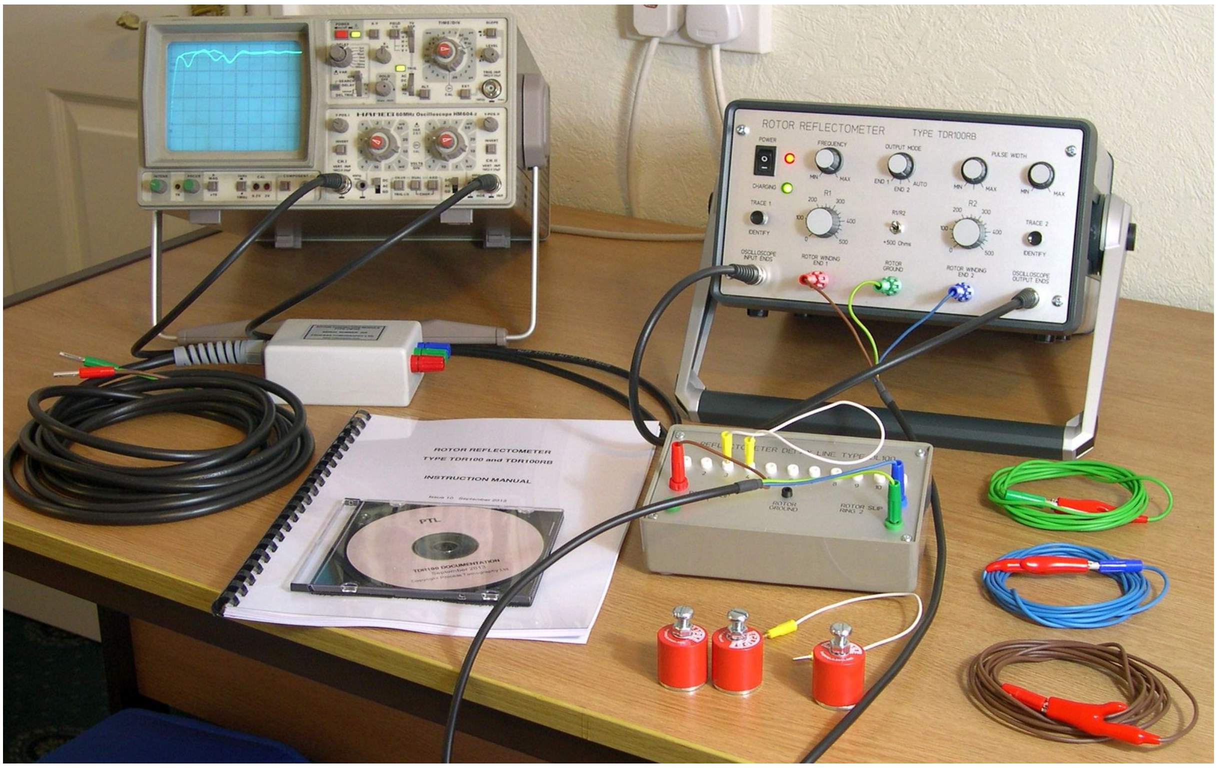
ROTOR RSO REFLECTOMETER

TYPE TDR100/200



INSTRUCTION MANUAL

OPERATION IN ANALOGUE MODE

Issue 18 June 2016

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CONTENTS

SAFETY WARNING

The use of this equipment on a rotor installed in an operational generator must be carried out with the explicit permission and under the supervision of the local plant operator. All local safety rules and procedures must be complied with.

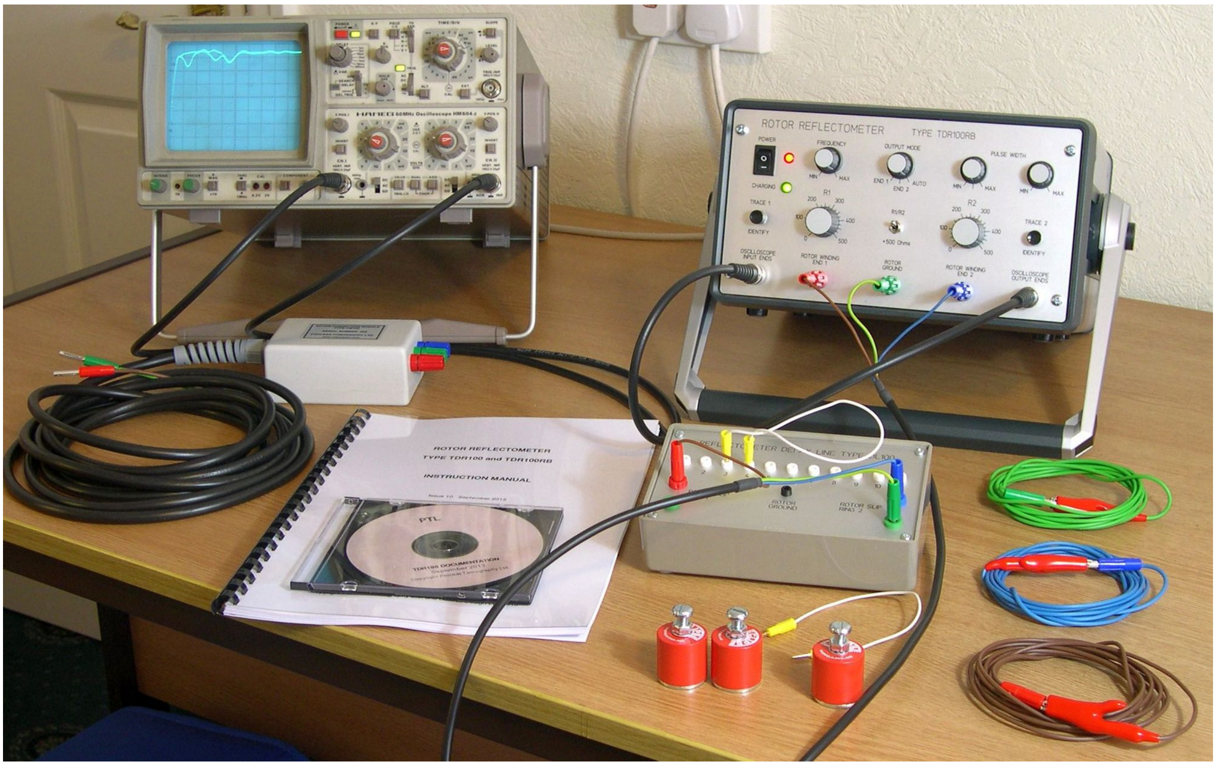
In particular, the equipment must only be connected to the generator rotor after the field supply has been disconnected and isolated in accordance with local safety regulations. Failure to comply with this instruction will damage the equipment and may endanger both the the plant and the operator.

FRONT VIEW OF TRDR100RB ROTOR REFLECTOMETER

REAR VIEW SHOWING MAINS INPUT AND BATTERY FUSE HOLDER

DETAILS OF EQUIPMENT SUPPLIED

The followings items are supplied with a standard **TDR100 RSO Reflectometer measurement system**:



TDR100/RB Rotor Reflectometer unit with mains lead

DL100 Demonstration Delay Line (including leads)

Terminal magnets (3)

5m 3-core test lead terminated in a connection module.

3 x 3m single core leads (Brown, Green, Blue) terminated in 4mm insulated banana plugs (Red, Green, Blue) at one (connection module) end and insulated crocodile clips at the other (rotor) end.

