T&R Test Equipment Ltd

DVS3 & 50A-3PH Application
TESTING DISTANCE RELAYS

1. Introduction

The DVS3 mk2 and 50A-3PH may be used to generate impedances for testing distance relays. Using these units the relay zone boundaries may be tested and the trip time of each zone ascertained.

In testing distance relays, the 50A-3PH acts as a simple current source, supplying 3 phase current to the relay under test and a phase reference to the DVS3. The magnitude and phase angle of the voltage is controlled on the DVS3 to give the desired impedance. The impedance may either be varied continuously or in steps.

An Excel spreadsheet is available to accompany this application note to simplify conversion between impedance values and test voltages and currents.

2. DISTANCE RELAYS AND IMPEDANCE CHARACTERISTICS

2.1 Distance Relay Types

Distance relays are impedance relays – they operate on the ratio and phase angle between the system voltage and current. The relay operating characteristics are usually represented on an RX diagram as a circle or quadrilateral. Many distance relays have multiple areas of operation, or zones. Points on the RX diagram inside a zone cause the relay to trip. Time delays can usually be set for different zones, with increasing delays set for zones relating to sections of line further away from the relay.
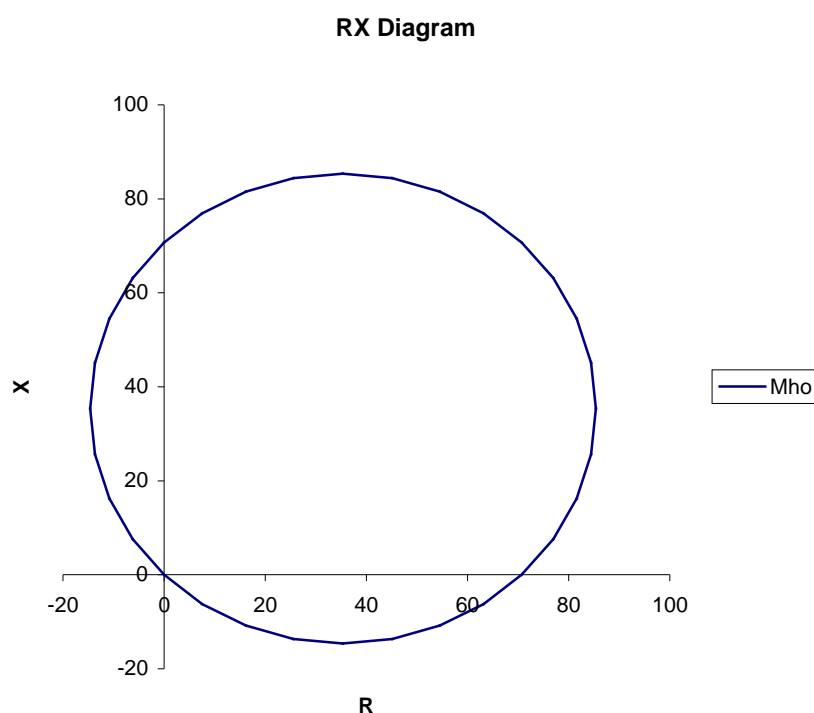
RX Diagram

Figure 1. Example RX Diagram – Mho Relay

Relays with other impedance characteristics are also available, including the quadrilateral characteristic implemented by many microprocessor relays.
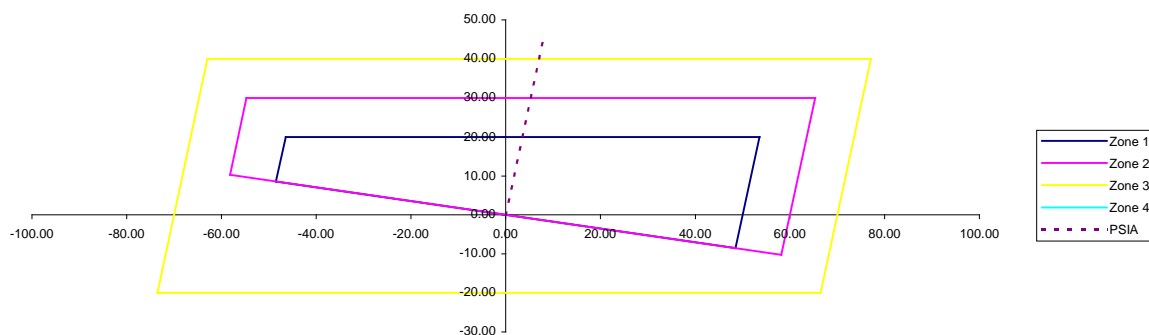

Figure 2. Example RX Diagram – Quadrilateral Relay

2.2 Primary System Impedance and Secondary Impedance

The relay may work in terms of primary system impedance or secondary impedances. In the examples in 2.2.1 and 2.2.2 a system will be considered with the following parameters:

- System voltage: 230kV
- System rated current: 1000A
- VT Ratio: 230kV/110V
- CT Ratio: 1000/1A
- Line positive sequence impedance 48.42Ω ∠79.41°

2.2.1 Secondary Impedance

Secondary impedances are calculated directly from the voltages measured on the secondaries of the protection VTs and CTs – the voltages and currents that the relay actually "sees". In this case, the rated VT secondary voltage is 110V, and the CT nominal secondary current is 1A. If secondary impedances are used, all system impedances must be scaled to secondary impedances before being used in relay setting calculations.

Many older distance relays work in terms of secondary voltages, currents and impedances.

