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APPLICATION NOTES

PRO▸N FAMILY

–

HIGH IMPEDANCE RESTRICTED EARTH FAULT PROTECTIVE RELAY

APPLICATION NOTE N°001

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USING PRO-N RELAYS AS HIGH IMPEDANCE RESTRICTED EARTH FAULT PROTECTIVE RELAY – APPLICATION NOTE

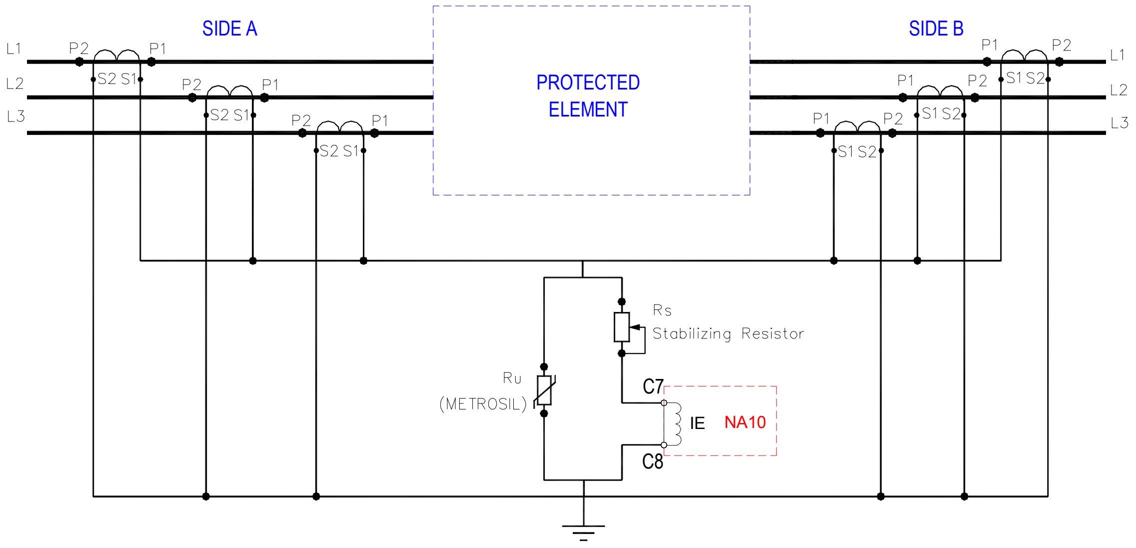

Fig. 1 current balance using a circulating current protection – general scheme

Suitable models[1]: NA10, NA11, NA20, NA30, NA50, NA60, NA70, NA80, NT10, NT20, NT30, NM10, NM20, NG20, NTGB, NTGP, NC10, NC20.

1 FOREWORD

A protective system adopting the high impedance restricted earth fault protective scheme is accomplishable with a residual overcurrent relay like NA10. A proper resistor in series to residual current analog input compares this relay to a high impedance relay.
It is possible to recognize two main fault conditions:

- Internal fault, within the protected zone.
- External fault, away from the protected zone.

This document is aimed to summarize an exhaustive treatment over this protective technique.

2 EXTERNAL FAULT AND CT SATURATION

When an external fault occurs a differential current could flows in circulating current connection and causes an un wanted trip, this is due to CT's saturation phenomenon.
In fact the CT's nominal ratio is not a linear function versus current magnitude and whether instantaneous overcurrent threshold is set low enough, in order give useful sensitivity to internal faults, the relay could operate erroneously on external faults (this is because the differential current could increase to a sensible value).
In case of external fault the CT core becomes saturated if:

- Appears a primary current DC component.
- The CT core has a residual magnetism.

When these two conditions are additive the flux produced generates the most onerous core saturating case. The behind graphs show its qualitative analysis relevant to primary-secondary current and flux variation when a CT is saturated and the other one (or set of CT) is totally linear.

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[1] Every PRO-N relay with residual overcurrent protective function (50N/51N) is accomplishable as high impedance restricted earth fault protective relay.

