MiCOM P12X

High Impedance Protection

Application Notes

APPLICATION NOTES FOR MICOM P12X HIGH IMPEDANCE PROTECTION

Date: **August 2007**

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FIGURES

1. INTRODUCTION

1.1 Theory of high impedance protection

The application of the P12x numerical overcurrent relays as differential protection for machines, power transformers and busbar installations is based on the high impedance differential principle, offering stability for any type of fault occurring outside the protected zone and satisfactory operation for faults within the zone.

A high impedance relay is defined as a relay or relay circuit whose voltage setting is not less than the calculated maximum voltage which can appear across its terminals under the assigned maximum through fault current condition.

It can be seen from Figure 1 that during an external fault the through fault current should circulate between the current transformer secondary's. The only current that can flow through the relay circuit is that due to any difference in the current transformer outputs for the same primary current. Magnetic saturation will reduce the output of a current transformer and the most extreme case for stability will be if one current transformer is completely saturated and the other unaffected.

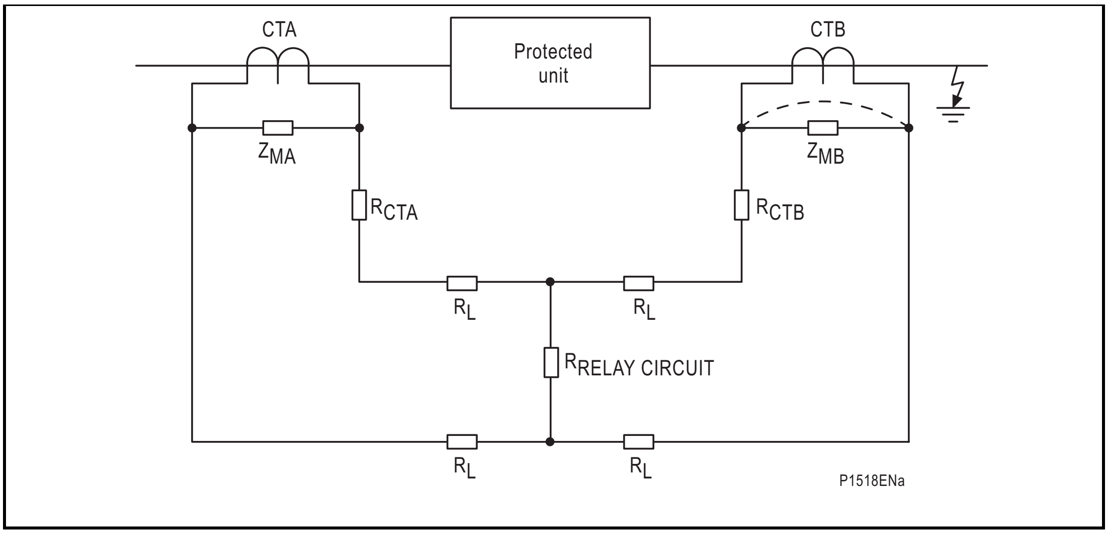

Figure 1: Principle of high impedance protection

Calculations based on the above extreme case for stability have become accepted in lieu of conjunctive scheme testing as being a satisfactory basis for application. At one end the current transformer can be considered fully saturated, with its magnetizing impedance Z_{MB} short circuited while the current transformer at the other end, being unaffected, delivers its full current output. This current will then divide between the relay and the saturated current transformer. This division will be in the inverse ratio of $R_{RELAY\ CIRCUIT}$ to (R_{CTB} + $2R_L$) and, if $R_{RELAY\ CIRCUIT}$ is high compared with R_{CTB} + $2R_L$, the relay will be prevented from undesirable operation, as most of the current will pass through the saturated current transformer.

To achieve stability for external faults, the stability voltage for the protection (V_S) must be determined in accordance with equation [1]. The setting will be dependent upon the maximum current transformer secondary current for an external fault (I_f) and also on the highest loop resistance value from the relaying point (R_{CT} + $2R_L$). The stability of the scheme is also affected by the characteristics of the differential relay and the application (e.g. restricted earth fault, busbar etc). The value of K in the expression takes account of both of these considerations. One particular characteristic that affects the stability of the scheme is the operating time of the differential relay. The slower the relay operates the longer the spill current can exceed its setting before operation occurs and the higher the spill current that can be tolerated.

$V_S \geq K\ I_F\ (R_{CT}+2R_L)$ -----[1]

Where:

R_{CT} = current transformer secondary winding resistance
R_L = maximum lead resistance from the current transformer to the relaying point
I_F = maximum secondary external fault current
K = a constant affected by the dynamic response of the relay and the application

NOTE: When high impedance differential protection is applied to motors or shunt reactors, the external fault current contribution from the motor/reactor is much smaller than the internal fault current. In these cases, the locked rotor current or starting current of the motor, or reactor inrush current, should be used in place of the external fault current used for stability calculations.

To obtain high speed operation for internal faults, the knee point voltage, V_K, of the CTs must be significantly higher than the stability voltage, V_S. This is essential so that the operating current through the relay is a sufficient multiple of the applied current setting.

The kneepoint voltage of a current transformer marks the upper limit of the roughly linear portion of the secondary winding excitation characteristic. This is defined exactly in the IEC standards as that point on the excitation curve where a 10% increase in exciting voltage produces a 50% increase in exciting current.

The current transformers should be of equal ratio, of similar magnetizing characteristics and of low reactance construction. In cases where low reactance current transformers are not available and high reactance ones must be used, it is essential to use the reactance of the current transformer in the calculations for the voltage setting. Thus, the current transformer impedance is expressed as a complex number in the form $R_{CT} + jX_{CT}$. It is also necessary to ensure that the exciting impedance of the current transformer is large in comparison with its secondary ohmic impedance at the relay setting voltage.

In the case of the high impedance relay, the operating current is adjustable in discrete steps. The primary operating current (I_{OP}) will be a function of the current transformer ratio, the relay operating current (I_r), the number of current transformers in parallel with a relay element (n) and the magnetizing current of each current transformer (I_e) at the stability voltage (V_S). This relationship can be expressed as follows:

Iop = CT ratio x (Ir+n Ie ----- [2]

In order to achieve the required primary operating current with the current transformers that are used, a current setting (I_r) must be selected for the high impedance relay, as detailed above. The setting of the stabilizing resistor (R_{ST}) must be calculated in the following manner, where the setting is a function of the relay ohmic impedance at setting (R_r), the required stability voltage setting (V_S) and the relay current setting (I_r).

$$R_{ST} = \frac{V_S}{I_r} - R_r \qquad \text{-----[3]}$$

The ohmic impedance of auxiliary powered numerical relays such as the P12x is extremely small and so R_r may be ignored in equation [3]. The standard resistors that can be supplied for use in the high impedance application are wire-wound, continuously adjustable and have a continuous rating of 145W based upon AREVA conjunctive testing.

NOTE: The resistors should not be adjusted below 60% of their nominal ohmic value otherwise there is a risk that the power dissipation during faults will be insufficient.

1.2 Use of non-linear resistors

When the maximum through fault current is limited by the protected circuit impedance, such as in the case of generator differential and power transformer restricted earth fault protection, it is generally found unnecessary to use non-linear voltage limiting resistors (Metrosils). However, when the maximum through fault current is high, such as in busbar protection, it is more common to use a non-linear resistor (Metrosil) across the relay circuit (relay and stabilizing resistor). Metrosils are used to limit the peak voltage developed by the current transformers under internal fault conditions, to a value below the insulation level of the current transformers, relay and interconnecting leads, which are typically able to withstand approximately 3000V peak.

The following formulae should be used to estimate the peak transient voltage that could be produced for an internal fault. This voltage is a function of the current transformer kneepoint voltage and the prospective voltage that would be produced for an internal fault if current transformer saturation did not occur.

NOTE: The internal fault level, I'_f, can be significantly higher than the external fault level, I_f, on generators where current can be fed from the supply system and the generator. Similarly the internal fault level on motors and shunt reactors will be considerably higher than the values used in the stability calculations (motor start/locked rotor and inrush currents respectively).

$$V_P = 2\sqrt{2V_K\left(V_F - V_K\right)} \qquad \text{-----[4]}$$

$$V_F = I'_F\left(R_{CT} + 2R_L + R_{ST} + R_R\right) \qquad \text{-----[5]}$$

Where:

V_P = peak voltage developed by the CT under internal fault conditions
V_K = current transformer knee-point voltage
V_F = maximum voltage that would be produced if CT saturation did not occur
I'_f = maximum internal secondary fault current
R_{CT} = current transformer secondary winding resistance
R_L = maximum lead burden from CT to relay
R_{ST} = relay stabilizing resistor
R_r = relay ohmic impedance at setting

When the value of V_P is greater than 3000V peak, non-linear resistors (Metrosils) should be applied. They are effectively connected across the relay circuit, or phase to neutral of the ac buswires, and serve the purpose of shunting the secondary current output of the current transformer from the relay circuit in order to prevent very high secondary voltages.