2.2.2 Primary Impedance

Primary impedances are referred to the actual system voltages and currents on the lines monitored by the relay. For a relay to work in terms of primary impedance the relay must be programmed with the VT and CT ratio. The primary voltages, currents and impedances are calculated by the relay from the CT and VT secondary values and the CT and VT ratios.

Most numerical distance protection works in terms of primary system voltages, currents and impedances.

2.2.3 Conversion Between Primary and Secondary Impedances

To convert a primary impedance to a secondary impedance or vice-versa the equations below may be used. The equations hold true for impedances expressed as complex values or as magnitude∠phase values. In the case of the magnitude∠phase values, the phase angle of the impedance is unchanged by the calculation.

$$Z_{\text{sec}} = Z_{pri} . \frac{Ratio_{VT}}{Ratio_{CT}}$$

$$Z_{pri} = Z_{\text{sec}} . \frac{Ratio_{CT}}{Ratio_{VT}}$$

e.g The line positive sequence above is 48.42Ω $\angle$79.41° as a primary system impedance. To calculate this expressed as an impedance referred to the CT & VT secondary, carry out the following calculation:

$$Z_{\text{sec}} = Z_{pri} . \frac{Ratio_{VT}}{Ratio_{CT}}$$

$$Z_{\text{sec}} = 48.42 \frac{230000/110}{1000/1}$$

$$Z_{\text{sec}} = 101.3\Omega \angle 79.41°$$

3. DISTANCE RELAY TEST STRATEGY

The basic strategy in testing a distance relay with the DVS3 and 50A-3PH is to generate a series of test impedances that check the locations of the boundaries of the zones under test. Unless separate contacts are available for each zone of operation, the operation of a particular zone is differentiated during test by the trip time of the relay.

The relay is tested by applying a series of impedances to the relay by leaving the current fixed and altering the voltage magnitude and phase angle using the DVS3. By typing in values for the voltage, step changes of impedance can be generated which step from outside of the trip zone of the relay to inside of any of the zones. The trip time of the relay then indicates which zone has operated. A series of points can be defined which will exercise the relay and verify the position of the zone boundaries.

3.1 Current and Voltage

Used together, the 50A-3PH and DVS3 mk2 are able to generate the impedances required to test a distance relay. In many cases, the required impedance could be generated by different combinations of current and voltage. It is, however, more convenient when testing to set the current on the 50A-3PH to a suitable value (e.g. I_n or $2I_n$) and control the impedance using the voltage controls on the DVS3. This allows steps of impedance to be generated very easily. There may, however, be impedances that cannot be generated without increasing the current. This is particularly true of older relays where the relays is unable to accurately operate with low input voltages. It is also necessary to increase the current to higher levels to generate very low impedances.

For example, to generate an impedance of 500mΩ a current of $10I_n$ may be required. The calculations shown are for a 1A relay.

$$V \quad = \quad IZ$$

$$V \quad = \quad 10A.0.5\Omega$$

$$V \quad = \quad 5V$$

Trying to generate this impedance with a current of I_n would have resulted in a voltage of 0.5V. When testing at high multiples of I_n it is important not to exceed the thermal ratings of the relay sense element. Leaving high currents flowing through the relay for too long will damage the relay.

3.2 Test Vectors

The simplest way to test a distance relay using a DVS3 is use the concept a test vector passing through the zero impedance point (the centre of the RX diagram). This allows any impedance along the line to be generated by changing just the voltage on the DVS3. Points on the test vector may then be chosen to verify the boundaries of the zones on the relay. To fully test the relay, it may be

necessary to use four or more vectors on different angles. Figure 3 shows a single test vector with test points at 5% above and below each zone boundary on the vector.
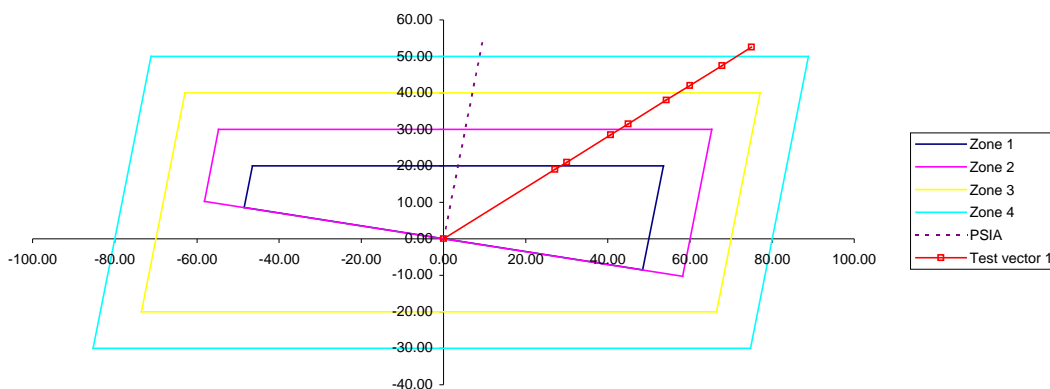
Figure 3. Test vector on quadrilateral relay characteristic

To test a relay exhaustively, test vectors must be set up to verify all boundaries of the relay zones. This is necessary for commissioning, but may not be required for maintenance testing, where a few vectors will verify operation of the relay and the position of the boundaries.

3.3   Applying Test Points/Vectors to the Relay

In applying test values to a relay, it is important to remember that the initial test point must lie outside of all of the zones, or the relay will trip erroneously before the test impedance is applied.

Figure 4. Test points to be applied to relay

The sequence to apply a test impedance to the relay is:

- Set the phase angle for the test vector on the DVS3. This remains constant throughout the test on a particular vector.