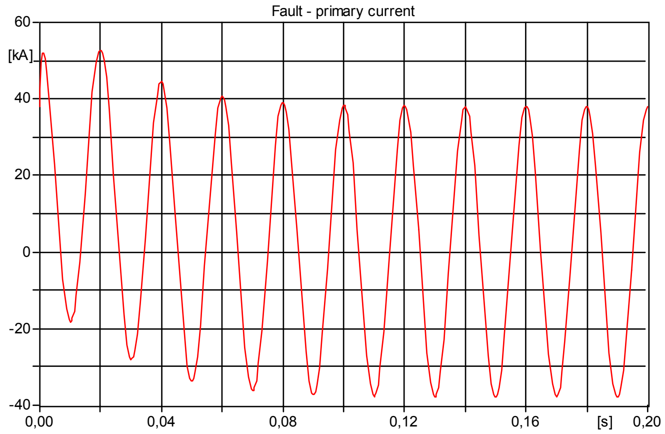

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Fig. 2 Primary fault current.

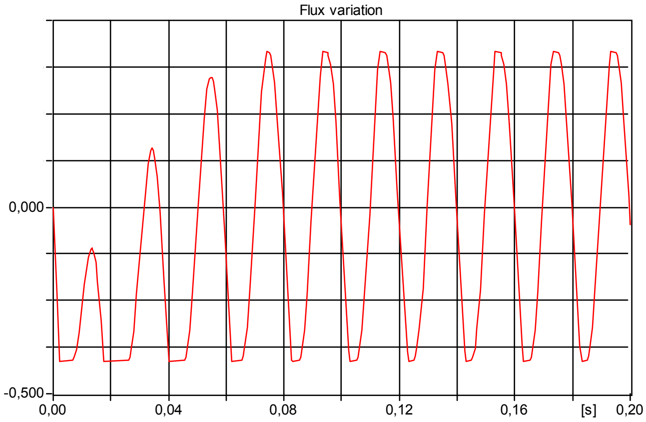

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Fig. 3 Flux variation in case of saturated CT.

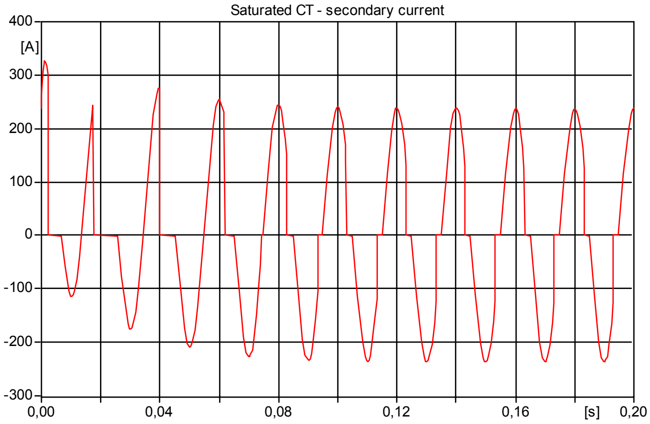

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Fig. 4 Secondary current of a saturated CT.

Fig. 3 and Fig. 4 show clearly that in case of saturated core the secondary current is perfectly null, when the saturation point is reached no further e.m.f. is produced and the secondary current will collapse instantaneously to zero.

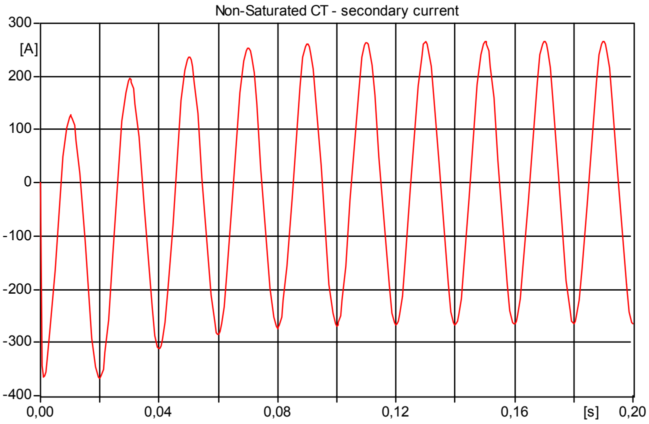

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Fig. 5 Secondary current for Non-saturated CT.