2 x 1.2m Coaxial oscilloscope leads with BNC connectors

1m Delay line 4mm plug lead (red, blue, green plugs)

This Instruction Manual

Documentation CD

Padded Carrying Case

Note that an additional oscilloscope (not supplied) is also required

0. QUICKSTART INSTRUCTIONS

0.1 OVERVIEW

The **TDR100 Rotor Reflectometer** is used with an **oscilloscope** (analogue or digital) to test the rotor winding of large electricity generator rotor windings and allows inter-turn and winding faults to be detected and displayed on the oscilloscope screen.

The principle of operation is described in section 1 and **Appendix 2** of this manual and detailed operating instruction are given in sections 2 and 3. In its normal mode of operation, the **TDR100** applies rectangular pulses to each end of the rotor winding alternately via a bridge switching network. The resulting input or output end waveforms are displayed on the channels of an oscilloscope as 2 alternating waveforms. Because the bridge switching network operates at a relatively high speed (around 500Hz), these appear as 2 superimposed waveforms on the oscilloscope screen, allowing any differences between these waveforms to be viewed directly. The pulse repetition rate is set by the **Frequency** control on the Reflectometer front panel and the width of the applied pulse is set by a pair of **Pulse Width** controls.

This **Quickstart section** decribes and demonstrates the operation of the **TDR100** unit using the supplied **DL100 delay line**. Detailed instructions for using the equipment with actual rotor windings can be found in section 2. Section 3 explains how to interpret the test results.

0.1 THE DEMONSTRATION DELAY LINE

The delay line unit, which simulates and approximates to a real rotor winding, is used to check that the Reflectometer is operating correctly and is also an aid to demonstrating and understanding the test method. It is a 10 section lumped component delay line with a characteristic impedance of 100Ω. The propagation time for a single pass through the unit is approximately 10µS. The junctions between each section of the delay line are connected to a set of white 2mm sockets, enabling external connections to be made to these points using a **patch lead**. The input and output ends of the unit are connected to 4mm sockets as shown in figure 0.1.1 below.

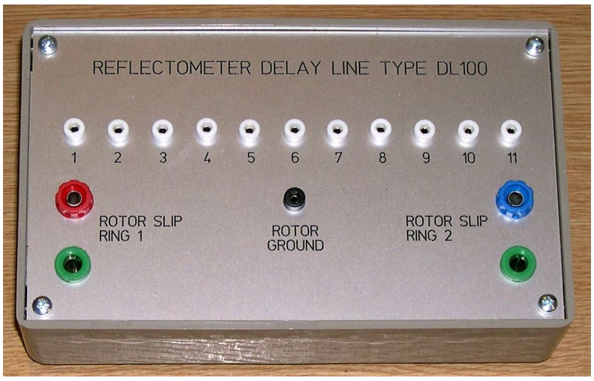


Figure 0.1.1 Delay line type DL100

Please note that the delay line is supplied for demonstration and checking purposes only. It is not required when testing a real rotor winding.

In use, the **Delay line** is connected to the **Reflectometer** using the **1m 3-core test lead** supplied and shown in figure 0.1.2. At the **Delay line** end, the **red banana plug** is connected to the **red input terminal** on the delay line, the **blue banana plug** is connected to the **blue output terminal** and the **green banana plug** is connected to one of the **green common terminals**. The same plug colour convention is used to connect the lead at the reflectometer end, as shown in figures 0.2.1 and 0.1.2.

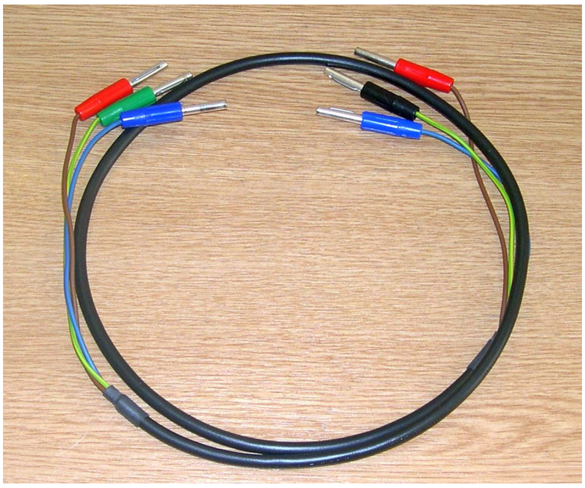


Figure 0.1.2. 1m delay line connection lead

0.2 SETTING UP THE EQUIPMENT

The following instructions assume the use of a conventional analogue oscilloscope. Information and advice on the use of digital oscilloscopes is given later in section 5.

1. Connect the **delay line** to the **TDR100** using the short connecting lead shown in figure 0.1.2 above. Ensure that the **delay line patch lead** (white lead with yellow plugs) is disconnected from the delay line terminals.

2. Connect the **Reflectometer** to the **oscilloscope** input terminals using the coaxial leads supplied.

3. Connect the mains lead to the mains supply and the rear panel connector and switch on using the front and rear panel supply on switches.

Note that on the **TDR100RB** version, operation of the rear panel switch charges the internal battery and lights the green Charging LED, while that on the front panel switches on the unit and lights the red Power LED.

The connection arrangements are shown in figures 0.2.1 and 0.2.2.