- Switch on the current on the 50A-3PH, and set each phase to the test current (I_n or other suitable value).
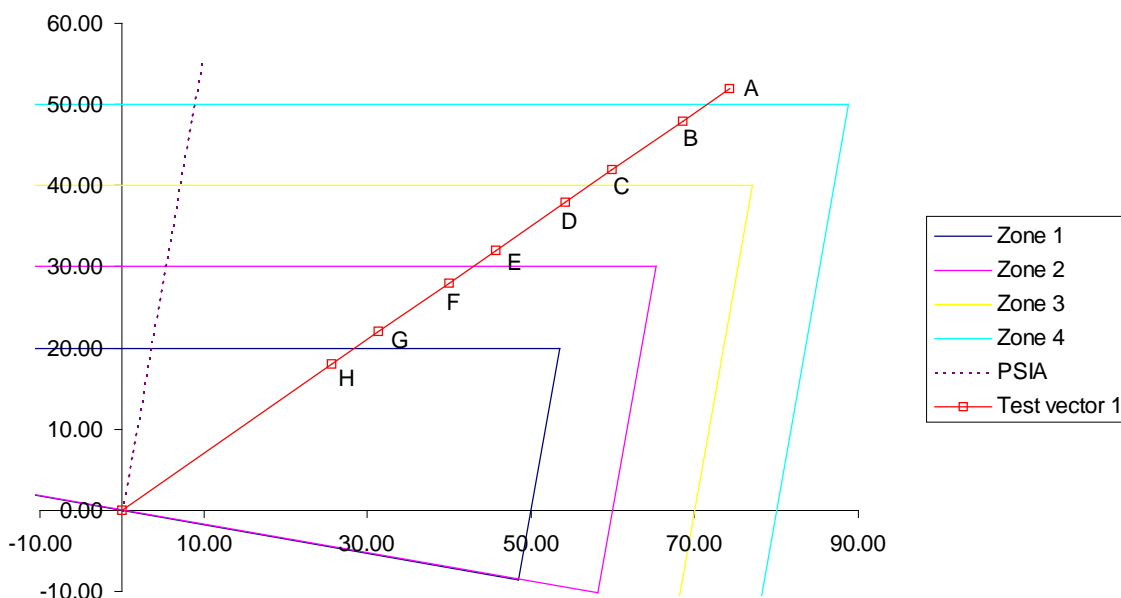
- Switch on the voltage on the DVS3.

- Apply an initial impedance to the relay outside all zones (point A on figure 4) by setting the voltage on the DVS3 to an appropriate value. This point is always on the angle of the test vector, and placed outside the outermost zone of operation.

- Apply the test impedance (for example point B on figure 4) by entering the new voltage on the test vector using the keypad on the DVS3. The relay will trip in the time appropriate for the zone, and the trip time will be displayed on the DVS3.

- Reset the DVS3 to the initial out of zone impedance ready for the next test point. The DVS3 timer will show the relay reset time.

After each test point it is important to return the impedance to the out of zone impedance to reset the relay ready for the next test point. Detailed instructions may be found in section 5 – Test Procedures.

4. TEST POINT/VECTOR CALCULATION

Test stimuli applied to the relay from the DVS3 and 50A-3PH are applied in terms of current (I), voltage (V) and phase (φ). It is therefore necessary to be able to convert impedances to V, I and φ and vice versa.

4.1 Conversion from Voltage, Current and Phase to Impedance

Conversion from voltage, current and phase information is a simple application of Ohm's law. Assuming that the current has a phase angle of 0°, the impedance will have the same phase angle as the voltage. The voltage magnitude can be calculated from Ohm's law:

$$Z \quad = \quad \frac{V}{I}$$

For example, if we inject a current of 1A and apply a voltage of 100V at 29°, the following impedance is generated:

$$Z \quad = \quad \frac{100}{1}$$
$$= \quad 100\Omega$$

The phase angle is unchanged at 29°, so the complete impedance is $100\angle29\Omega$.

4.2 Conversion from Impedance to Voltage, Current and Phase

Using the 50A-3PH and DVS3, the current phase angle is again 0°, and the voltage phase is the same as that of the impedance. A suitable value of current needs to be chosen (often I_n for the relay), and then the voltage may be calculated:

$$V \quad = \quad I.Z$$

For example, if the impedance to be generated is $100\angle30\Omega$ (100Ω at 30°) and the test current is 1A, the required voltage may be calculated as follows:

$$V \quad = \quad I.Z$$
$$= \quad 1A.100\Omega$$
$$= \quad 100V$$

The phase angle of the voltage will be the same as the phase angle of the impedance, so the voltage is $100\angle30V$.

4.2.1 *Impedance Using Complex Notation*

Impedances expressed in complex notation need to be converted to magnitude∠phase notation. For example, an impedance of 86.6 + j50Ω is first converted to magnitude∠phase notation:

$$|Z| = \sqrt{86.6^2 + 50^2}$$
$$= 100\Omega$$
$$\theta = \tan^{-1}\left[\frac{50}{86.6}\right]$$
$$= 30°$$

The voltage and phase angle may then be calculated as in section 4.1.1.1. Alternatively, the voltage may be calculated in complex notation, and then converted to magnitude and phase values.

5. TEST PROCEDURES

It is advisable to decide on the number of test vectors and test points required to effectively test the relay before starting to test. These points can then be converted to currents, voltages and phase angles using the calculation spreadsheet. The calculated test points are then applied to the relay in turn and the operation of the relay verified. If the relay impedances are given as primary system values, these will have to be converted to impedances referred to the VT and CT secondary values.