Traditionally, Metrosils are externally mounted and take the form of annular discs, of 152mm diameter and approximately 10mm thickness. Their operating characteristics follow the expression:

$$V = CI^{0.25} \qquad \text{-----[6]}$$

Where:

V = instantaneous voltage applied to the non-linear resistor (Metrosil)
C = constant of the non-linear resistor (Metrosil)
I = instantaneous current through the non-linear resistor (Metrosil)

With a sinusoidal voltage applied across the Metrosil, the RMS current would be approximately 0.52x the peak current. This current value can be calculated as follows:

$$I_{RMS} = 0.52\left(\frac{V_{S(RMS)}\sqrt{2}}{C}\right)^4 \qquad \text{-----[7]}$$

Where:

$V_{S(RMS)}$ = rms value of the sinusoidal voltage applied across the Metrosil

This is due to the fact that the current waveform through the Metrosil is not sinusoidal but appreciably distorted.

For satisfactory application of a non-linear resistor (Metrosil), the current through the non-linear resistor at the relay voltage setting should be as low as possible but no greater than approximately 30mA rms for 1A CTs and approximately 100mA rms for 5A CTs.

2. APPLYING THE MICOM P12X RANGE

The P12x range are numerical phase overcurrent and earth fault relays with 3 stages of phase and/or earth fault protection, I>/ I_e>, I>>/ I_e>> and I>>>/ I_e>>> which can be used in high impedance applications. The P121, P122 and P123 are three phase relays and can be applied for use as 3 phase differential protection or restricted earth fault (REF) protection whereas the P120 is a single phase relay which can be used for REF protection only.

The protection element used for this specific application depends upon the type of P12x relay chosen. In the case of the P120 and P121 relays and the first two stages of protection on the P122 and P123, all stages use an identical Fourier algorithm. However, the third stage (I>>>/ I_e>>>) on the P122 and P123 may be set to use an element that is peak measuring (samples) which gives a significant improvement in operating time over the Fourier algorithm employed by the other protection elements. In all cases the time delay characteristic should be set to definite time (DT) and with a setting of zero seconds to give no intentional delay.

The “Trip Commands” menu (AUTMAT.CTRL) should be used to allocate the chosen protection elements (e.g. tI>>> etc) to the trip relay RL1. Any elements allocated in the trip commands menu will cause RL1 to pulse for 100ms but for applications where a 100ms pulse is insufficient, the pulse time can be extended up to 5 seconds in the “tOpen pulse” cell (AUTOMAT.CTRL/CB Supervision). This feature is not available in the P120 and P121 models but an alternative approach, which is available in all P12x relays, is to latch the trip output following a protection operation. This can be done by selecting the appropriate protection element (e.g. tI> etc) in the “Latch Functions” menu (AUTOMAT.CTRL).

Any elements not being used should be disabled by selecting “No” in the appropriate location.

The setting ranges of the P12x elements are:

Phase Overcurrent		**Input Board Rating: 0.1 to 40 I_n**	
I>		0.1 – 25 I_n	
I>>		0.5 – 40 I_n	
I>>>		0.5 – 40 I_n	
Earth Fault	**Input Board Rating**		
	0.002 to 1 I_{en}	0.01 to 8 I_{en}	0.1 to 40 I_{en}
I_e>	0.002 – 1 I_{en}	0.01 – 8 I_{en}	0.1 – 25 I_{en}
I_e>>	0.002 – 1 I_{en}	0.01 – 8 I_{en}	0.1 – 40 I_{en}
I_e>>>	0.002 – 1 I_{en}	0.01 – 8 I_{en}	0.5 – 40 I_{en}

Further details of the general setting capability and use of the MiCOM P12x relay may be found in the Technical Guide (P12x/EN T).

Since the performance of the P12x relay varies depending upon application, consideration must be given to which relay and protection element to use. The following data should be used as a guide in order to obtain the best performance from the relay.

NOTE: It is recommended that the dual powered MiCOM P124 relay is not used for differential protection because of the start-up time delay when powered from the CTs alone. Additionally, the minimum setting of the phase overcurrent elements, 0.2In, would limit its application for differential protection.

2.1 Restricted earth fault (REF or [87N]) applications

For REF applications it is generally recommended that the 0.01 to 8 I_{en} input board is used as this provides a good compromise of sensitivity and CT sizing. For advice on using the other earth fault input boards (0.002 to 1 I_{en} and 0.1 to 40 I_{en}), please contact AREVA T&D UK Ltd, or your local representative.

On the P120 or P121 any of the three earth fault elements may be used as they all use the same Fourier based algorithm. However, on the P122 and P123 the third stage element, Ie>>>, may be used and set to peak measuring (samples) as this will give improved operating times.

After extensive conjunctive testing of these elements in this application it has been found that the value of K used in equation [1] should be 1 and that generally a ratio of $V_K/V_S \geq 4$ will be adequate. In other words, for REF applications we can state that;

$$\text{Relay Stability Voltage, } V_S = I_F(R_{CT} + 2R_L)$$

$$\text{and CT kneepoint voltage, } V_K \geq 4V_S$$

For REF applications with a reduced system X/R ratio of ≤40 then it is possible to reduce the V_K/V_S to ≥2.

The recommended relay current setting for restricted earth fault protection is usually determined by the minimum fault current available for operation of the relay and whenever possible it should not be greater than 30% of the minimum fault level.

Figures 2 to 5 show how the P12x earth fault elements can be utilized in REF applications.

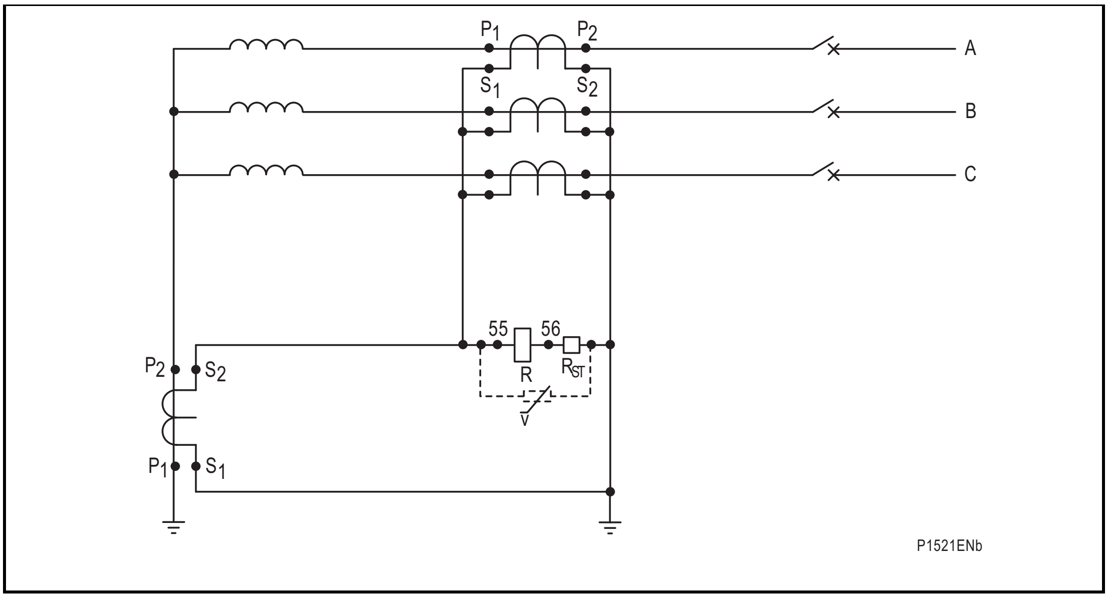

Figure 2: Restricted earth fault protection of a 3 phase, 3 wire system applicable to star connected generators or power transformer windings with neutral earthed at generator/transformer starpoint. (1A connections shown)