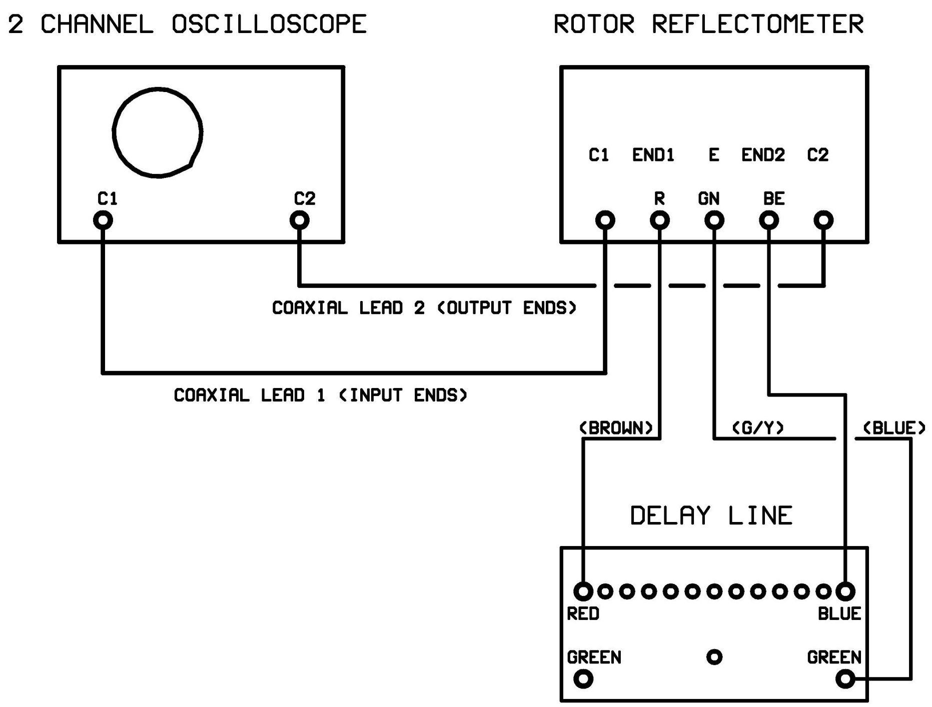


Figure 0.2.1 Connection diagram using delay line

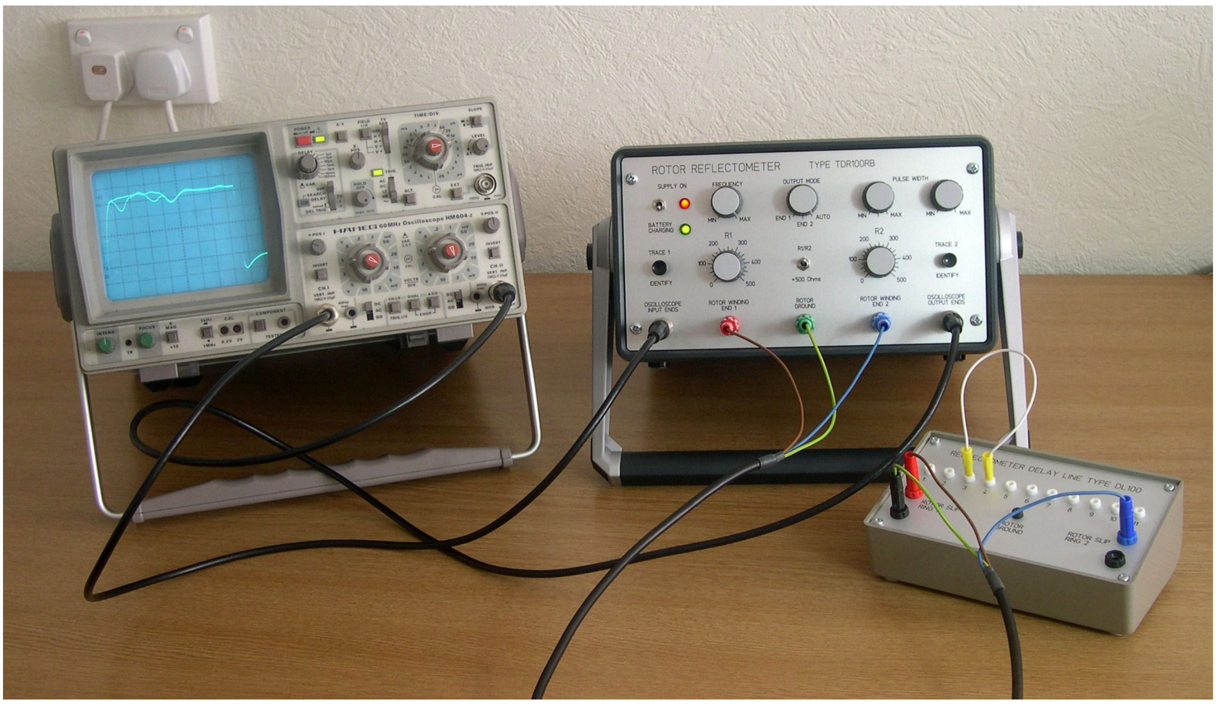


Figure 0.2.2 Physical realisation

0.3 SETTING THE TDR100 FRONT PANEL CONTROLS

Set the controls on the **Reflectometer** initially as follows:

R1= R2 =	:100Ω
PULSE FREQUENCY	: Fully clockwise
PULSE WIDTH SWITCH	: Centre position
PULSE WIDTH POTENTIOMETER	: Mid scale
OUTPUT MODE SWITCH	: Auto
R1/R2 TOGGLE SWITCH	: Up (0 - 500 Ohms)

0.4 SETTING THE OSCILLOSCOPE CONTROLS

For reasons explained later, best results will be obtained using a conventional analogue oscilloscope, as this allows each pair of RSO waveforms to be displayed and viewed in real time. In this case, a simple digital camera can be used to capture the screen shots for permanent records.

Set the oscilloscope controls initially as follows:

DISPLAY			: Channel 1
VERTICAL SENSITIVITY			: 1V/CM (Both channels)
TRIGGER CONTROLS			
	-	MODE	: Normal
	-	SOURCE	: Channel 1
	-	LEVEL	: Positive
	-	SLOPE	: Positive
	-	COUPLING	: D.C.
	-	TIME BASE	: 5 µsec/division

0.5 TYPICAL OSCILLOSCOPE WAVEFORMS UNDER MATCHED CONDITIONS

0.5.1 Input end waveforms

With the oscilloscope monitoring the input ends of the delay line, adjust the pulse width so that the display resembles that shown in Fig. 0.5.1(a). Under these conditions, R1 and R2 match the characteristic impedance of the delay line and the pulses pass through the delay line and are absorbed without reflection in R2. The sharp waveform dip is caused by a deliberate impedance mismatch at the ends of the delay line.

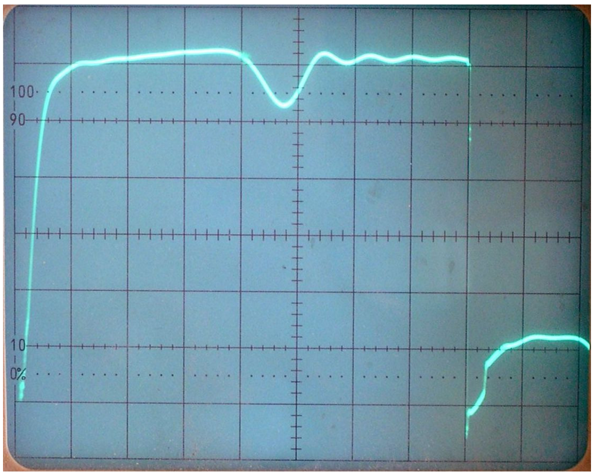


Figure 0.5.1 (a) Input ends waveforms with R1 = R2 = 100 Ohms

0.5.2 Output end waveforms

Now set the oscilloscope to monitor the output ends of the delay line and set the time base to 2 uS/division. Ensure that the triggering remains set to the input ends signals and reset R1 = R2 = 100 Ohms. The output end waveforms should now appear as shown in figure 0.5(b).

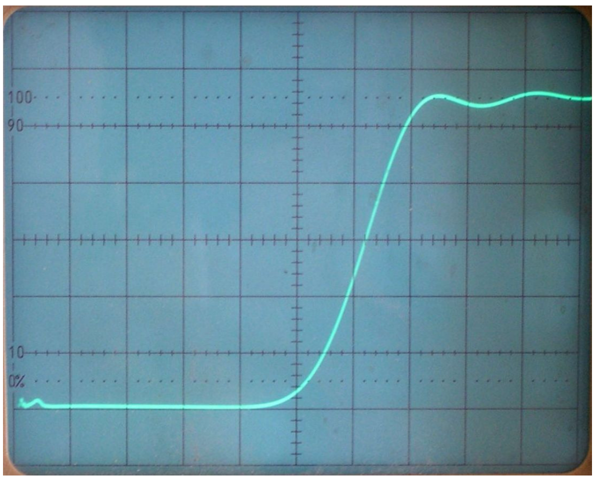


Figure 0.5.1 (b) Output ends waveforms with R1 and R2 = 100 Ohms

Figure 0.5.1(b) shows that no signal is received at the far end of the delay line until a time delay of approximately 10uS (4 divisions). This delay time is known as the single-pass transit time. The slow risetime of the output waveform is a characteristic of the delay line itself and not the TDR100 unit.