5.1 Calculating the Test Points

Before calculating the test points, it is necessary to decide how far inside or outside of a zone a test point will be. This can be decided on the accuracy required for the results of the position of the boundary. If it is acceptable to verify points either side of the zone boundary, offsets from the test value may be chosen depending on the accuracy required (e.g. ±3% of zone boundary impedance or ±1Ω). If it is necessary to determine the zone boundary value more accurately, it may be better to use the procedure in section 5.3 to determine the zone boundary and perform timing tests separately at an arbitrary point in each zone.

5.2 DVS3 and 50A-3PH Connections

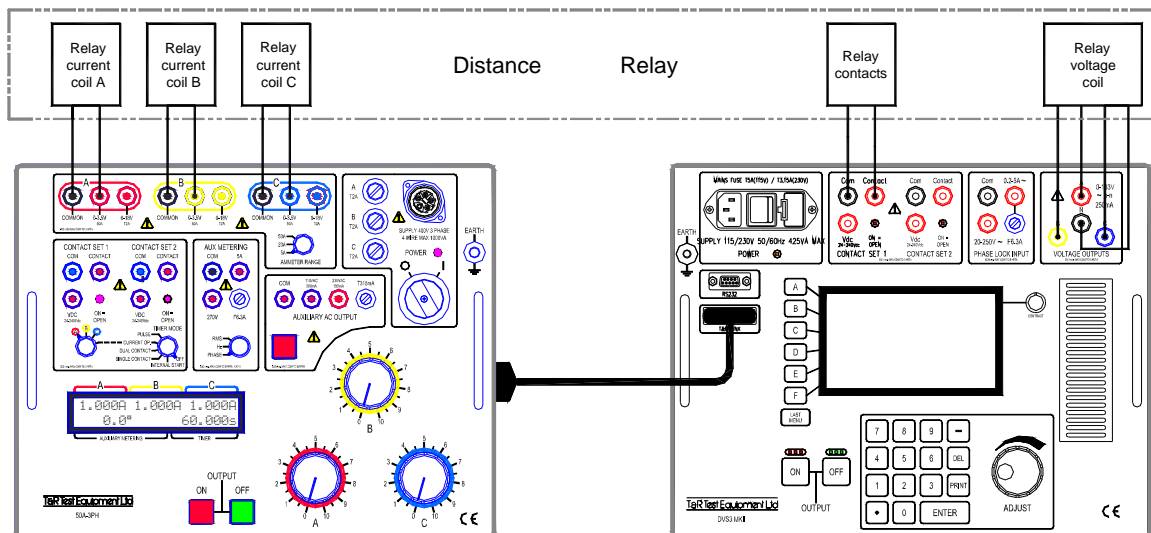Figure 5 shows the connection between the 50A-3PH, DVS3 and the relay under test.

Figure 5. Connections

> ⚠ **WARNING**
>
> **Before making any connections, ensure that the system under test is dead and earthed.**
> **Connecting to a live system may result in personal injury or equipment damage.**

- Connect the output from the DVS3 to the voltage coil of the relay.

- Connect the 50A-3PH to the current coils of the relay, observing polarity of each coil.

- Connect the T&R link output from the 50A-3PH to the T&R link input of the DVS3 using T&R Link Lead 1. This locks the phase relationship between the DVS3 and the 50A-3PH.

- The relay will also require an auxiliary supply (not shown in figure 5).

An auxiliary supply of 110Vac or 230Vac is available from the 50A-3PH to power the relay, and if other voltages are required, a range of optional auxiliary supply converters are available.

5.3   Determining Zone Boundaries

It is possible to either test for definite trip/no trip points on the relay characteristic or to determine the actual boundary value at the edge of a zone. If zones other than the zone under test can be disabled, or if separate contacts are available for each zone, follow the procedure in 5.3.1. If all zones must be tested together, follow the instructions in 5.3.2.

5.3.1   *Determining Zone Boundaries by Continuous Variation of Impedance*

This method only works if other zones can be disabled, or the trip signal for each zone is available on a separate contact from the relay.
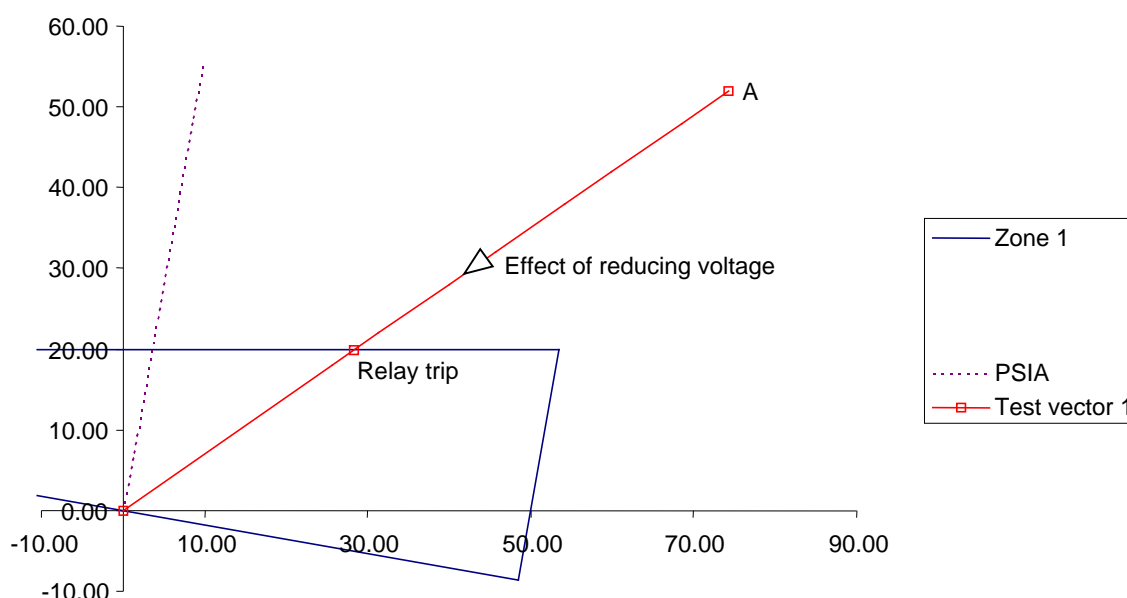