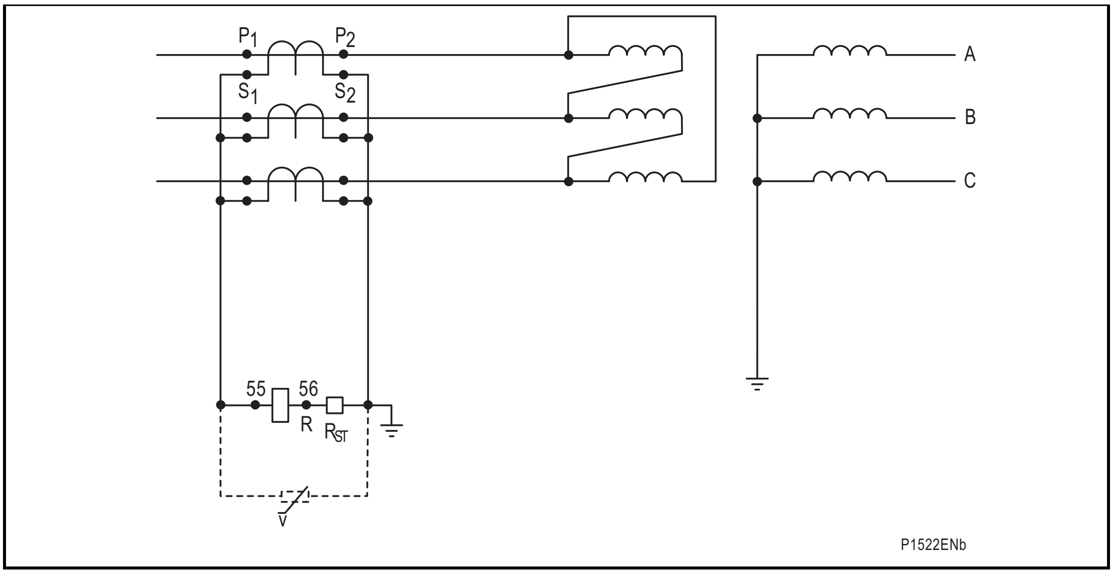

Figure 3: Balanced or restricted earth fault protection for the delta winding of a power transformer with supply system earthed (1A connections shown)

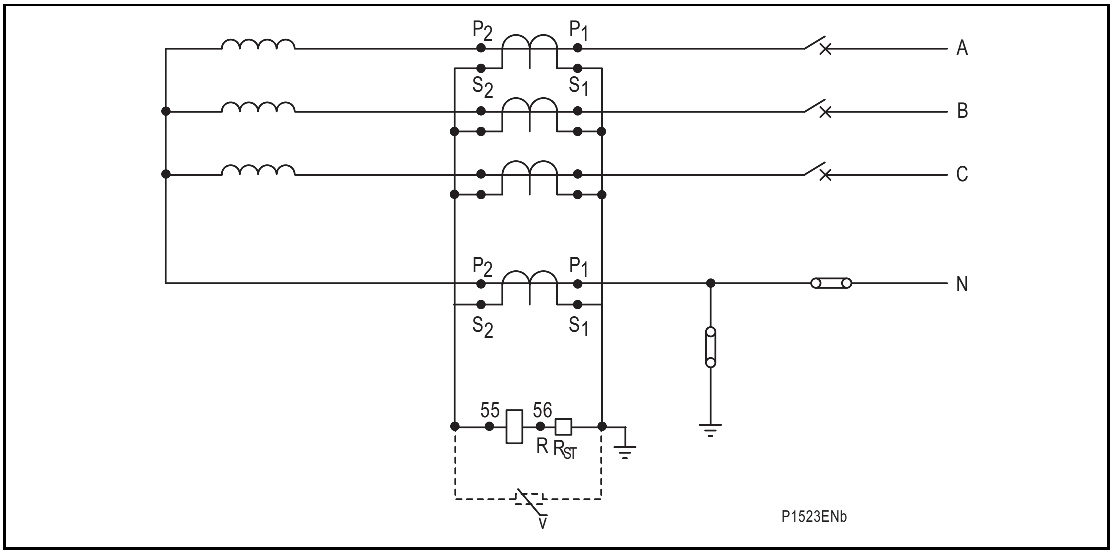

Figure 4: Restricted earth fault protection of a 3 phase, 4 wire system applicable to star connected generators or power transformer windings with neutral earthed at switchboard (1A connections shown)

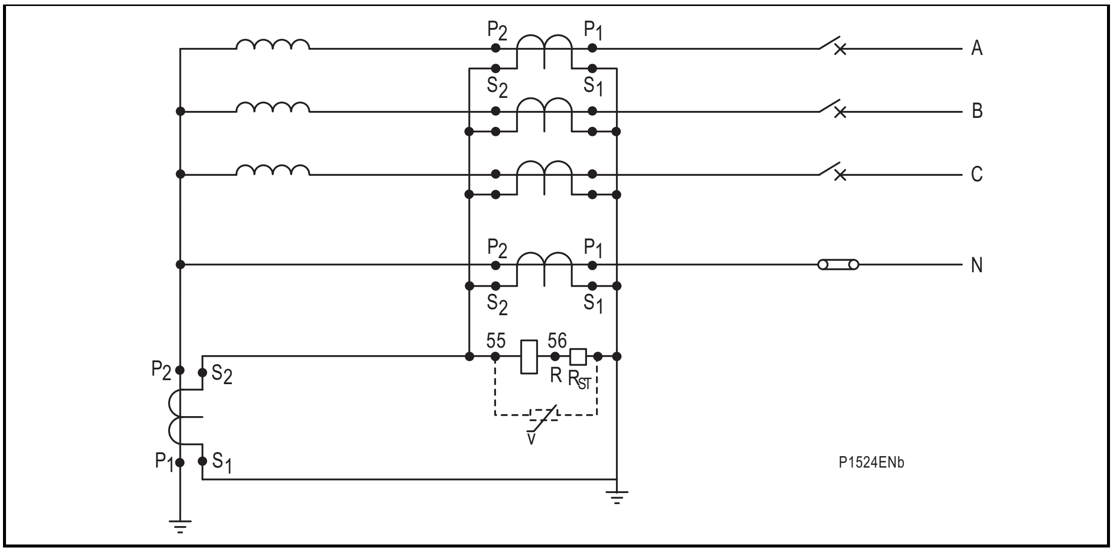

Figure 5: Restricted earth fault protection of a 3 phase, 4 wire system applicable to star connected generators or power transformer windings with neutral earthed at generator/transformer starpoint. (1A connections shown)

2.2 Three phase ([87]) applications

On the P121 any of the three overcurrent elements may be used as they all use the same Fourier based algorithm. These elements are suitable for applications where the system X/R ratio does not exceed 40. Higher system X/R ratios will have a detrimental effect on relay operating time and hence it is recommended that the third stage element set to peak measuring (samples) of a P122 or P123 is used as this will give improved performance.

After extensive conjunctive testing of these elements in this application it has been found that the value of K used in equation [1] should be 1.4 and that generally a ratio of $V_K/V_S \geq 4$ will be adequate. In other words, for three phase applications we can state that;

$$\text{Relay Stability Voltage, } V_S = 1.4 I_F (R_{CT} + 2R_L)$$
$$\text{and CT kneepoint voltage, } V_K \geq 4V_S$$

For busbar applications with a reduced system X/R ratio of ≤40 then it is possible to reduce the V_K/V_S to ≥2.

For busbar protection, it is considered good practice by some utilities to set the minimum primary operating current in excess of the rated load such that if one of the current transformers becomes open circuit, the high impedance relay does not maloperate. Other utilities prefer to set the relay as sensitive as possible and use a second check relay connected to a separate set of current transformers to provide security against maloperation.

For generator and motor protection, the relay is generally set as sensitive as possible to maximize fault coverage. In these applications it is important to recognize that the external fault level contribution from the generator or motor may be significantly lower than the internal fault level. The external fault level should be used for the calculation of stability voltage and resistor requirements whereas the internal fault level (that includes system contribution) should be used for non-linear resistor (Metrosil) calculations.

Figures 6 to 8 show how the P12x overcurrent elements can be utilized in differential protection applications.

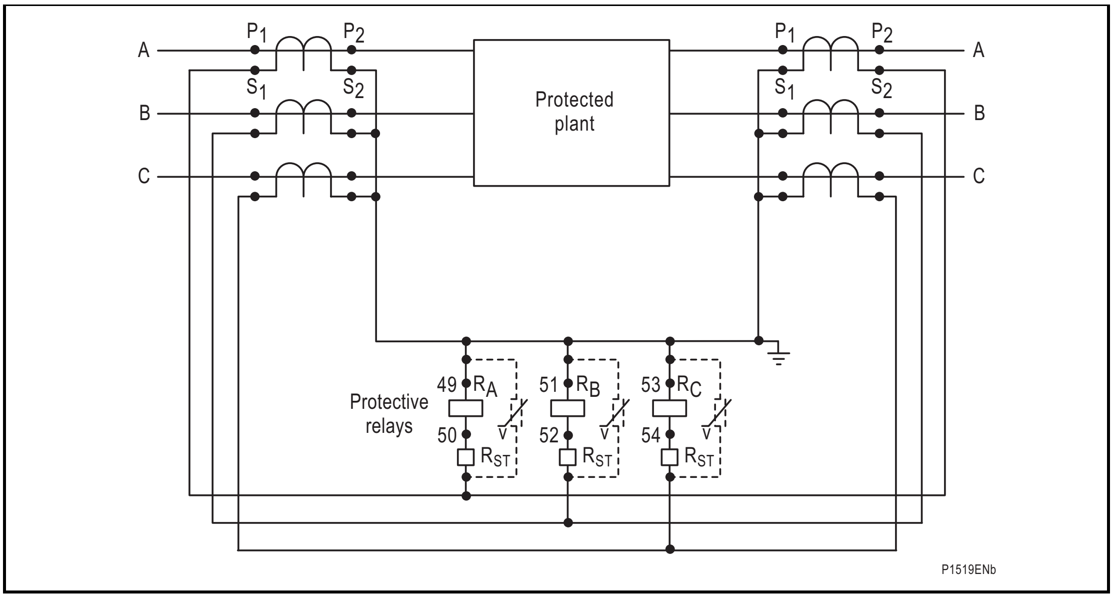

Figure 6: Phase and earth fault differential protection for generators, motors or reactors (1A connections shown)