0.6 SETTING THE IMPEDANCE MATCHING CONTROLS R1 AND R2

The **impedance matching controls R1 and R2** have a major effect on the displayed waveforms. However, the effects are identical for both sets of RSO waveforms and it is impossible to obtain different waveforms for each half-winding of a fault-free rotor winding by incorrect setting of these controls. The correct values of R1 and R2 for use with the delay line are approximately 100 Ohms. However, for a real rotor winding, this value will be unknown initially and must be measured as described in section 0.62 below.

0.6.1. CHANGING THE VALUE OF R1

The effect of adjusting R1 is primarily to adjust the amplitudes of the displayed RSO waveforms. In practice, R1 is normally set to the same value as R2, once the correct value for R2 has been found, as described below.

0.6.2. CHANGING THE VALUE OF R2

The effect of mismatching the value of the output end terminating resistor R2 can be demonstrated by changing the setting of R2 on the Reflectometer.

When R2 is set to zero, the output pulses are reflected back to the input ends of the delay line with opposite polarity, so that the pulse amplitude monitored at the input end of the winding becomes zero after a time delay which allows the pulses to pass through the delay line and back again. This delay time is known as the double-pass transit time.

Fig. 0.6.2(a) shows the input end waveforms when R2=0. The double pass transit time is seen to be approximately 20µS (4 divisons).

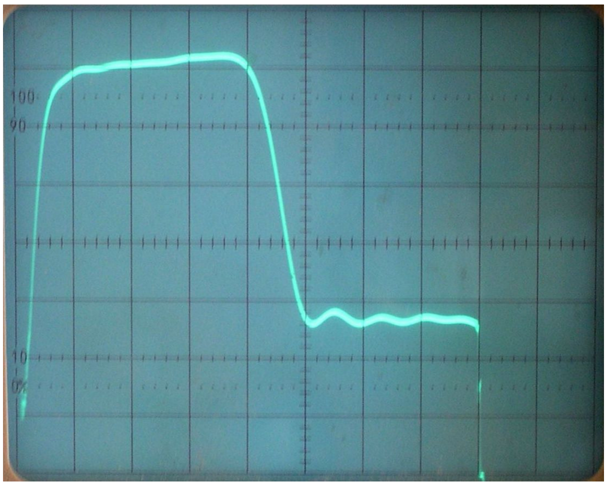


Figure 0.6.2 (a) Input ends waveforms with R1 = 100 Ohms and R2 = 0 Ohms

Now slowly increase the vaule af R2 from 0 to 100 Ohms, and note that the reflected pulse amplitude is reduced and becomes zero when R2 = 100 Ohms..

Similarly, when the value of R2 is set to a value large than that of the delay line characteristic impedance, partial reflection of the the pulses again occurs, but now they are reflected back to the input ends of the delay line with positive polarity. The pulse amplitude monitored at the input end of the winding therefore increases after the double-pass transit time. A typical example is shown in Fig. 0.6.2 (b), which shows the input-end waveforms obtained with R2 set to 150 Ohms.

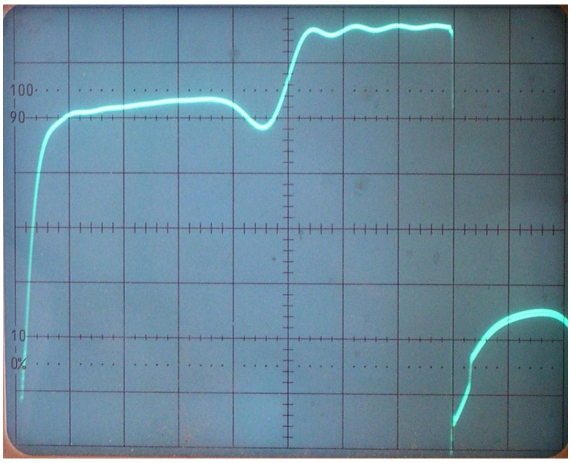


Figure 0.6.2 (b) Input ends waveforms with R1 = 100 Ohms and R2 = 150 Ohms

0.6.3 SETTING THE OPTIMUM VALUES FOR R1 AND R2

The optimum value for R2 (and hence R1) is that which causes no net reflection at the output ends of the rotor winding, so that the waveforms are similar to those shown in figure 0.5.1 (a). Setting R1 and R2 to these values ensures that all tests are carried out under repeatable conditions and minimises the effect on the waveforms caused by multiple pulse reflections at each end of the delay line or rotor winding.

0.6.4 CHECKING FOR 2 WAVEFORMS USING TRACE IDENTIFY BUTTONS

In all of the examples listed to-date, the oscilloscope has displayed 2 superimposed waveforms. To conform this, push in each of the trace identify buttons in turn, which connects a high value resistor across the selected winding end. This allows the individual waveforms at each end of the winding to be identified.

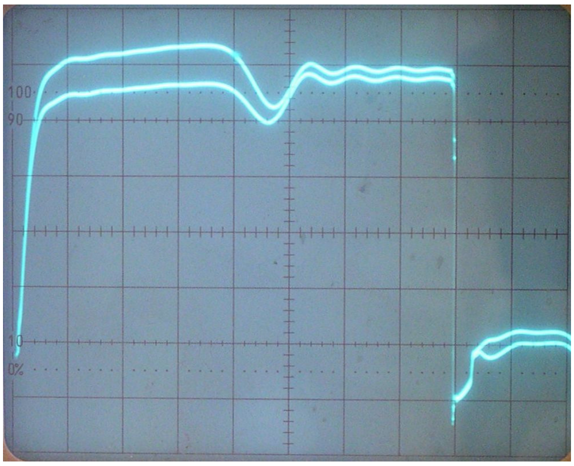


Figure 0.6.4 Operation of trace identification buttons

0.7 DEMONSTRATING WINDING FAULTS WITH THE DL100 DELAY LINE

0.7.1 Simulated inter-coil fault

The effect of a **shorted turn or coil** can be demonstrated by shorting out one or more delay line sections. Figure 0.7.1 shows the RSO input end waveforms when the patch lead is connected between terminals 4 and 5 on the delay line. The approximate fault location can be estimated by comparing the time at which the waveforms start to diverge with the double-pass transit time.

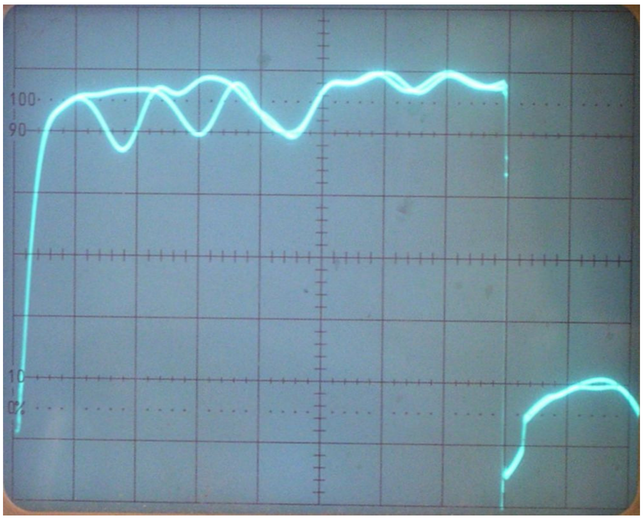


Figure 0.7.1 Short applied between terminals 4 and 5 on delay line

Note that a single shorted turn on a real rotor winding will give a much smaller difference between the input end waveforms.

