text{Fint}}^2}{R_{\text{stab}}} \quad \text{Where: } V_{\text{Fint}} \geq \sqrt[4]{(V_K^3 \times R_{\text{shunt}} \times I_{\text{Fint}})} \times 1.3$$

$$I_{\text{Fint}} = \frac{2800}{200} = 14\text{A}$$

$$V_{\text{Fint}} \geq \sqrt[4]{(V_K^3 \times R_{\text{shunt}} \times I_{\text{Fint}})} \times 1.3$$

$$V_{\text{Fint}} \geq \sqrt[4]{(450^3 \times 2700 \times 14 \times 1.3)} = 1771\text{V}$$

$$P_{1\text{SEC}} \geq \frac{1771^2}{2700} = 1161\text{W}$$

Summary of Relay Settings and Components

$$V_s = 120\text{V}$$

$$R_{\text{shunt}} = 2700 \text{ Ohms, } 45\text{W continuous (typical manufacturers data)}$$

Additional external Metrosil – not required.

$$\text{POC (Fault Setting)} = (3(I_{\text{MAGLCT}}) + I_{\text{MAGNCT}} + I_{\text{MAGECT}} + I_s + I_{\text{shunt}}) / T$$

$$\text{POC} = (3(0.007) + 0.004 + 0.009 + 0.02 + 0.044) \times 600 = 59\text{A}$$

5. Appendix

5.1 CT Magnetising Curve

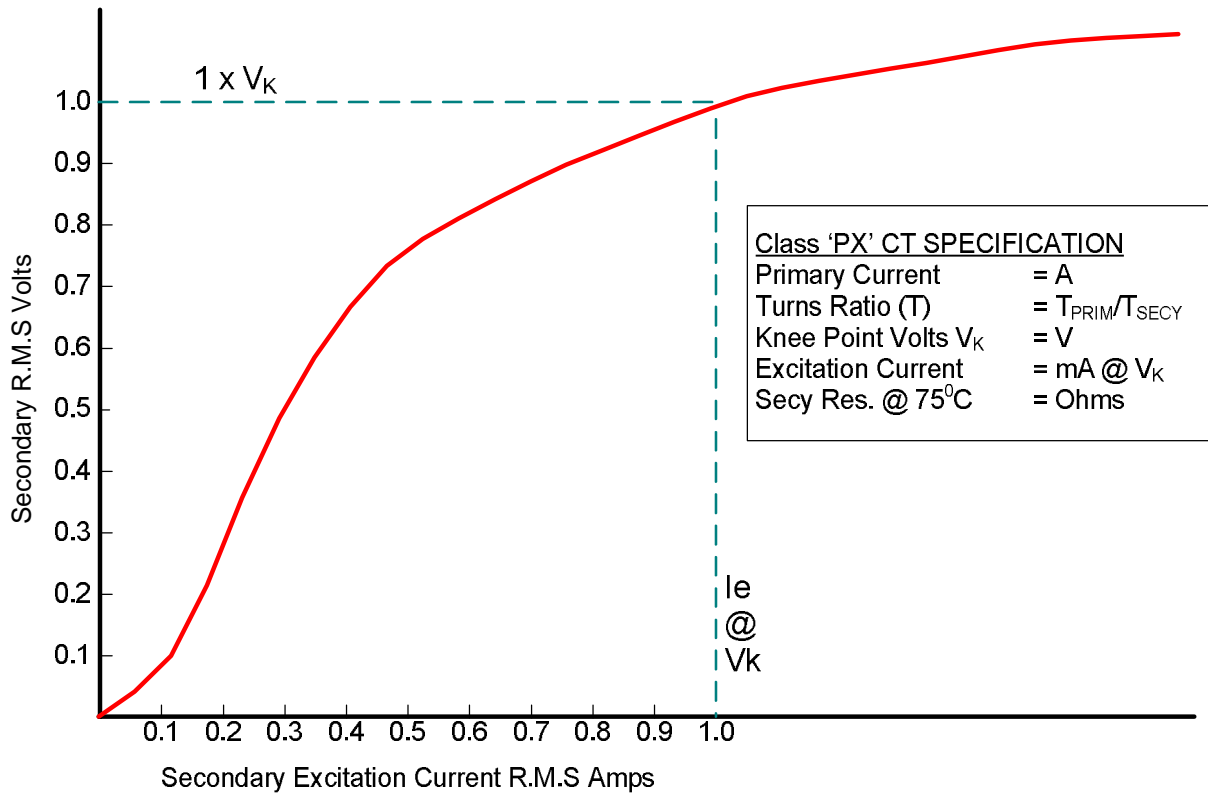


Figure 5-1 Typical CT Magnetising Curve (Class PX to IEC60044)

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