Figure 6.Finding a zone boundary by varying the voltage

- Connect contact input 1 of the DVS3 to the contacts relating to the zone under test.

- Set the phase angle for the test vector on the DVS3.

- Switch on the current on the 50A-3PH, and set each phase to the test current (I_n or other suitable value).

- Switch on the voltage on the DVS3.

- Apply an initial impedance to the relay outside all zones (point A on figure 6) by setting the voltage on the DVS3 to an appropriate value. This point is always on the angle of the test vector, and placed outside the outermost zone of operation.

- Slowly decrease the DVS3 voltage until the relay trips. The result is accurate for a zone with instantaneous trip time, but dependant on the rate of change of voltage on a zone with delayed operation. Zones with delays require a much slower approach to the trip value.

- Calculate the impedance at the trip point from the voltage and current (Z=V/I). The angle of the impedance is the same as the angle of the voltage.

5.3.2   *Determining Zone Boundaries Using Discrete Steps of Impedance*

This method may be used if only one trip contact is available from the relay. The zone of operation for each test point is shown by the trip time of the relay. A series of test impedances are applied to the relay centred around the expected operating impedance on the impedance angle selected. The zone boundary is be found by applying values either side of the boundary but approaching the boundary with successive tests. After a number of test values, the result will converge, giving an accurate result for the zone boundary.

- Set the phase angle for the test vector on the DVS3.

- Switch on the current on the 50A-3PH, and set each phase to the test current (I_n or other suitable value).

- Switch on the voltage on the DVS3.

- Apply an initial impedance to the relay just outside the zone boundary under test (point A on figure 7) by setting the voltage on the DVS3 to an appropriate value using the keypad. The relay should trip in the time appropriate to the zone in which the impedance lies (zone 4 in figure 7).

- Type in a new voltage value on the DVS3 that should cause the relay to trip in the next zone (point B, zone 3 on figure 7). The relay should trip in the zone 3 delay time.

- If the relay has tripped as expected, take a point mid-way between the two test points and enter this voltage. If this trips the relay in the same time as point A, apply the next point mid-way between point B and C. If it trips the relay in the same time as point B, apply the next test mid-way between point A and B.

- The aim is to reduce the impedance between two tests so that points either side of the zone boundary but adjacent to it are found.

- Calculate the impedance at the zone boundary from the voltage and current (Z=V/I). The angle of the impedance is the same as the angle of the voltage.
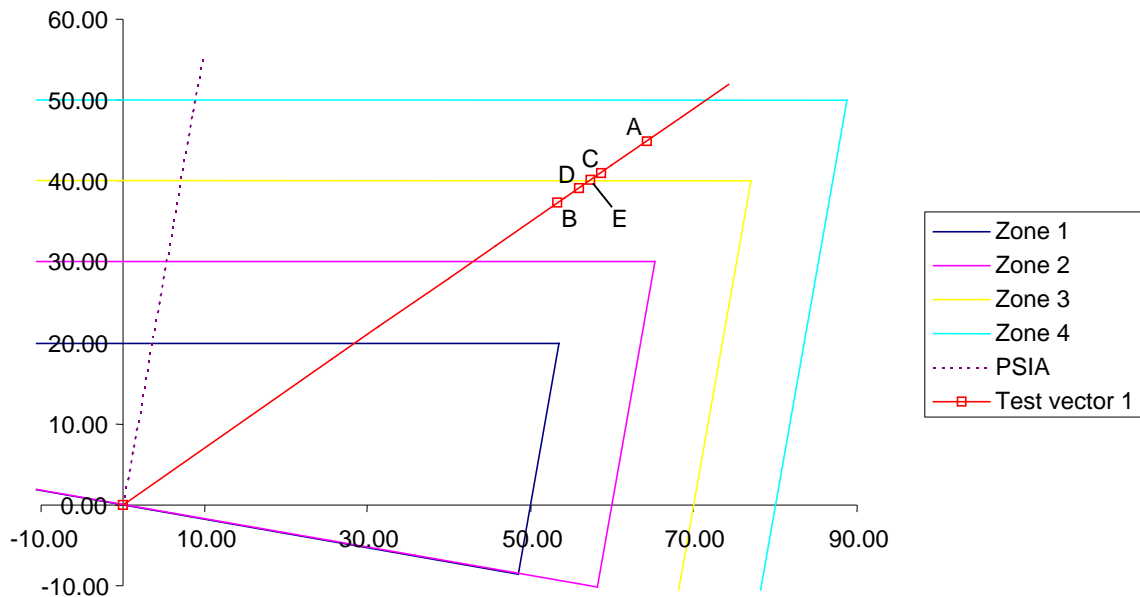
Figure 7.Finding a zone boundary by binary search

5.4 Zone Timing Tests

To test the timing of each zone of operation, test points can be picked in each zone of operation as shown in figure 8.