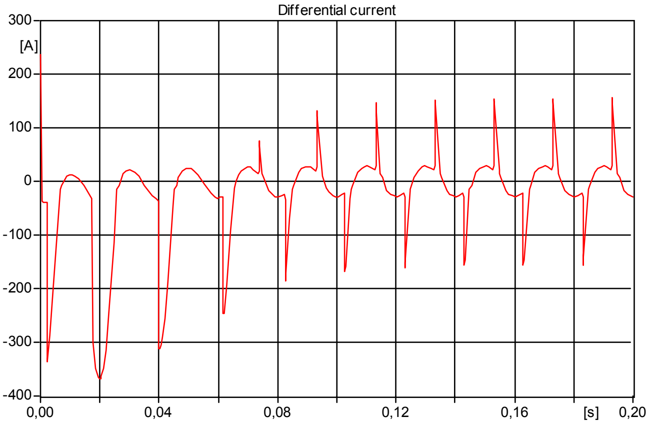

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Fig. 6 Differential current flowing in relay coil.

The differential current is the vector sum of the secondary currents illustrated in Fig. 4 and Fig. 5, in some cases could rise to significative values.
Therefore avoiding an unwanted trip is necessary add, in series to relay coil, a proper resistor in order to obtain a differential current value less then the minimum threshold of residual current stage even in worst case of CT's asymmetry, keeping the protective function stabilized.

3 BASIS OF CALCULATING THE STABILIZING RESISTOR

The stabilizing resistor is calculated in order to match these conditions:

a. Avoiding nuisance trip in case of external fault obtaining a stability level starting from the minimum pick up current value.
b. Keeping CT's working in linear zone in case of external fault.

The most onerous condition for stability arise when

1. Maximum short circuit current in plant[2].

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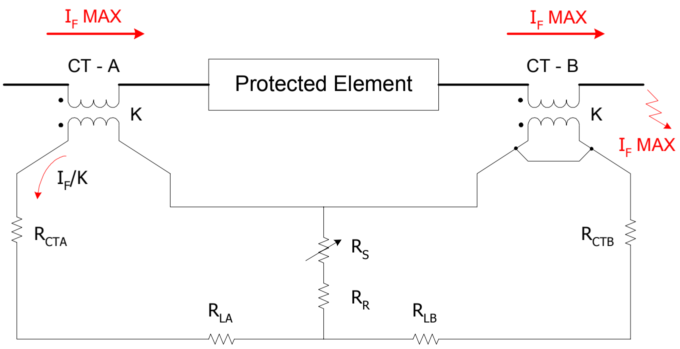
[2] The conditions which would flow the maximum fault current in plant are usually reachable when e.g. power transformer are in parallel, the fault arc resistance is zero and voltage is at highest value.

2. One CT saturates completely due to asymmetry of the fault current (DC component).
3. The other one does not saturate at all and gives as output the correct reproduction of primary current.
4. The saturated CT is the most far from relay.

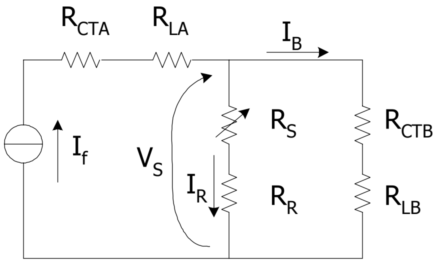
As first case let's analyze the basic scheme with two groups of current transformer:



Defining:

– *CT-A*	Non saturated current transformer
– *CT-B*	Saturated current transformer
– I_F	Maximum fault current
– $I_{E>min}$	Minimum relay setting current
– *K*	Turns ratio of all CT's
– R_L	Lead loop resistance (from CT to the relay and back)
– R_{CT}	Secondary winding resistance of CT
– R_S	Stabilizing resistor resistance
– R_R	Relay current input resistance
– V_{KNEE}	Knee-point voltage of CT's.