0.7.2 Simulated earth fault

The effect of a simulated earth fault may be demonstrated by shorting one of the delay line junctions to earth using the 2mm plug lead supplied. Fig. 0.5.2 (a) shows the result of shorting junction 4 to earth.

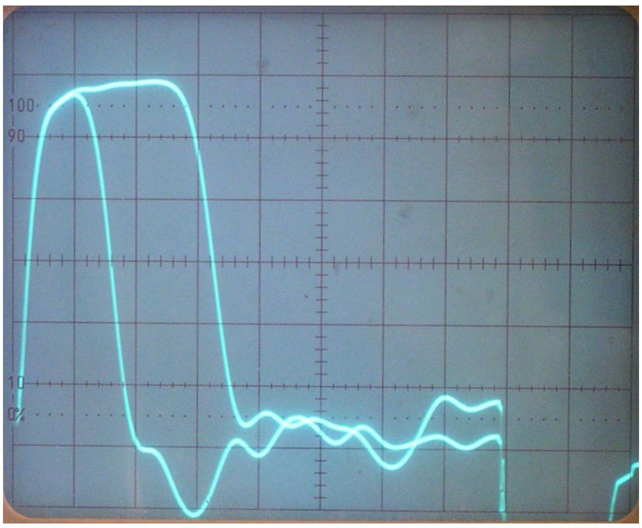


Figure 0.7.2 Short applied between terminals 4 and ground on delay line

0.8 INTERPRETING THE WAVEFORMS

A **normal fault-free rotor winding** is characterised by **2 identical waveforms** at each end of the rotor winding. More information about interpreting the **RSO waveforms** is given in section 3

0.9 THE NEXT STEPS

This concludes the **Quickstart** section.

Detailed information about the **RSO test** and practical advice on using this test method on real rotor windings can be found in the remaining sections of this manual and also in a number of technical papers included in the supplied **documentation CD**.

1. INTRODUCTION

1.1 GENERATOR ROTOR WINDING FAULTS

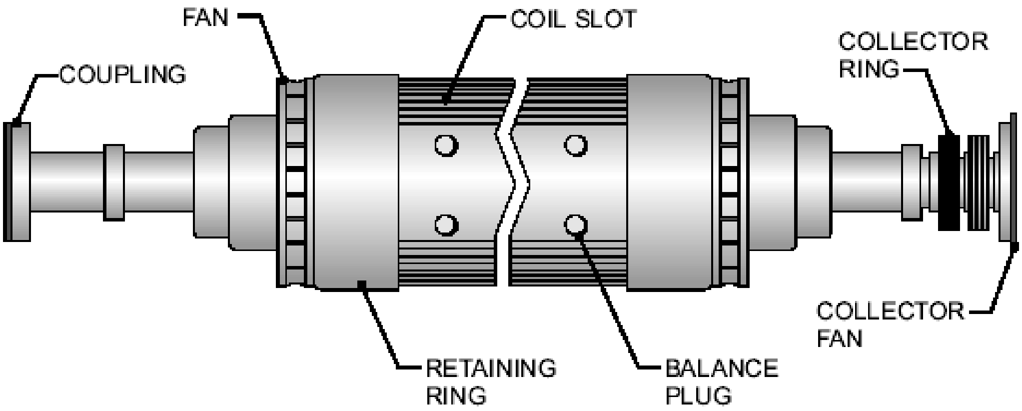


Figure 1.1 A typical generator field rotor (courtesy of GE Power Systems**)**

Large high-speed electrical generators use a rotating magnetic field produced by a rotor in the form of a cylindrical electromagnet having either 2 or 4 magnetic poles*. The rotor body is a solid steel forging containing radial slots for the coils which make up the electromagnets (rotor windings). The turns of the coils are rectangular copper bars insulated with an epoxy material and in a 2-pole rotor, there are typically 8 pairs of slots for each pole of the electromagnet, with each slot containing up to 20 conductor turns. A cross-section of a typical radial slot (in this case, containing 15 turns of insulated copper bar) is shown in figure 1.2.

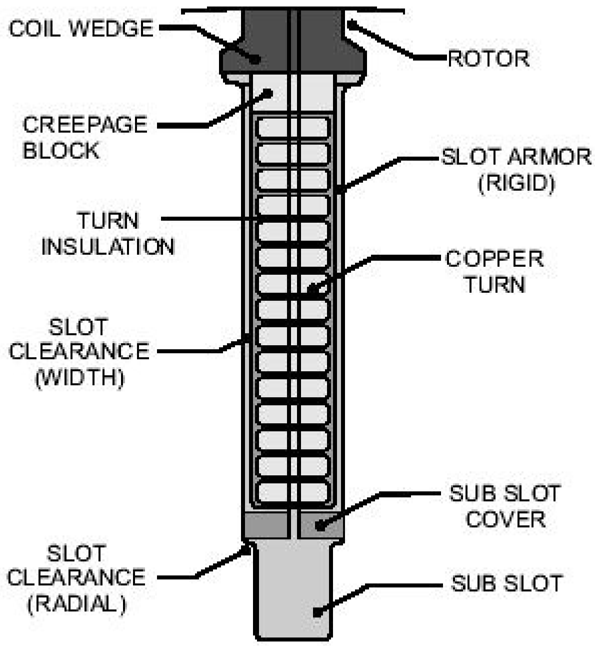


Figure 1.2 Cross-sectional view of a radial slot containing the rotor field winding. (courtesy of GE Power Systems**)**

At the ends of the rotor body, the turns pass from the end of one slot to its equivalent slot on the other side of the magnetic pole and are held in place in the end regions by steel end rings. A direct current of typically 3000 amps flows through the rotor winding to produce the magnetic field, which is at right-angles to the axis of rotation, with clearly-defined north and south poles.

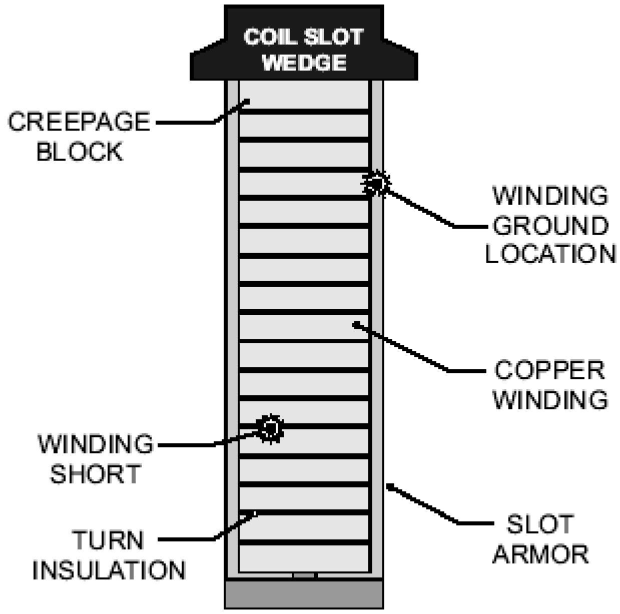


Figure 1.3. Examples of coil insulation breakdown (courtesy of GE Power Systems**)**

A 2-pole rotor rotates at 3000/3600 rpm to produce a 50Hz or 60Hz alternating voltage in the (3-phase) stator windings. The rotor windings experience large centrifugal forces, which can damage the insulation, leading to either shorts between the rotor winding and ground or between adjacent turns as shown in the figure above. As the DC current is large and the short circuits will have finite resistance, large quantities of heat can be generated at the fault location and this can cause damage to the remaining insulation, resulting in severe damage to the rotor windings. Short circuits can also cause magnetic imbalance, giving rise to increased vibration levels.