Figure 8. Test points for timing tests

- Set the phase angle for the test vector on the DVS3.

- Switch on the current on the 50A-3PH, and set each phase to the test current (I_n or other suitable value).

- Switch on the voltage on the DVS3.

- Apply an initial impedance to the relay just outside all of the zones of operation (point A). The relay should not trip.

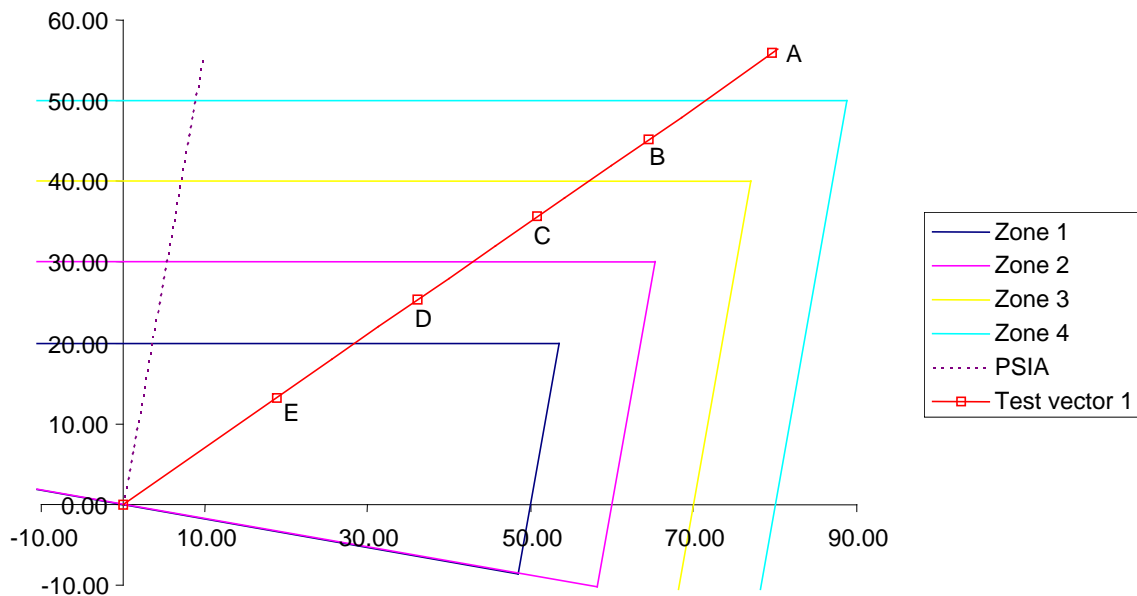- Type in a new voltage value on the DVS3 that should cause the relay to trip in the outer zone (point B, zone 4 on figure 8). The DVS3 timer will display the zone 4 trip time.

- Type in the point A voltage to return the relay to its non-tripped state. The DVS3 timer will display the relay reset time.

- Repeat the process for each of the other test points for the other zones.

5.5   Power Swing Blocking

Many distance relays are provided with a power swing blocking feature that is able to recognise a stable power swing situation that enters the relay tripping characteristic and ignore it. To test such a function, a test vector can be applied to the relay and the impedance altered manually by altering the voltage to simulate a power swing.
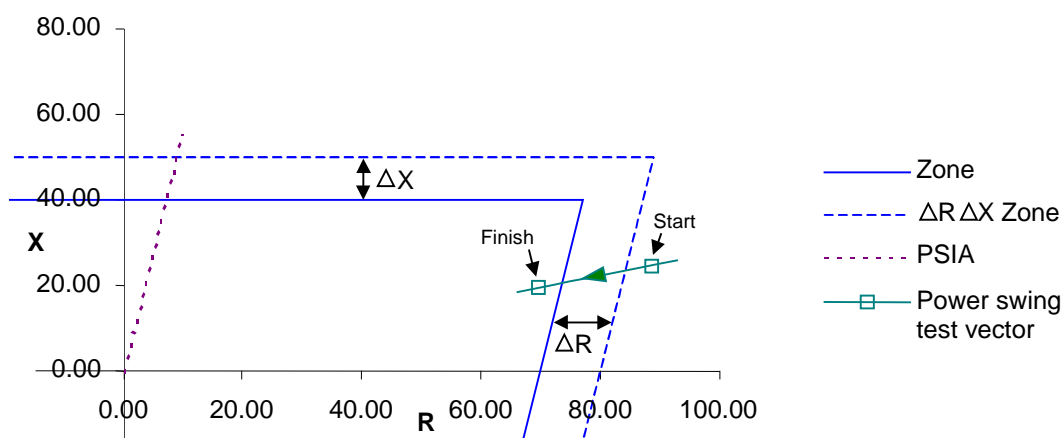

Figure 9 Power swing blocking test vector

On the Alstom Micom P440 relay range the power swing blocking is implemented using a ΔR and ΔX zone. A power swing will cause the impedance to cross the ΔR ΔX zone into the tripping zone. If the impedance takes more than 5ms to cross the zone, the relay does not trip.

Figure 8 shows a power swing test vector in green. A starting impedance is calculated that is outside the zone under test and the ΔR ΔX zone using a current of I_n or $2I_n$. An ending impedance is then calculated that would usually trip the relay (inside the zone under test, but outside any inner zones).