From this equivalent circuit



$$I_f = \frac{I_F}{K}$$

Results:

$$\begin{cases} I_f = I_R + I_B \\ (R_S + R_R)\cdot I_R = (R_{CTB} + R_{LB})\cdot I_B \end{cases}$$ (leaving the magnetizing current of CT-A)

$$I_R = \frac{I_F}{K}\cdot\frac{R_{CTB} + R_{LB}}{(R_R + R_S + R_{CTB} + R_{LB})} \qquad [1]$$

In order to satisfy the condition **a.** must be: $I_R < I_{E>min}$
Hence

$$R_S > (R_{CTB} + R_{LB})\cdot\frac{I_F}{K \cdot I_{E>\min}} - (R_R + R_{CTB} + R_{LB})$$

[2]

Condition **b.** implies that knee-point voltage must be quit double than voltage of relay-stabilizing resistor serie V_S.

$$V_{KNEE} > (1.5 \div 2)\cdot V_S \quad [3]$$

A suitable value of R_S is the one that satisfies both [2] and [3].
According to resistor international standard[3] the thermal withstand must be ten times the rated power for five seconds.
Its continuous power rating is $P_S = R_S \cdot I_{E>}{}^2$ [W] but in case of external fault is $P_S = R_S \cdot I_f{}^2$ [W]. This value is obviously higher than the first one but it is possible assume that the fault is extinguished in one second. This energy must be compared with the thermal withstand as mentioned in above standard.

4 INTERNAL FAULT – VARISTOR AS OVERVOLTAGE TRANSIENT SUPPRESSOR

The secondary voltage applied to current transformer connection, in case of internal fault at maximum fault current, is: $(R_R + R_S)\cdot\dfrac{I_F}{K}$

Usually it is a very high value, e.g. if K=200, I_F=40kA, R_R+R_S=500Ω is establishing an overvoltage $500 \cdot \dfrac{40000}{200} = 100$ kV and obviously CT's are saturating and seriously damaged.
Under these overvoltage conditions, due to internal fault and CT saturation, the formula due to Mathews[4]

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[3] MIL-R-26.

[4] *Protective current transformer and circuits* by P. Mathews (Chapman Hall, 1955)

gives a reasonable approximation to the peak voltage produced:

$$V_{pk} = 2\cdot\sqrt{2\cdot V\cdot V_{KNEE}}$$

- V_{pk} is the peak value of the distorted voltage waveform.
- V is the rms value of the voltage that would appear in case of non-saturated CT condition.

Therefore it is necessary a protection devices for such a big amount of voltage applied to CT's.
The most commonly adopted solution is the use of the Varistor, a non-Linear resistor (voltage dependent resistor) that limits overvoltage transient, connected as shown in Fig. 1. Its voltage-current characteristic is generally as indicated in below figure. Traditionally the relationship is expressed by:
$V = C\cdot I^{\beta}$ For dc or instantaneous values.

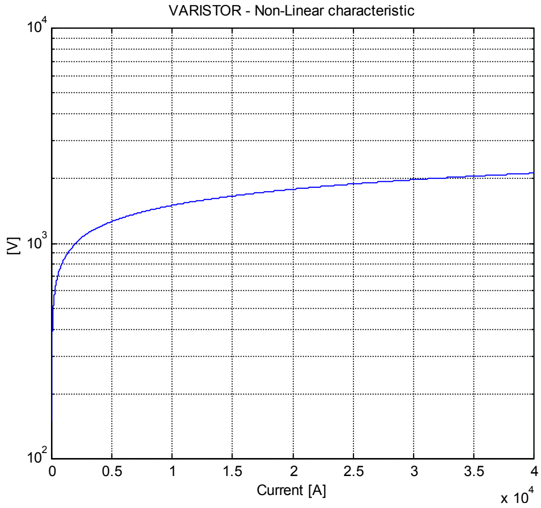
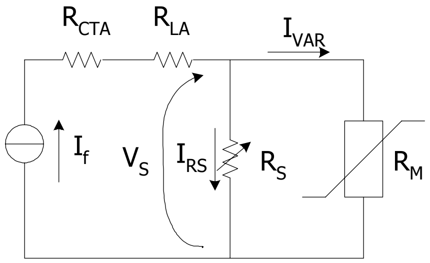


Fig. 7 Volt/Ampere characteristic of a non linear resistor

Where *C* and *β* (<<1) are constants provided by manufacturer. The value of *C* and *β* depends on the physical dimensions of the varistor, its composition and the manufacturing process.