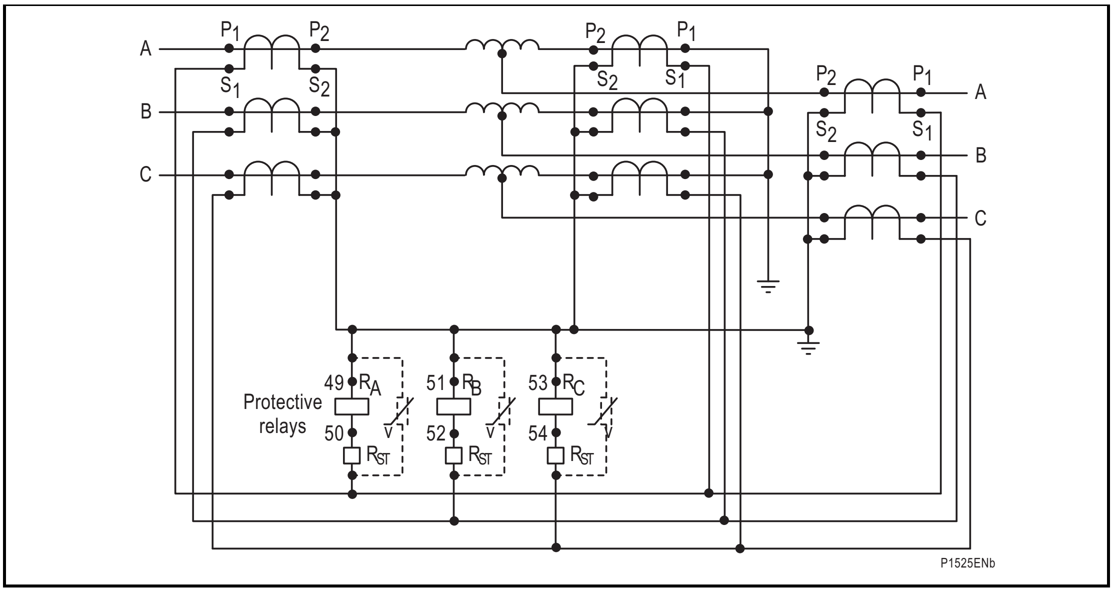

Figure 7: Phase and earth fault differential protection for an auto-transformer with CTs at the neutral star point (1A connections shown)

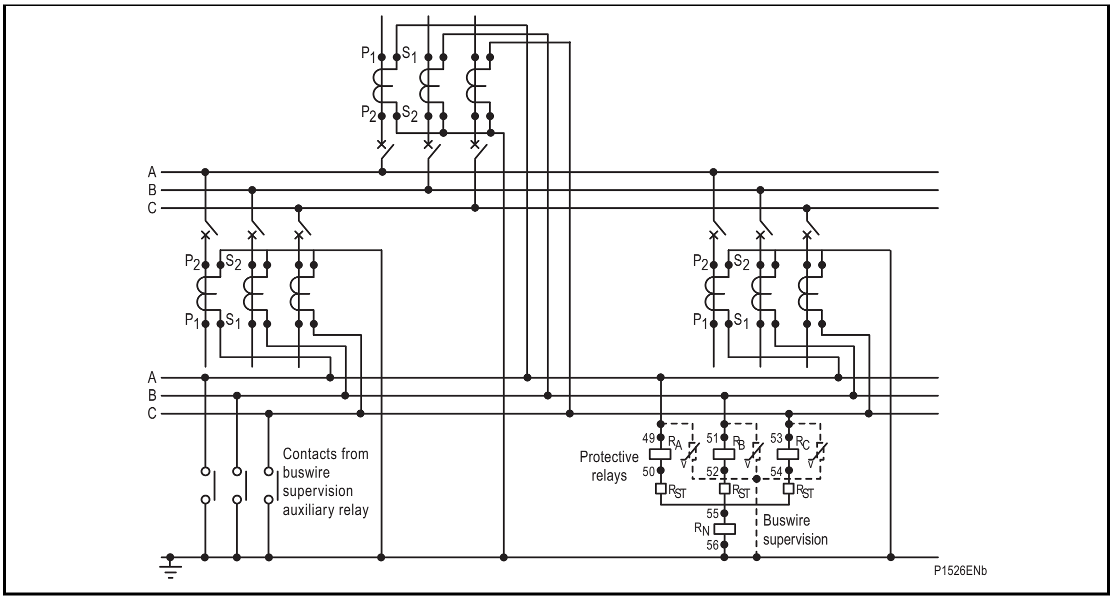

Figure 8: A simple, single zone phase and earth fault busbar protection scheme with buswire supervision (1A connections shown)

2.2.1 Buswire supervision

The Ie> earth fault element with its low current settings can be used for buswire supervision. When a CT or the buswires become open circuited the 3 phase currents will become unbalanced and residual current will flow. This infers that operation for three phase problems in the CTs or buswires is not guaranteed since the currents through the supervision element may summate to zero. The Ie> earth fault element should give an alarm for most open circuit conditions but will not stop a maloperation of the differential element if it is set below rated load. For this reason, a check zone relay is usually used (fed from a separate set of CTs mounted on incoming and outgoing feeders only) to ensure that the busbar is stable even though there may be a wiring or CT problem.

The supervision element should be time delayed to prevent spurious operation during through fault conditions. The supervision element should be used to energize an auxiliary relay with mechanically latched contacts connected to short circuit the buswires and render the busbar zone protection inoperative thereby preventing thermal damage to the scheme. Contacts may also be required for busbar supervision alarm purposes.

Whenever possible the supervision primary operating current should not be more than 25A or 10% of the smallest circuit rating, whichever is the greater. The earth fault element (Ie>) should be connected at the star point of the stabilizing resistors, as shown in Figure 8. The time delay setting for the supervision elements (tIe>) is generally 3 seconds or more.

NOTE: It is important that the residual current is checked when the busbar is under load to ensure that the supervision threshold Ie>, is set above any standing unbalance current. The measured residual current may be viewed in the Measurements of the relay.

The earth fault based supervision element may be supplemented with a spare phase protection stage (I>) set to the same setting as the Ie> element, or the lowest available setting of 0.1In, if Ie> is set lower than this.

2.3 Typical operating times

The typical operating times for REF applications are given in table 1.

Relay Element	System X/R ratio	VK/VS Ratio	Constraints	Typical Operating time (in ms)
P120/P121 all elements. P122/P123 all elements not set for sample operation.	≤ 120	≥ 4	-	<30
	≤ 40	≥ 2	Fault level ≤20In	<30
P122/P123 stage 3 elements set for sample operation	≤ 120	≥ 4	-	<30
	≤ 40	≥ 2	-	<40

Table 1: REF application typical operating times

The typical operating times for Busbar applications are given in table 2.

Relay Element	System X/R ratio	VK/VS Ratio	Constraints	Typical Operating time (in ms)
P120/P121 all elements. P122/P123 all elements not set for sample operation.	≤ 120	≥ 4	-	<40
	≤ 40	≥ 2	Fault level ≤20In	<40
P122/P123 stage 3 elements set for sample operation	≤ 120	≥ 4	Fault level ≥5xIs	<40
	≤ 40	≥ 2	Fault level ≥5xIs	<30

Table 2: Busbar application typical operating times

For X/R ratios greater than 40 it is strongly recommended that the P122/P123 I>>> element is used.

2.4 Advanced application requirements

As stated in section 2.1 and 2.2 a ratio of $V_K/V_S \geq 4$ will be appropriate for most P12x high impedance applications. However, in some instances the V_S calculated using the standard formula may lead to large kneepoint voltage requirements, especially for busbar applications. In this case, it is possible to reduce the V_S setting based upon transient stability limits derived from the conjunctive testing.

For three phase applications where the system X/R ratio is less than 40, the formula for the required voltage setting V_S may be modified to:

$$\text{Relay Stability Voltage, } V_S = \left(0.007\frac{X}{R} + 1.05\right) I_F \left(R_{CT} + 2R_L\right) \qquad \text{---[8]}$$

If the system X/R ratio is more than 40, the standard formula should be used with the K-factor being 1.4.