To test the relay, first apply the starting impedance. Using the output control on the DVS3, gradually reduce the output voltage until the finish voltage (and hence impedance) is reached. The relay should not trip because the slow traverse across the ΔR ΔX zone has taken more than 5ms.

6. DISTANCE TEST SPREADSHEET

A Excel spreadsheet is available from T&R Test Equipment to accompany this application note. It allows easy calculation of test voltages from impedances and vice-versa. It also allows a quadrilateral relay characteristic to be entered and the impedance calculation results superimposed on the R-X diagram for the relay.

This spreadsheet is designed for Excel 97 onwards. Please note that Excel must have the Analysis ToolPak installed for this spreadsheet to function. To check that the analysis toolpak is installed, go to the "Tools" menu and select "Add-Ins". Check that "Analysis TooPak" is checked in the dialogue box that appears. If not, tick the box and click OK.

Values that may be changed on the spreadsheet appear as bold red values in boxes. If other values are typed over or altered, the calculation functions of the spreadsheet may stop working.

1 A

6.1 System Parameters

It is possible to use the impedance converter for secondary impedance values only without entering any system parameters. If the power system parameters are entered, calculations may be carried on primary impedances.

To use these facilities, enter the following parameters into the spreadsheet as shown in figure 10:

- Nominal system voltage, in kV
- Rated current in A
- CT rated secondary current
- VT rated secondary voltage

The CT and VT ratio is calculated and displayed along with the primary values.

In addition, the required test current from the 50A-3PH is entered at this point. This may be the nominal CT secondary current, or another value if this is not acceptable. This value is used throughout the impedance calculations in the sections below.

A drop-down box is provided in this section to select between primary and secondary impedances. If the "Primary" option is selected, impedances are entered and displayed referred to the power system values. If "Secondary" is selected impedances are referred to the secondary values of the CT and VT.
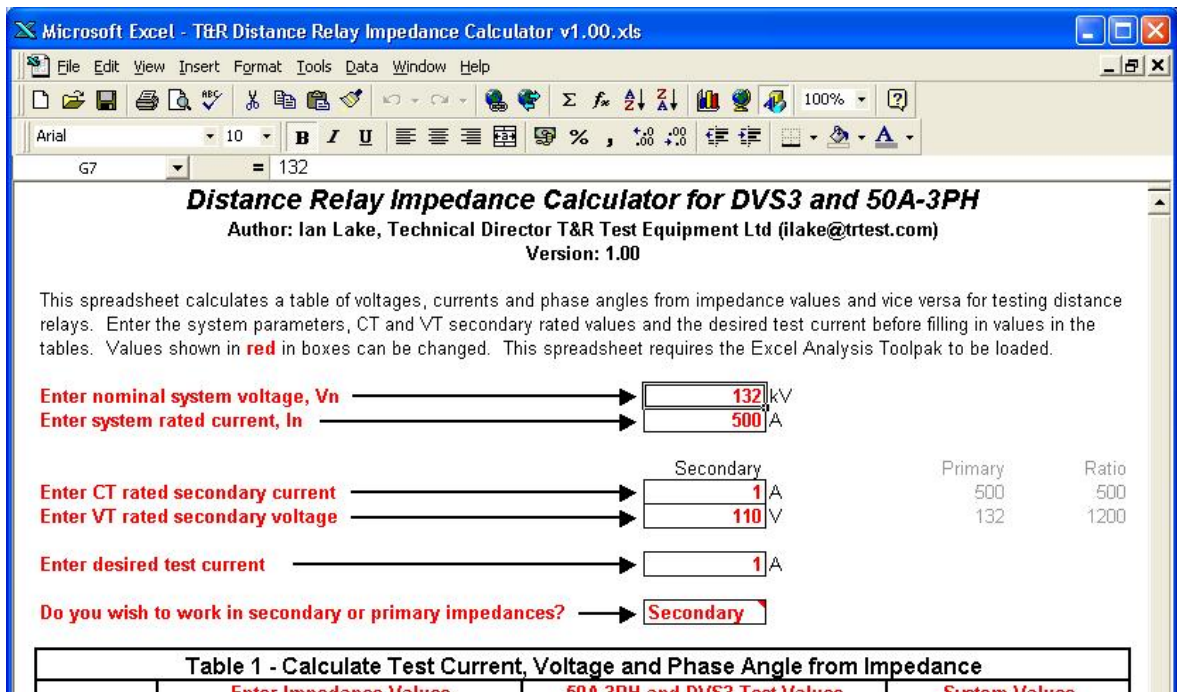
Figure 10. Entering power system parameters and test current

6.2   Conversion from Impedance to V, I and ϕ Test Values

The second section of the spreadsheet (Table 1) allows impedances to be entered into a table as either magnitude∠angle or complex values. If both types of value are entered for a line in the table, the magnitude∠angle value will be ignored and the complex value will be used.

	Enter Impedance Values Secondary			50A-3PH and DVS3 Test Values			System Values	
	Z test x<y		Z test	Test current	Test voltage magnitude	Test V phase angle		
	Magnitude	Angle (deg)	x+yj	A	V	Degrees	A	V
Example 1	70.7	45		1	70.7	45	500	84840
Example 2			50+50j	1	70.7	45	500	84840
Test 1	15	45		1	15	45	500	18000
Test 2	20	45		1	20	45	500	24000
Test 3	30	45		1	30	45	500	36000
Test 4	40	45		1	40	45	500	48000
Test 5	50	45		1	50	45	500	60000
Test 6	60	45		1	60	45	500	72000
Test 7	70	45		1	70	45	500	84000
Test 8	80	45		1	80	45	500	96000
Test 9	90	45		1	90	45	500	108000
Test 10	100	45		1	100	45	500	120000

Figure 11. Conversion from impedance to V, I and phase

The table displays the current to be injected from the 50A-3PH and the voltage magnitude and phase angle to be generated by the DVS3. If the "Primary" impedance option is selected in the first section of the spreadsheet, the impedance values are taken to be primary values. The table also displays the system voltages and currents that the impedance relates to.