Generator rotors are routinely tested to detect these types of fault, usually during construction and also before and after routine generator maintenance. One standard test method used is time-domain reflectometry. However, unlike the similar technique used for testing transmission lines, a custom test instrument (reflectometer) is required, because the rotor winding is a very imperfect transmission line and produces a large number of reflections at each change in impedance between the sections of conductors inside the radial slots and the sections in the cross-over end regions.

The basis of the RSO test method for use on rotor windings was first described by A.E Grant in 1973 and a copy of this paper is included in Appendix 3 of this manual.

* Note that the design of rotors for large hydro-electric generators differs from that described above as they rotate at lower speeds and have multiple sets of magnetic poles. However, in some cases, these types of windings can be tested in the same way as for high-speed turbo-generator rotors.

1.2 OVERVIEW OF TEST METHOD

The method used to test rotor windings for earth faults or shorted turns relies on the fact that the rotor winding is symmetrical. For example, a 2-pole rotor contains two nominally-identical half-windings, one for the North pole and the other for the South pole, both of which are connected in series. A four pole rotor is similarly symmetrical.

This symmetry property is used to compare the response of the 2 halves of the rotor winding to a short voltage pulse applied between each slip-ring and the rotor body. The pulses and any reflected signals are monitored at each end of the rotor winding using an oscilloscope. If the rotor winding is fault-free, two identical waveforms will be observed at each slip ring. However, if one half-winding contains a fault, the two waveforms will differ. The test details are described below.

A (typically square wave) pulse (12V) is applied between one of the rotor slip rings and ground and the transmitted pulse received at the remote end of the rotor and the reflected pulse at the sending end are monitored using a dual-trace oscilloscope as shown below.

A pair of adjustable matching resistors are used to test the rotor winding under repeatable conditions and are normally set so that the pulse generator and terminating resistor match the characteristic impedance of the rotor winding (typically values in the range 30 - 1000 Ohms).

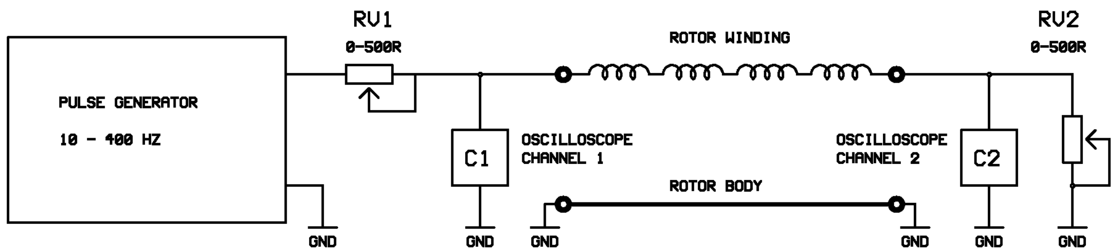


Figure 1.4 Rotor winding test method

The tests are carried out by applying pulses from each end of the rotor winding in turn and the oscilloscope traces are recorded and compared. If the rotor is fault-free, the oscilloscope traces will be identical.

In practice, the **TDR100** test instrument has a switching circuit which applies pulses alternately from each end of the rotor winding so that the waveforms are automatically superimposed when viewed on a single channel oscilloscope.

Note: The easiest way to gain familiarity with the RSO test method is to use the Reflectometer with the D**emonstration Delay Line**, which is supplied with the equipment and as described in section 4. **New users** should follow the instructions given in **section 4** to acquaint themselves with the test method before attempting to carry out the test on a real rotor winding. Further detailed information about the test method is given later.

1.3. MEASUREMENT DETAILS

Electrical faults in generator rotors fall into two main categories, faults from the winding to the rotor body ('earth faults') and faults between parts of the winding ('inter-winding faults'). The existence of an earth fault is detectable with a simple multimeter. A single earth fault on a rotor is frequently tolerated and many generators run in this condition (preferably with some form of alarm system to detect the onset of a second earth fault). The existence of an inter-winding fault is not easily detected by simple electrical methods. However, a rotor winding with a serious inter-turn fault will frequently overheat, leading to more serious local damage, or display excessive mechanical vibration and may have to be taken out of service.

The rotor Reflectometer uses a technique known as time domain reflectometry. The application of this technique to testing rotors is known as the RSO (recurrent surge oscillograph) method by power engineers in the U.K.

The method involves applying a D.C. voltage step between one end of the rotor winding and the rotor body. The reflected wave at the input end of the winding and the transmitted wave at the far end of the winding are monitored using two oscilloscope channels. If the voltage step is applied from each end of the rotor winding alternately, then two oscilloscope traces will be obtained which may be superimposed on the oscilloscope screen. A healthy rotor winding will have two identical traces. A rotor with a fault will have differing traces and the positions of the fault may be deduced by scaling in the time domain.

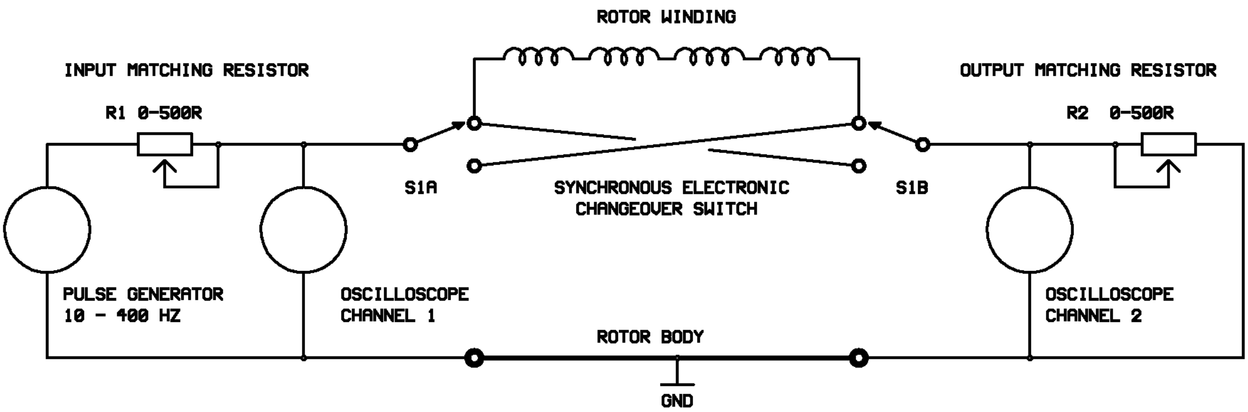
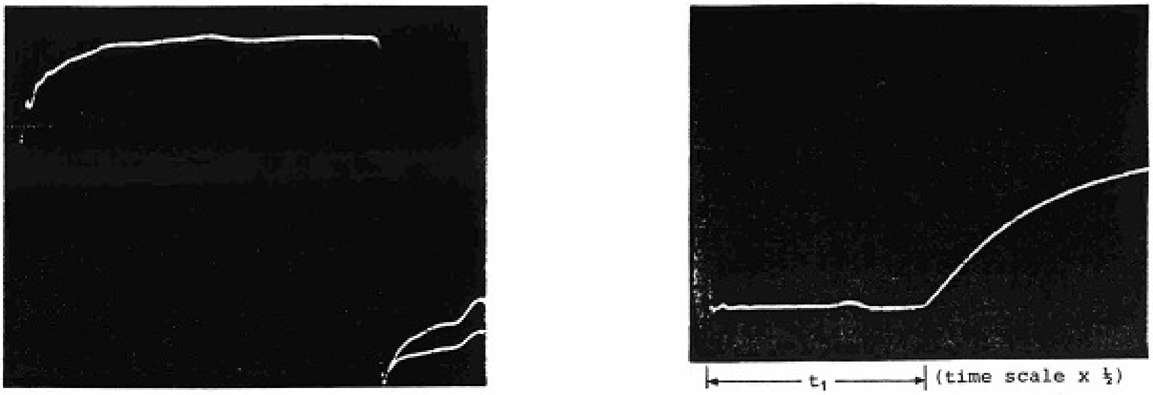