This reduced stability voltage only applies to three phase applications – the stability voltage calculation for REF applications cannot be modified for the P12x relays.

2.5 Recommended non-linear resistors

2.5.1 Metrosils

The Metrosil units normally recommended are as follows:

Metrosil Units for 1A CT's		
Relay Stabiliy Voltage Setting (VS)	Recommended Metrosil Type	
	Single Pole	Three Pole
Up to 125V rms	600A/S1/S256 C = 450	600A/S3/I/S802 C = 450
125 – 300V rms	600A/S1/S1088 C = 900	600A/S3/I/S1195 C = 900

Metrosil Units for 5A CT's (single pole shown only)				
Secondary Internal Fault Current	Recommended Metrosil Type			
	Relay Stability Voltage Setting (VS)			
	Up to 200V rms	250V rms	275V rms	300V rms
50A rms	600A/S1/S1213 C = 540/640	600A/S1/S1214 C = 670/800	600A/S1/S1214 C = 670/800	600A/S1/S1223 C=740/870
100A rms	600A/S2/P/S1217 C = 470/540	600A/S2/P/S1215 C = 570/670	600A/S2/P/S1215 C = 570/670	600A/S2/P/S1196 C = 620/740
150A rms	600A/S3/P/S1219 C = 430/500	600A/S3/P/S1220 C = 520/620	600A/S3/P/S1221 C = 570/670	600A/S3/P/S1222 C = 620/740

Table 3: Recommended metrosils for use with the MiCOM P12x relays

The single pole Metrosil units recommended for use with 5A CTs can also be used with triple pole relays and consist of three single pole units mounted on the same central stud but electrically insulated from each other. A 'triple pole' Metrosil type and the reference should be specified when ordering. Metrosil units for higher stability voltage settings and fault currents can be supplied if required.

2.5.2 Integrated non-linear resistor and resistors

As an alternative to utilizing individual resistors and Metrosils, it is also possible to utilize an integrated unit of resistors and non-linear resistors (X2/DVZ3R). The X2/DVZ3R unit contains a number of fixed resistors capable of providing a stabilizing resistance of 500Ω, 1000Ω or 2000Ω per phase, dependent upon connection. Since the resistances are fixed value it must be considered that limitations in the available stability voltage will occur. For example, the minimum stability voltage that can be achieved with a 0.1A setting is 50V, 100V and 200V for the 500Ω, 1000Ω or 2000Ω resistances. The connections for the X2/DVZ3R unit are shown in figures 9 to 11.

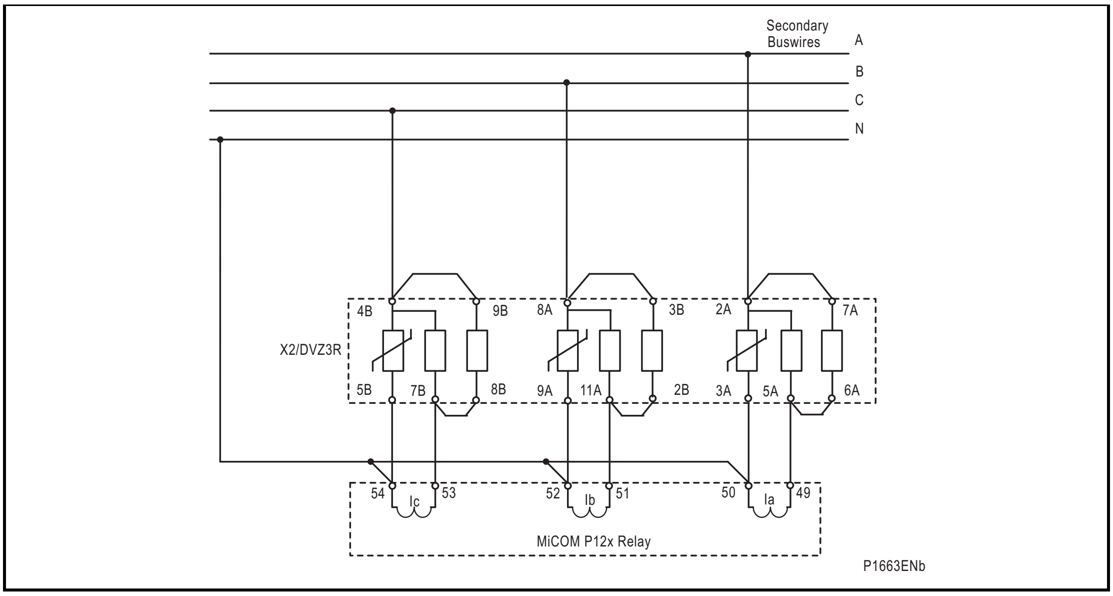

Figure 9: X2/DVZ3R connections for 500Ω stabilizing resistance (1A connections shown)

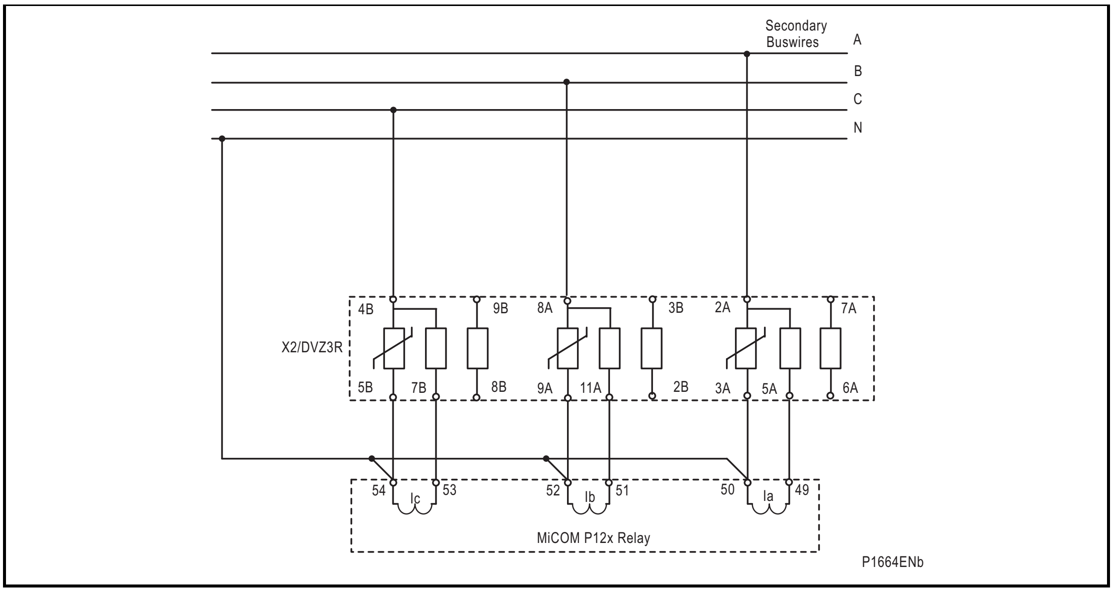

Figure 10: X2/DVZ3R connections for 1000Ω stabilizing resistance (1A connections shown)

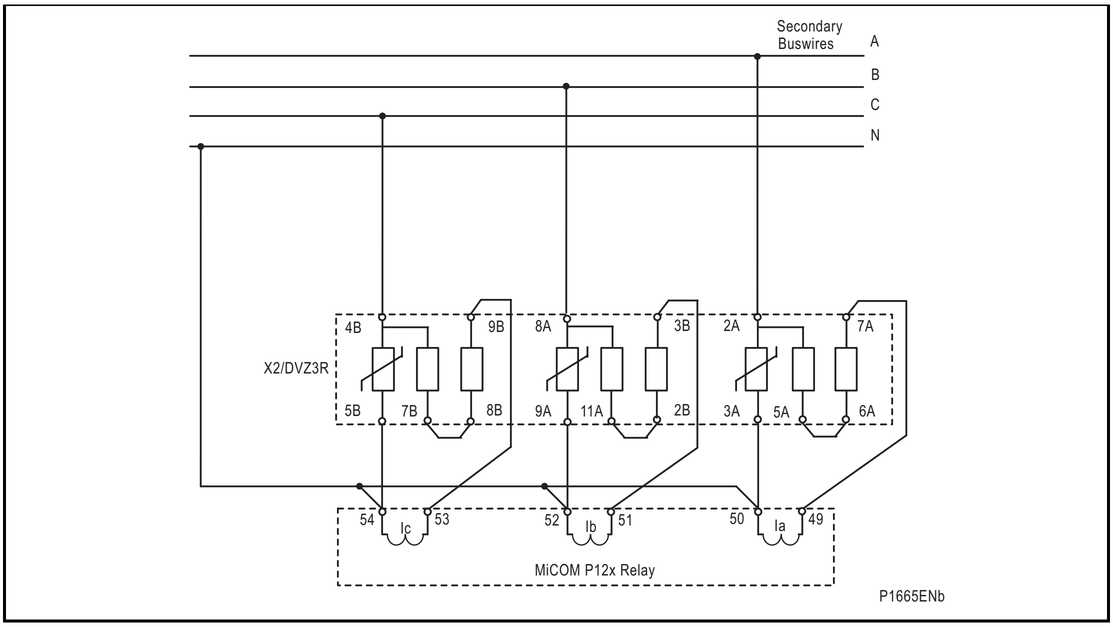

Figure 11: X2/DVZ3R connections for 2000Ω stabilizing resistance (1A connections shown)

In addition to the stabilizing resistors, non-linear resistors are included for each phase that will limit the voltage across the circuit to approximately 2200V.