5 THERMAL WITHSTAND

The simplified circuit is composed by the series of $R_S + R_R \cong R_S$ in parallel with the varistor.



The current in varistor[5] is $I_{var} = 0.52\cdot\left(\frac{V_{s\cdot}\cdot\sqrt{2}}{C}\right)^{\frac{1}{\beta}}$

and the current in stabilizing resistor is $I_{RS} = \frac{V_S}{R_S}$

$$I_f = I_{RS} + I_{VAR} \rightarrow I_f = \frac{V_S}{R_S} + 0.52\cdot\left(\frac{V_{s\cdot}\cdot\sqrt{2}}{C}\right)^{\frac{1}{\beta}}$$

In this plan the current/voltage characteristic is represented where C=900 and β=0.25.

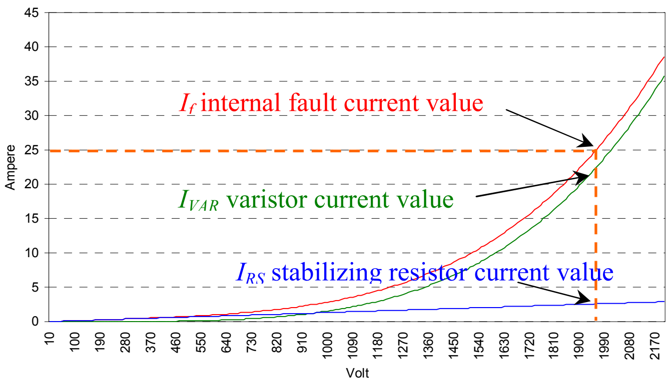


Fig. 8 – Current in varistor/RS parallel

Referring to the internal fault current value I_f it is possible to determine the right value of current flowing in stabilizing resistor I_{RS} and in the varistor I_{VAR}.
In case of circuit breaker opening failure it is assumed a conservative maximum extinguishing time of 1s. During this time is flowing the maximum energy:

$$E_{ST} = R_S\cdot I_{RS}{}^2\cdot 1[\mathrm{J}]$$

The stabilizing resistor must be designed in accordance to this value.

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[5] From METROSIL data sheet http://www.metrosil.com/english/PDFFiles/MEREYBRO.PDF

6 REAL OPERATING THRESHOLD

The actual current that carry out the trip of this protective function is higher than the one relevant to the threshold in relay setup, its value must be checked to ensure hunted function of the protective relay.

In case of internal fault the current flowing in the Varistor is calculated according to:

$$I_{\text{var}} = 0.52 \cdot \left(\frac{V_{S} \cdot \sqrt{2}}{C} \right)^{\frac{1}{\beta}}$$ (The varistor manufacturer provides values of *C* and *β*)[6].

The connection scheme in Fig. 1 shows that in case of internal fault the secondary current flows in all CT's magnetizing branch, current input of relay and varistor.

This new value I_{EI} must be compared with the expected one.

$$I_{EI} = K \cdot (I_{E>} + I_{\text{var}} + N_{CT} \cdot I_0)$$

Where N_{CT} is the number of CT in protective scheme. I_0 is the magnetizing current[7] corresponding to the stabilizing voltage $V_S = I_f \cdot (R_L + R_{CT})$.

7 CURRENT TRANSFORMER REQUIREMENTS

The CT's must be:

1. low leakage reactance type according to IEC Class PX, TPS or BS Class X;
2. secondary resistance not greater than R_{CT}[8];
3. magnetizing curve with knee-point voltage $V_{KNEE} \geq 2 \cdot V_S$;
4. same manufacturer and same model in both sides.