Figure 1.5 Reflectometer operating principle

The basic Reflectometer system is shown in Fig. 1.5. A pulse generator supplying a 12V pulse of variable length at a repetition rate of up to 500Hz is connected via a 500Ω variable resistor to an electronic changeover switch S1 synchronised to the pulse repetition rate. The changeover switch enables the rotor to be excited from each end of the winding in turn, alternate pulses exciting the rotor from opposite ends. The rotor is terminated in a second variable resistor R2 via the changeover switch. The pulse generator, synchronous changeover switching network, matching resistors and terminals are all contained within the Reflectometer unit. Two oscilloscope channels monitor the voltage at the input end of the rotor (channel C1) and at the output end (channel C2). The values of R1 and R2 are chosen to match, approximately, the characteristic wave impedance of the rotor winding, to eliminate reflections of the pulse at each end of the rotor.

The pulse repetition rate and pulse length are adjustable by means of three controls on the front panel of the Reflectometer. The synchronous changeover switch first excites the rotor at end 1 and the pulse propagates along the rotor winding, emerges at end 2 and is absorbed by R2. The switch then operates and the next pulse excites the winding at end 2, propagates through the winding to end 1 and is again absorbed in R2. The changeover switch returns to the first condition and the sequence is repeated continuously. Hence successive pulses from the pulse generator excite the rotor from each end in turn and energy is always supplied via R1 and absorbed by R2. The changeover switch is arranged to operate approximately half way in time between successive pulses so that the operation of the changeover switch does not adversely affect the leading edge of the pulse. A single channel oscilloscope connected between S1a and earth as shown will therefore display two traces corresponding to the signals applied to each end of the rotor.

1.3.1 Measured waveforms for a fault-free rotor winding



Input ends

Output ends

Figure 1.6 Typical oscilloscope traces for a fault-free rotor winding

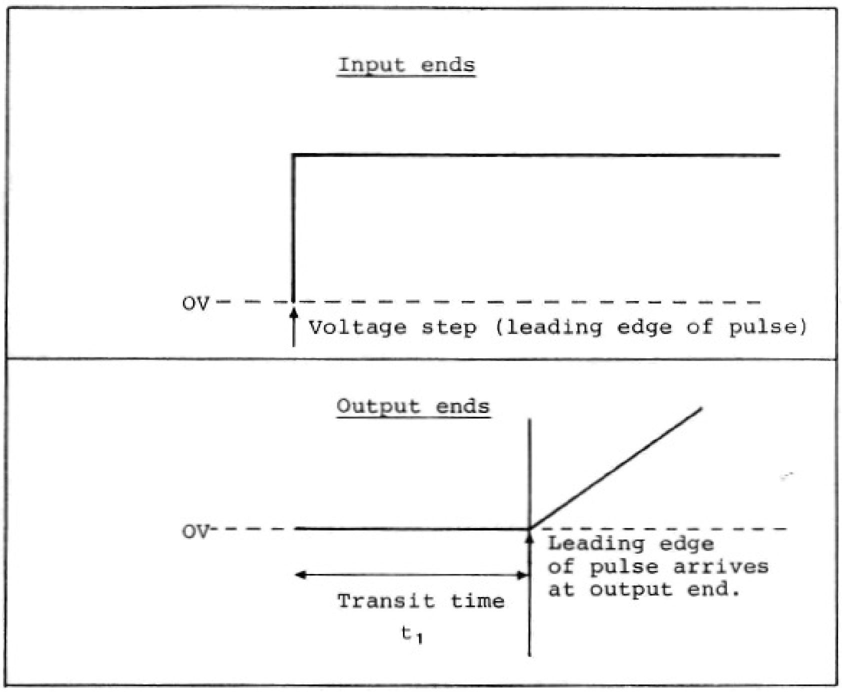


Figure 1.7 Simplified oscilloscope traces for fault-free rotor winding

The voltage waveforms at the input and output ends for a typical sound rotor are shown in Fig. 1.6 and simplified versions of these traces are shown in Fig. 1.7. A sound rotor will appear to be symmetrical with respect to either slip ring and therefore, the two traces that either C1 or C2 monitor will be identical and will be superimposed on the oscilloscope screen. The pulse will take a finite amount of time (the transit time) to travel from the input end of the rotor to the output end. As a result, the traces monitored by C2 will display zero voltage for this period (the transit time) and the transit time may therefore be measured directly from the C2 traces.

1.3.2 Measured waveforms for a rotor winding with an earth fault

When an earth fault occurs part way along the winding, the traces that occur are shown as measured, in Fig. 1.8 and in simplified form in Fig. 1.9.

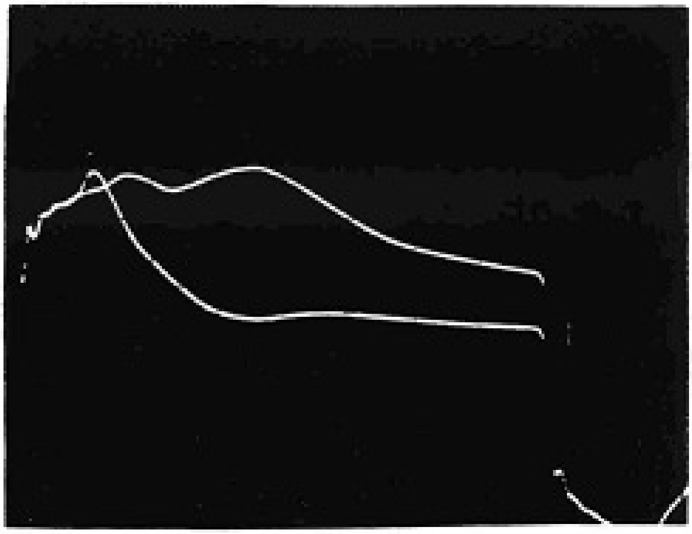


Figure 1.8. Short circuit to rotor body at end of 5th coil slot (16 coils in winding)