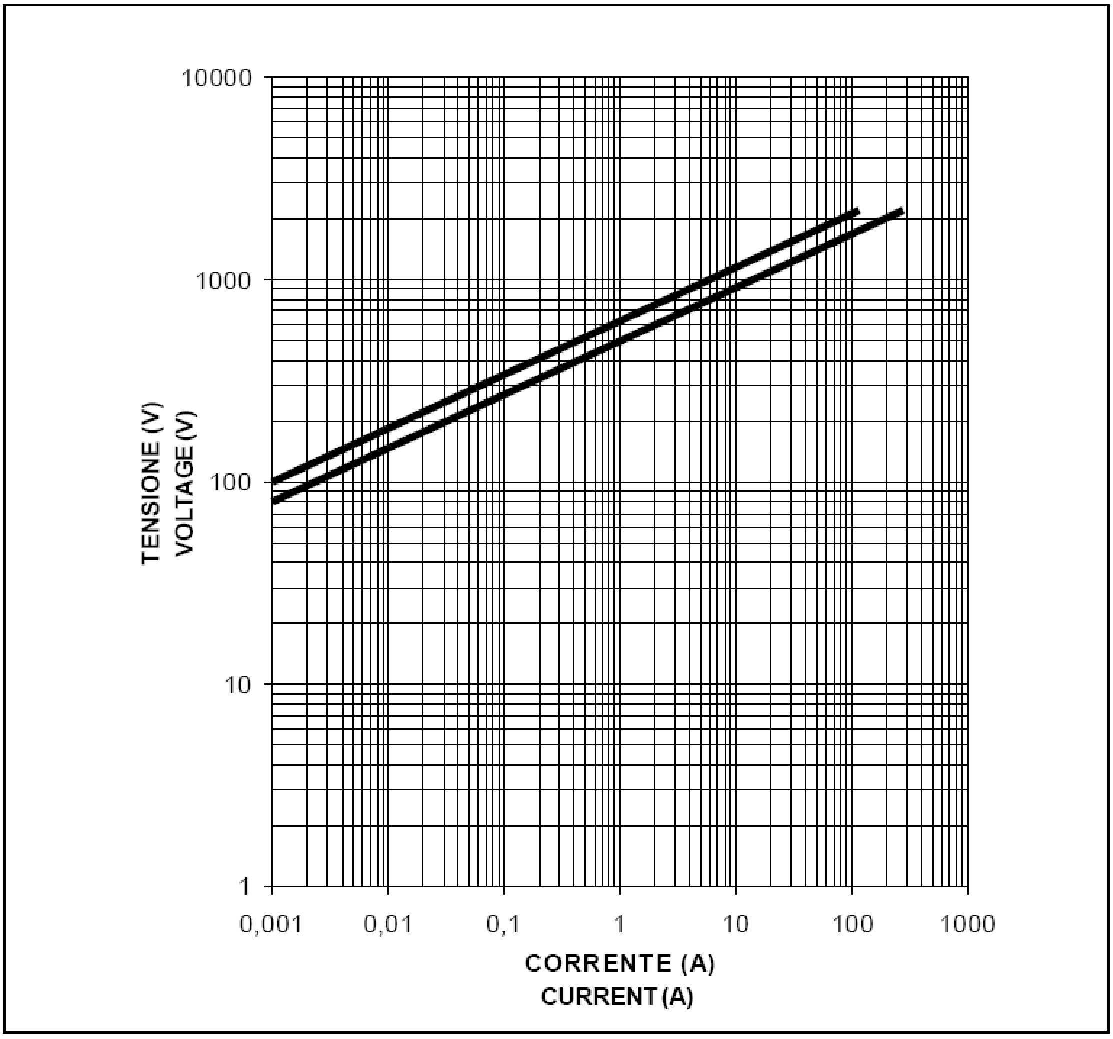

Figure 12: Characteristic of the non-linear resistors used in the X2/DVZ3R

When using the X2/DVZ3R integrated unit, it is recommended that following operation of the differential element, the stabilizing resistor or the entire differential path be short-circuited to help reduce the power dissipation requirements of the scheme. This shorting can be performed using contacts of the P12x relay itself or an external auxiliary device triggered from the P12x high impedance trip function. If the entire differential path is bypassed in this manner, it may be necessary to ensure that the trip contacts are latched at least until the fault has been cleared.

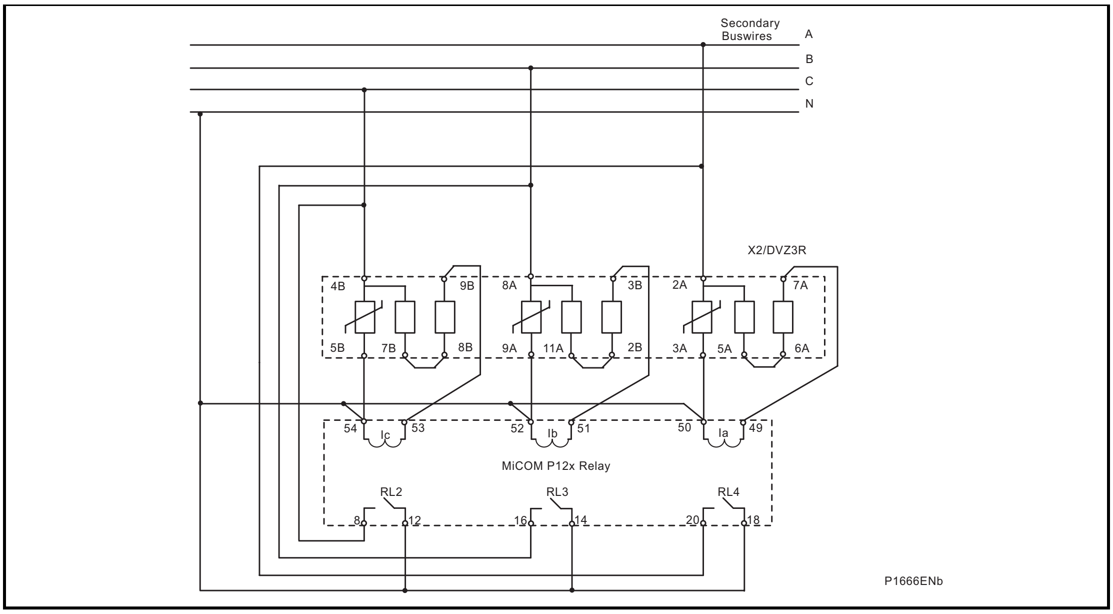

Figure 13: Example connection of the X2/DVZ3R with the entire differential path short-circuited following operation. (1A connections shown)

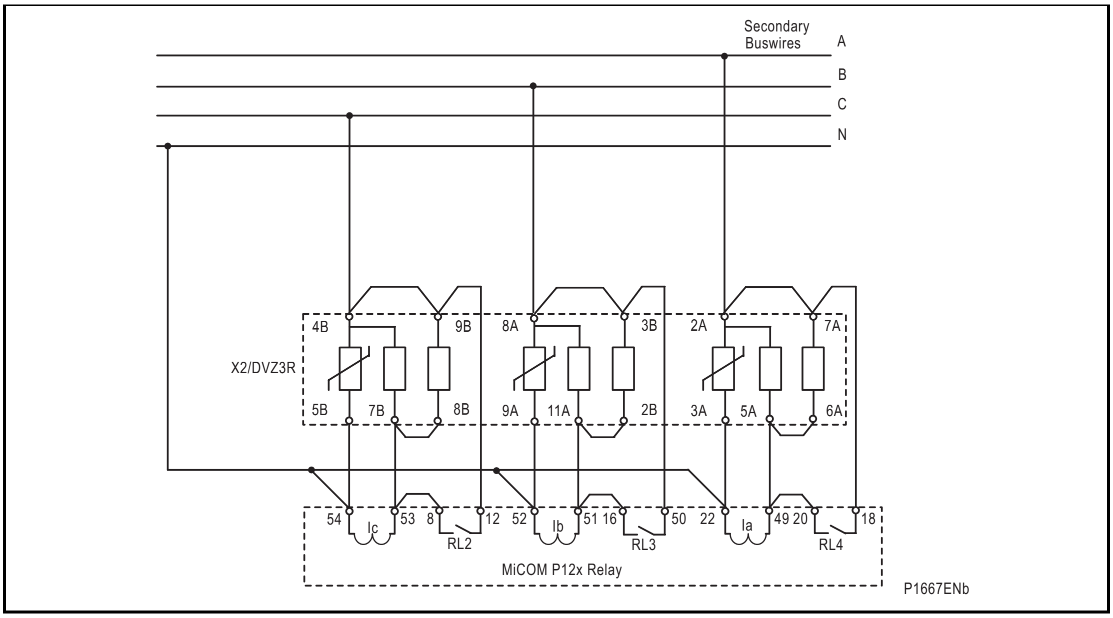

Figure 14: Example connection of the X2/DVZ3R with the stabilizing resistor short-circuited following operation. (1A connections shown)

3. SETTING EXAMPLES

3.1 Restricted earth fault application

The application of a P12x relay as a high impedance relay can be best illustrated by means of an example. Figure 13 shows an application for which REF protection is required on the LV winding of a power transformer. In this example the earth fault input is used to provide the restricted earth fault protection and any remaining phase inputs could be utilized to provide normal overcurrent based protection.