6.3   Conversion from V, I and ϕ Test Values to Impedance

The third section (Table 2), converts from applied test voltages and currents to primary or secondary impedances. The test current is taken from section 1, and the voltage and phase are entered.   The impedance values and primary system voltages and currents are calculated.

Table 2 - Calculate Impedance from Test Current, Voltage and Phase Angle							
	Enter Test Values (V, I, phase)			Calculated Impedance Values Secondary			System Values	
	Test current	Test voltage magnitude	Test V phase angle	Z test magnitude<angle		Z test cmplx		
	A	V	Degrees	Magnitude	Angle (deg)	x+yj	A	V
Example	1	110	30	110	45	77.8+77.8j	500	132000
Test 1	1	10	30	10	30	8.7+5j	500	12000
Test 2	1	20	30	20	30	17.3+10j	500	24000
Test 3	1	30	30	30	30	26+15j	500	36000
Test 4	1	40	30	40	30	34.6+20j	500	48000
Test 5	1	50	30	50	30	43.3+25j	500	60000
Test 6	1	60	30	60	30	52+30j	500	72000
Test 7	1	70	30	70	30	60.6+35j	500	84000
Test 8	1	80	30	80	30	69.3+40j	500	96000
Test 9	1	90	30	90	30	77.9+45j	500	108000
Test 10	1	100	30	100	30	86.6+50j	500	120000

Figure 12. Conversion from V, I and phase to impedance

6.4   Display of Results on R-X Diagram

The impedance results from table 1 and table 2 may be displayed on an R-X diagram with a quadrilateral relay characteristic in the final section of the spreadsheet.
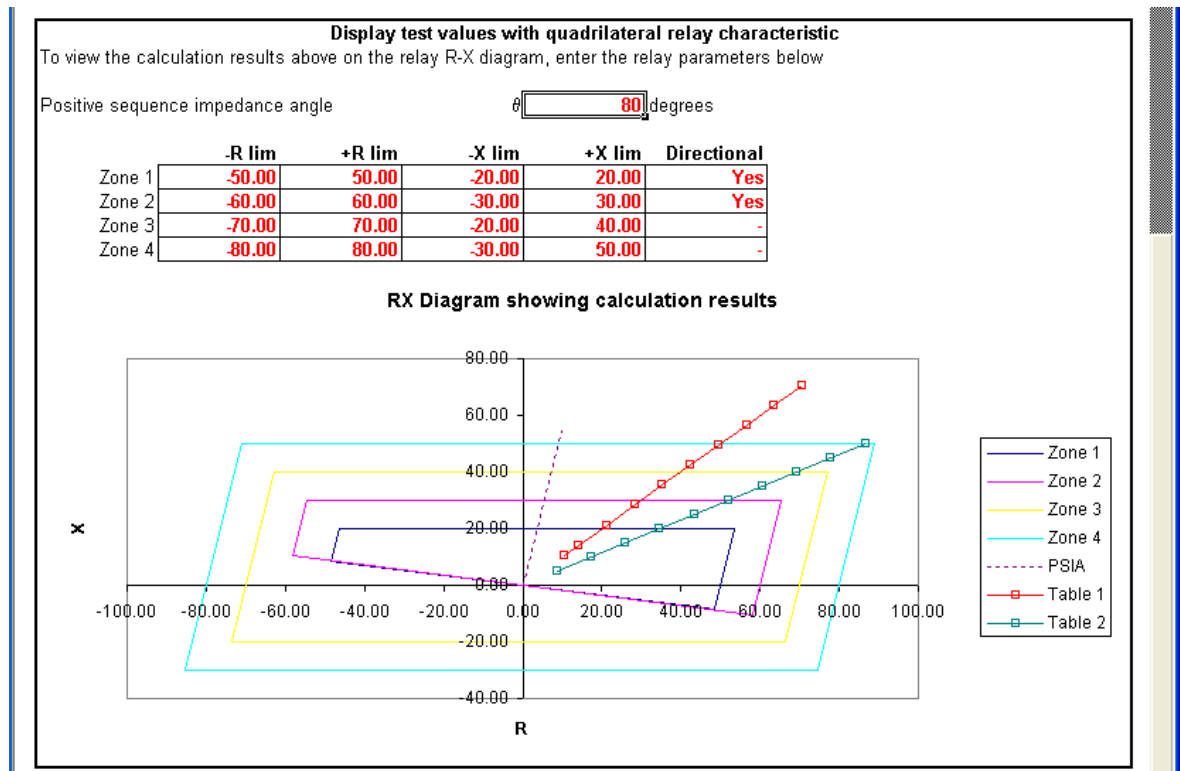

Figure 13. Results display on R-X diagram

Values are entered for the relay positive sequence impedance angle and the point at which the characteristic crosses the R and X axis for each zone. Zone 1 and zone 2 may also have a directional characteristic selected.

The relay zones are then plotted, and the test vectors from table 1 and table 2 plotted on the graph.

If you have any comments or questions about this procedure or the associated spreadsheet, please contact Ian Lake, ilake@trtest.com.

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