8 GENERAL CASE CONNECTION SCHEME

In case of external fault remain valid all concepts explained in chapter 2 noting that the worst conditions arise when only one CT is saturating.

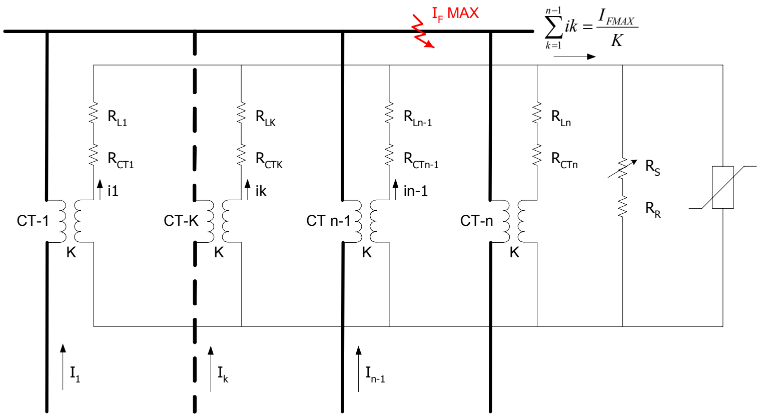

Fig. 9 General connection scheme.

9 NUMERICAL EXAMPLE

9.1 STABILIZING RESISTOR CHOICE

Let's assume a more simplified approach[9] than the above explained.

$$V_S = \frac{I_F}{K} \cdot (R_{CT} + R_L)$$

$$V_S \leq I_{E>} \cdot (R_S + R_R) \quad \rightarrow \quad R_S \geq \frac{V_S}{I_{E>}} - R_R$$

This is a short representation of [2], most conservative for a fast calculus.

Where:

- V_S stability voltage
- I_f maximum fault current
- $I_{E>}$ relay setting current
- K turns ratio of CT
- R_L lead loop resistance (at 75°)
- R_{CT} secondary winding resistance of CT (at 75°)
- R_S stabilizing resistor resistance
- R_R relay current input resistance

R_S must be variable type in order to fit different values of setting current. A suitable range is obtainable from taking the lower fault current in plant and half Knee-point voltage of the CT's.

For example, assuming:

- K 2000A/1A;
- I_f 39.7kA;
- $I_{E>}$ 0.45A (0.45[pu]);

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[6] For applied sinusoidal voltages.

[7] The CT's manufacturer provides the magnetizing curve

[8] During design task could be possible have not R_{CT} value. It can be calculated as in APPENDIX B.

[9] Coercing $I_B = I_f$

– R_{CT} 16.2 Ω;

The lead resistance at 20° can be calculated as

$$R_L = 0.018\frac{l[m]}{S[mm^2]}[\Omega]$$

"l" is the total length of CT's secondary loop, e.g. a CT 15m far from relay the total length is 30m.

Referring this value to the higher temperature 75°

$$R_{L75^\circ} = 1.22 \cdot R_{L20^\circ}[\Omega]$$

– R_L 0.018*20/4 = 0.09 Ω → 0.11 Ω (75°) side A;

– R_L 0.018*30/4 = 0.135 Ω → 0.16 Ω (75°) side B;

For the saturation of side A

$$V_S = 39700 \cdot \frac{1}{2000} \cdot (16.2 + 0.11) \cong 321\mathrm{V}$$

For the saturation of side B

$$V_S = 39700 \cdot \frac{1}{2000} \cdot (16.2 + 0.16) \cong 324\mathrm{V}$$

Referring to NA10 manual the residual current input circuit has a burden of 0.1VA in case of 1A as nominal residual current.

$$R_R = \frac{0.1}{1^2} = 0.1\Omega$$

$$R_S = \frac{324}{0.45} - 0.1 \cong 720\Omega$$

Its thermal withstand is calculated in continuous power rating as:

$$P_S = R_S \cdot I_{E>}{}^2\,[\mathrm{W}] \rightarrow P_S = 720 \cdot 0.45^2 = 145\ \mathrm{W}$$