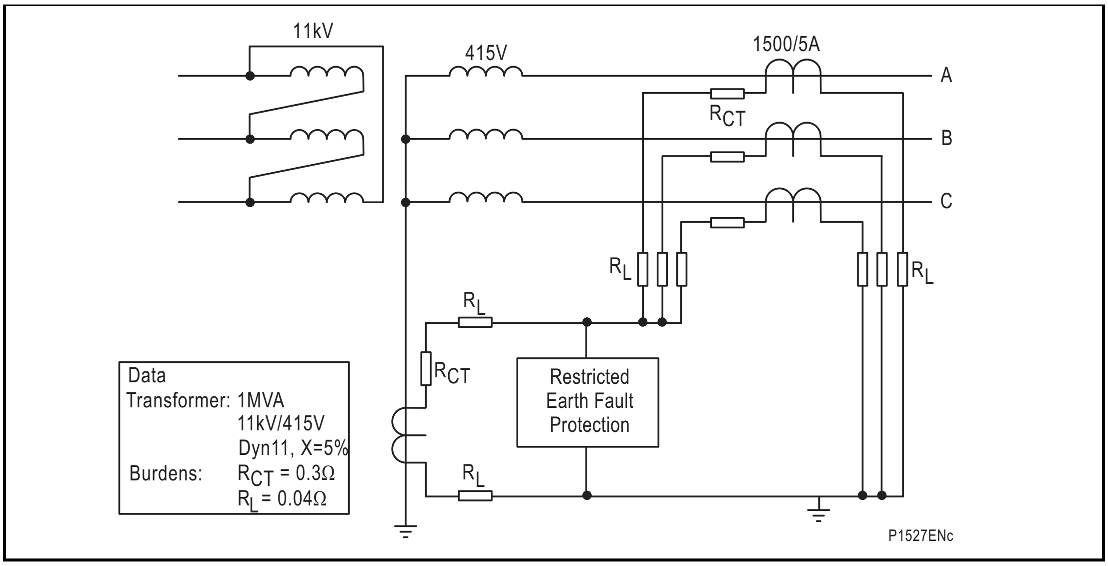

Figure 15: Restricted earth fault protection on a transformer

3.1.1 Stability voltage

The transformer full load current, I_{FLC}, is:

$$I_{FLC} = \frac{1MVA}{415\sqrt{3}}$$
$$= 1391.2A$$

Maximum through fault level, ignoring source impedance, I_F, is:

$$I_F = \frac{I_{FLC}}{X_{TX}}$$
$$= \frac{1391.2A}{5\%} = 27824A$$

Required relay stability voltage, V_S, and assuming one CT saturated is:

$$V_S = KI_F(R_{CT} + 2R_L)$$
$$= 27824x\frac{5}{1500}(0.3 + 0.08)$$
$$= \mathbf{35.24V}$$

3.1.2 Stabilizing resistor

Assuming that the relay effective setting for a solidly earthed power transformer is approximately 30% of the full load current, we can calculate that a setting of less than 1.391A is required on the relay. Assuming that a setting of 1A is selected the stabilizing resistor, R_{ST}, required is:

$$R_{ST} = \frac{V_S}{Ie >} = 35.24\Omega$$

For this application a 47Ω resistor can be supplied on request which can be adjusted to any value between 28Ω and 47Ω. Thus a setting of 35.2Ω is available.

3.1.3 Current transformer requirements

To ensure that internal faults are cleared in the shortest possible time and since no information is provided concerning system X/R ratio, the kneepoint voltage of the current transformers should be at least 4 times the stability voltage:

$$\text{Kneepoint Voltage, } V_K \geq 4V_S$$
$$\geq 141V$$

By re-arranging equation [2], the excitation current for each of the current transformers at the relay stability voltage can be calculated:

$$\text{CT Magnetising current at stability voltage, } I_e \leq \frac{\frac{I_S}{\text{CT Ratio}} - I_R}{n}$$
$$\leq \frac{1.391 - 1}{4}$$
$$\leq 0.1A$$

In summary, the current transformers used for this application must have a kneepoint voltage of 141V or higher, with a secondary winding resistance of 0.3Ω or lower and a magnetizing current at 35.2V of less than 0.1A.

3.1.4 Non-linear resistor requirements

If the peak voltage developed across the relay circuit under maximum internal fault conditions exceeds 3000V peak then a suitable non-linear resistor (Metrosil) should be connected across the relay and stabilizing resistor, in order to protect the insulation of the CTs, relay and interconnecting leads. Using equation [5] we can calculate the maximum fault voltage assuming no CT saturation:

$$V_F = I_F^{'}(R_{CT} + 2R_L + R_{ST} + R_R)$$
$$= 27824x\frac{5}{1500}(0.3 + 0.08 + 35.24)$$
$$= 92.75(35.62)$$
$$= 3303.6V$$

Based upon this and assuming that the CT kneepoint voltage is 141V, we can estimate the peak voltage as:

$$V_P = 2\sqrt{2V_K(V_F - V_K)}$$
$$= 2\sqrt{2x141(3303.6 - 141)}$$
$$= 1888.76V$$

This value is below the peak voltage of 3000V and therefore a non-linear resistor (Metrosil) is not required.

NOTE: The kneepoint voltage value used in the above formula should be the actual voltage obtained from the CT magnetising characteristic and not a calculated value.

3.2 Busbar applications

Figure 14 shows an application of the P12x for high impedance protection of a typical 132kV double bus generating station, consisting of two 100MVA generators and step-up transformers, two bus-couplers and four overhead transmission lines. Each busbar is sectionalized and therefore gives a requirement for four discriminating zone and one overall check zone.

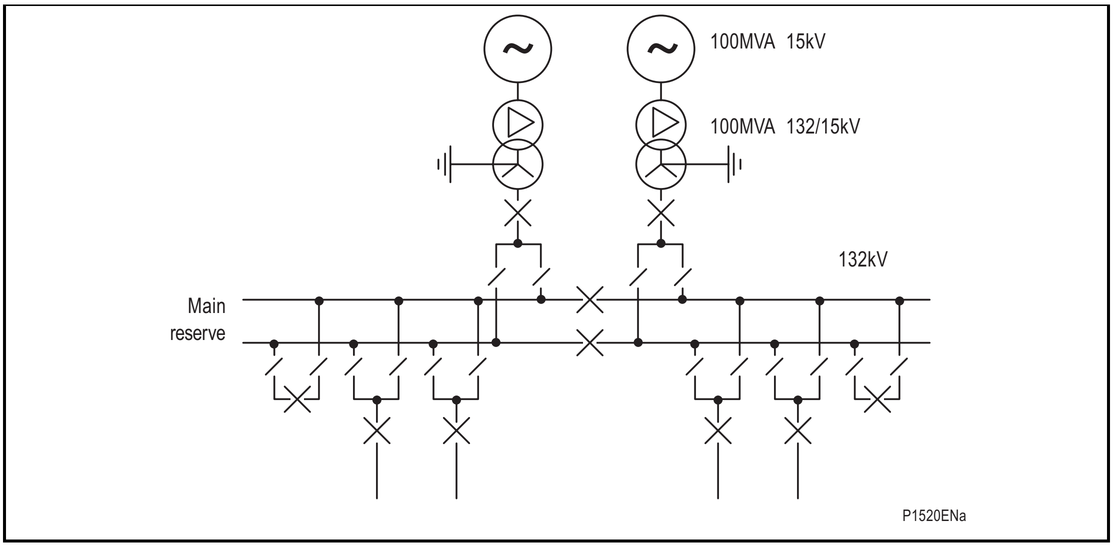

Figure 16: Three phase and earth fault protection of a double busbar generating station

For the purpose of this example it is assumed that all switchgear is rated for 3500MVA, that the system is solidly earthed and the system X/R ratio is 20. All circuits have the same CT ratio of 500/1A with a secondary winding resistance of 0.7Ω and the largest loop lead resistance is 2Ω.

3.2.1 Stability voltage

The stability level of the busbar protection is governed by the maximum through fault level which is assumed to be the switchgear rating. Using the switchgear rating also allows for any future expansion of the busbar:

$$\text{Maximum through fault current, } I_F = \frac{\text{Switchgear rating}}{\text{Voltage x }\sqrt{3}}$$

$$= \frac{3500\text{MVA}}{132\text{kV}\sqrt{3}}$$

$$= 15308\text{A}$$

Required relay stability voltage, V_S, and assuming one CT saturated is:

$$V_S = KI_F(R_{CT} + 2R_L)$$

$$= 1.4\text{x}15308\text{x}\frac{1}{500}(0.7 + 2)$$

$$= \mathbf{116V}$$

3.2.2 Discriminating zone effective setting

The primary operating current should be made less than 30% of the minimum fault current and more than the full load current of one of the incomers. Thus, if one of the incomer CTs becomes open circuit the differential protection will not maloperate. It is assumed that 30% of the minimum fault current is more than the full load current of the largest circuit.

$$\text{Full Load current, } I_{FLC} = \frac{100\text{MVA}}{132\text{kV}\sqrt{3}}$$
$$= 437.4\text{A}$$

Now if we assume that the magnetizing current taken by each CT at 116V is 0.072A and the relay current setting is 0.8A, we can calculate for the discriminating zone:

$$\text{Primary Effective Operating current, } I_{OP} = \text{CT Ratio}\left(I_r + nI_e\right)$$
$$= \frac{500}{1}\left(0.8 + \left(5\text{x}0.072\right)\right)$$
$$= 580\text{A}$$
$$= 132\% \text{ of } I_{FLC}$$

Since the primary effective setting is greater than the full load current, we can say that that relay setting of 0.8A is suitable for the discriminating zone.

3.2.3 Check zone effective setting

Using the same reasoning and assumptions as already used for the discriminating zone, we can calculate for the check zone:

$$\text{Primary Effective Operating current, } I_{OP} = \text{CT Ratio}\left(I_r + nI_e\right)$$
$$= \frac{500}{1}\left(0.8 + \left(6\text{x}0.072\right)\right)$$
$$= 616\text{A}$$
$$= 141\% \text{ of } I_{FLC}$$

Since the primary effective setting is greater than the full load current, we can say that that relay setting of 0.8A is suitable for the check zone.

3.2.4 Stabilizing resistor

The required value of stabilizing resistor, R_{ST}, is:

$$R_{ST} = \frac{V_S}{I>}$$
$$= \frac{116}{0.8}$$
$$= 145\Omega$$

For this application a 220Ω resistor can be supplied on request which can be adjusted to any value between 132Ω and 220Ω. Thus a setting of 145Ω is available.

3.2.5 Current transformer requirements

To ensure that internal faults are cleared in the shortest possible time and since the system X/R ratio is less than 40, the kneepoint voltage of the current transformers should be at least 2 times the stability voltage:

$$\text{Kneepoint Voltage, } V_K \geq 4V_S$$
$$\geq 464\text{V}$$

In summary, the current transformers used for this application must have a kneepoint voltage of 232V or higher, with a secondary winding resistance of 0.7Ω or lower and a magnetizing current at 116V of less than 0.072A.

3.2.6 Non-linear resistor requirements

If the peak voltage developed across the relay circuit under maximum internal fault conditions exceeds 3000V peak then a suitable non-linear resistor (Metrosil) should be connected across the relay and stabilizing resistor, in order to protect the insulation of the CTs, relay and interconnecting leads. Using equation [5] we can calculate the maximum fault voltage assuming no CT saturation:

$$
\begin{aligned}
V_F &= I'_F\left(R_{CT} + 2R_L + R_{ST} + R_R\right) \\
&= 15308x\frac{1}{500}\left(0.7 + 2 + 145\right) \\
&= 30.616(147.7) \\
&= 4522V
\end{aligned}
$$

Based upon this and assuming that the CT kneepoint voltage is 232V, we can estimate the peak voltage as:

$$
\begin{aligned}
V_P &= 2\sqrt{2V_K\left(V_F - V_K\right)} \\
&= 2\sqrt{2x464\left(4522 - 464\right)} \\
&= 3881.1V
\end{aligned}
$$

This value is below the peak voltage of 3000V and therefore a non-linear resistor (Metrosil) is not required. However, if a Metrosil was required it should be chosen based upon the CT secondary rating, maximum internal fault level and voltage setting. For example, if a V_K/V_S ratio of 4 had been used then the peak voltage would have been 3881.1V, and for this case the most appropriate type is 600A/S3/I/S1195. This Metrosil consists of three discs connected independently for this three phase application.

NOTE: The kneepoint voltage value used in the above formula should be the actual voltage obtained from the CT magnetising characteristic and not a calculated value.

3.2.7 Busbar supervision

Assuming that 25A is greater than 10% of the smallest circuit current we can calculate the supervision setting as:

$$
\begin{aligned}
\text{Buswire supervision setting} &= \frac{25A}{\text{CT Ratio}} \\
&= 0.05A
\end{aligned}
$$

Therefore the I_e> element should be set to 0.05A with a time delay setting, t I_e>, of 3s.

3.2.8 Integrated non-linear resistor and resistors

Instead of using the external resistors and Metrosils, the X2/DVZ3R integrated unit could be used in this application. In this case, the stabilizing resistance is fixed as either 500Ω, 1000Ω or 2000Ω which infers that the relay setting current must be modified. (The stability voltage is fixed by the requirements of the scheme). On this basis, and by rearranging the stabilizing resistor calculation we can state:-

$$
\begin{aligned}
\text{Required Relay Setting}, I> &= \frac{V_S}{R_{ST}} \\
&= 0.24A\ \left(\text{for } R_{ST} = 500\Omega\right) \\
&= 0.12A\ \left(\text{for } R_{ST} = 1000\Omega\right) \\
&= 0.06A\ \left(\text{for } R_{ST} = 2000\Omega\right)
\end{aligned}
$$

Since the minimum setting for the phase overcurrent element, I>, is 0.1A it can be seen that it is not possible to use the 2000Ω stabilizing resistor, but that either the 500Ω or 1000Ω resistance connections could be used. In both cases, it would be necessary to use the integrated non-linear resistor to protect the circuit.

Another consideration of utilizing this integrated box is the effect of the lower relay settings on the effective setting of the scheme. With either lower setting, the effective setting will be lower than full load current for all the discriminating and check zones and this may be perceived as unsatisfactory. In this case, additional shunt resistors may be required to increase the effective setting – please contact your local AREVA T&D representative for advice in this case.

3.2.9 Advanced application requirements

In order to reduce the kneepoint voltage of the CTs being used, it is possible to decrease the stability voltage for applications where the system X/R ratio is lower than 40. In this example, the system X/R ratio is 20 and therefore we can apply formula [8] to reduce the stability voltage:

$$\text{Relay Stability Voltage, } V_S = \left(0.007\frac{X}{R} + 1.05\right) I_F \left(R_{CT} + 2R_L\right)$$

$$= (0.14 + 1.05)\frac{15308}{500}(0.7 + 2)$$

$$= 98.37\text{V}$$

Based upon this revised stability voltage, it is possible to revise the stabilizing resistor to:

$$R_{ST} = \frac{V_S}{I>}$$

$$= \frac{98.37}{0.8}$$

$$= 123\Omega$$

For this application a 150Ω resistor can be supplied on request which can be adjusted to any value between 90Ω and 150Ω. Thus a setting of 123Ω is available.

To ensure that internal faults are cleared in the shortest possible time and since the system X/R ratio is less than 40, the kneepoint voltage of the current transformers should be at least 2 times the stability voltage:

$$\text{Kneepoint Voltage, } V_K \geq 2V_S$$

$$\geq 197\text{V}$$

In summary, the current transformers based upon the advanced formula must have a kneepoint voltage of 197V or higher, with a secondary winding resistance of 0.7Ω or lower and a magnetizing current at 98.4V of less than 0.072A. This is a reduction of kneepoint voltage of nearly 20% when compared to the calculated requirements based upon the standard formula.

3.3 Motor / generator applications

The same calculation principles that apply for the three phase protection of busbars can be applied to motors and generators, although special consideration of the fault current will be required. For these applications, the machine contribution to an external fault should be used in the stability voltage calculation and this can be significantly lower than the maximum internal fault current that should be used in the non-linear resistor calculation. For motors the starting current or locked rotor current value is usually used in the stability calculation and this will lead to relatively small CT requirements. Often the most sensitive relay settings are used and buswire supervision is rarely applied.

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