In case of internal fault the resistor is capable to accept the short time power rating at least as long as the operating time of the protective system (conservatively assumed 1s). The current flowing in the stabilizing resistor during this period is deducted from diagram showed in Fig. 8[10], where $\frac{39700}{2000} = 19.85$ A is $I_{RS} = 2.54$ A.

$$E_{ST} = P_{ST} \cdot t = [\mathrm{J}] \rightarrow E_{ST} = 720 \cdot 2.54^2 \cdot 1 = 4.65\ \mathrm{kJ}$$

If the minimum fault current is 30kA and Knee-point Voltage (V_{KNEE}) is 800V:

$$V_S = 30000 \cdot \frac{1}{2000} \cdot (16.2 + 0.16) \cong 245\mathrm{V} \quad \rightarrow$$

$$R_S MIN = \frac{245}{0.45} - 0.1 \cong 545\Omega$$

V_{KNEE} = 800V →

$$R_S MAX = \frac{400}{0.45} - 0.1 \cong 890\Omega$$

Hence a suitable stabilizing resistor could be:

1. Nominal resistance range : 0 – 1000 Ω.
2. Rated power: 150 W.
3. Maximum thermal energy permissible 5kJ upon 1 second.

9.2 VARISTOR CHOICE

Data required for manufacturer are:

1. Relay Setting Voltage = 325Vrms.
2. Secondary Internal Fault Current = 20Arms.
3. CT Secondary Rating = 1Arms.

In order to avoid dangerous overvoltage in the secondary circuit and guarantee good sensitivity to protective relay:

4. Required Protection Voltage < 1500 Vrms.
5. Maximum Leakage Current @ Relay Setting Voltage < 60mArms.

9.3 VERIFYING RELAY SETTING CURRENT

In case of internal fault the real current that cause a trip is greater than $I_{E>} \cdot K$. It is necessary take into account the CT's magnetizing current and the leakage varistor current according to:

$$I_{EI} = K \cdot (I_{E>} + I_{\mathrm{var}} + N_{CT} \cdot I_0)\,[\mathrm{A}]$$

Where N_{CT} is the number of CT's, in case of neutral distributed network and grounded transformer is equal to 5. Referring to the scheme in page 3 N_{CT} is 6.

$$I_{\mathrm{var}} = 0.52 \cdot \left(\frac{324 \cdot \sqrt{2}}{900}\right)^{\frac{1}{0.25}} \cong 35\ \mathrm{mA}$$

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[10] Assuming $C = 900$ and $\beta = 0.25$.

The CT's manufacturer provides the magnetizing curve and for e.g. V_{KNEE} =800V, I_{KNEE} = 25mA. Corresponding to 325V I_0 is approximatively:

$$I_0 = 0.025 \cdot \left(\frac{325}{800} \right) \cong 10 \text{ mA}$$

In case of neutral distributed network and transformer 1250kVA at nominal voltage 400V the lowest fault current value, providing the maximum sensitivity, is:

$$I_{EI} = 2000 \cdot (0.45 + 0.035 + 5 \cdot 0.010) = 1070 \text{ A}$$

and related to transformer nominal current $1250000 \div (400 \cdot \sqrt{3}) \cong 1805$ A this value is the 60%.

9.4 CURRENT TRANSFORMER REQUIREMENTS

The CT's must be:

1. low leakage reactance type according to IEC Class PX, TPS or BS Class X;
2. secondary resistance not greater than R_{CT} = 16.2 Ω ;
3. magnetizing curve with knee-point voltage $V_{KNEE} \geq 800$ V ;
4. same manufacturer and same model for both sides.

REFERENCES

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(Electricity Association Services Limited 1995. ISBN 0 85296 837 X)

P. Mathews: Protective current transformers and circuits
(Chapman & Hall 1955)

KEYWORDS

Restricted earth fault protection, high impedance restricted earth fault protection, REF, 87N, 87NHIZ, varistor, CT's saturation, stabilizing resistor, residual current analog input.