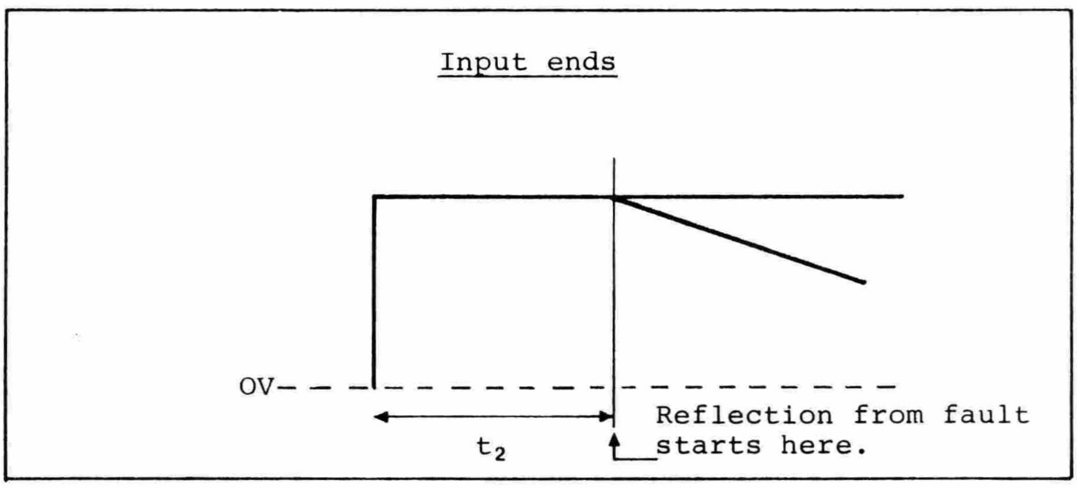


Figure 1.9 Simplified input end oscilloscope traces for rotor winding with earth fault

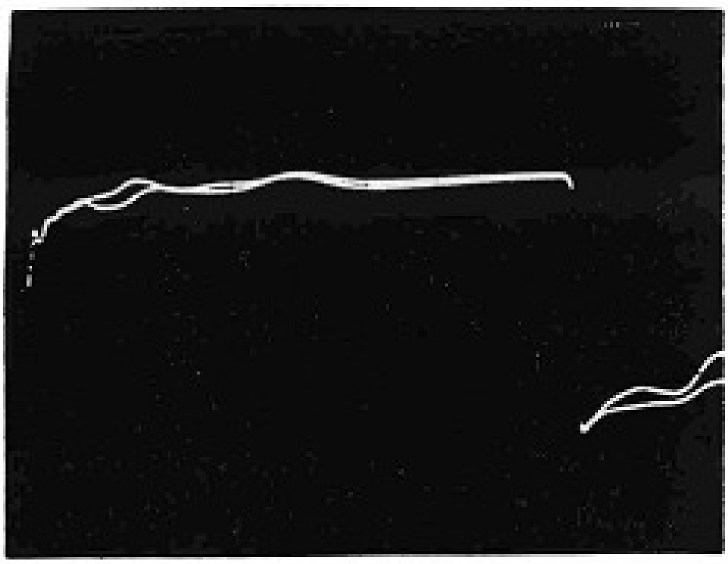
At the short circuit to earth, the input pulse is reflected with reverse polarity and when it returns to the input end, a decrease in voltage is observed. Assuming that the fault is not exactly in the centre of the winding, the reflection will occur at different positions for the two traces. The traces will therefore diverge as shown in Fig. 1.6. The trace that is deflected first corresponds to the end nearest to the fault. A rough estimate of the position of the fault may be found by noting the time to the fault as indicated by the input trace ($\mathbf{t_2}$ seconds).

By linear scaling, the fault will be approximately $\mathbf{t_2} \; / \; \mathbf{(2t_1)} \; \times 100\%$ of the winding from one end. However, the apparent propagation velocity of the pulse through the rotor winding is not uniform and care must therefore be exercised in locating faults by this method, as explained in Appendix 4.

The best method for locating the position of the fault is outlined in Section 2 (c). This involves removing the rotor from the generator and probing the winding in the end region or down the radial cooling holes if these exist. The detection and location of interwinding faults may be carried out in a similar manner.

1.3.3 Measured waveforms for a rotor winding with an interturn fault

If there is an interturn fault, the waveform at the slip ring nearest the fault is characterised by a slight increase in voltage followed by a decrease down to a minimum, followed by a slow voltage rise, as shown in the figure below.



(b) Short circuit between outer two turns in 5th slot coil.

Figure 1.10. Measured waveforms for a rotor winding with a single shorted turn.

The shape of the traces for an interturn fault can be explained by considering the effect on the incident pulse of a single shorted turn, as shown in the figure below.

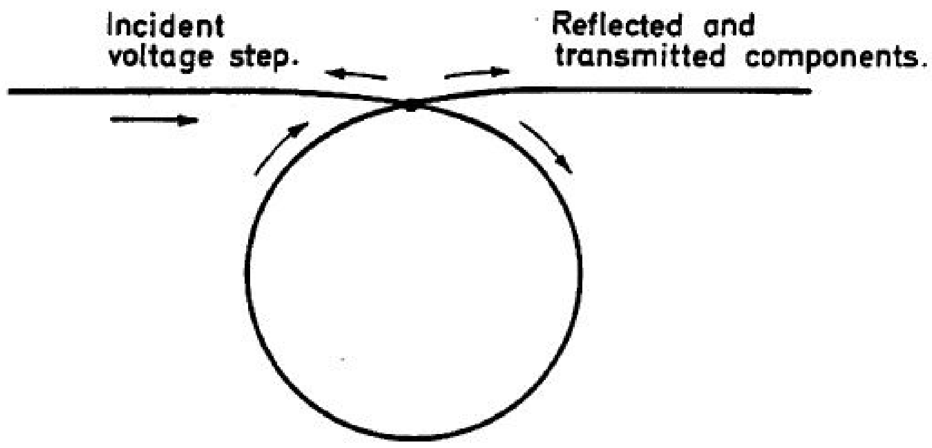


Figure 1.11 Simple representation of a shorted turn

When the voltage step reaches the short circuit between the turns, it can take one of 3 paths in the forward direction, instead of a single path in the fault-free case. The impedance that the voltage step sees looking in the forward direction will therefore be Zo/3, where Zo is characteristic impedance of the winding

This causes the transmission line to appear unmatched at this point and a proportion of the voltage will be reflected with opposite polarity to the incident voltage step, leading to a decrease in voltage when observed at the input end.

However. the rest of the voltage step will propagate away from the short circuit and two of the three paths available (round the shorted turn) will return the voltage step to the point of the short circuit. Part of this voltage will then be returned to the input end of the winding leading to an Increase in voltage. The part of the voltage step which travels round the shorted turn will do so continuously, causing the energy to be returned to the main rotor winding over an extended period of time.

Further details of the waveforms resulting from various fault conditions are shown and discussed in section 3.

2. OPERATING INSTRUCTIONS

2.1 DETAILS OF EQUIPMENT SUPPLIED

The followings items are supplied with a standard TDR100 Reflectometer measurement system:

TDR100/RB Rotor Reflectometer unit with mains lead

DL100 Demonstration Delay Line (inc. leads)

Terminal magnets (3)

5m 3-core test lead terminated in a connection module.

3 x 3m single core leads (Brown, Green, Blue) terminated in 4mm insulated banana plugs (Red, Green, Blue) at one (connection module) end and insulated crocodile clips at the other (rotor) end.

2 x 1.2m Coaxial oscilloscope leads

1m Delay line 4mm plug lead (red, blue, green)

This Instruction Manual

Padded Carrying Case

2.2 MEASUREMENT OPTIONS*

There are several modes in which the Reflectometer can be used:

1) Testing stationary rotor in generator.

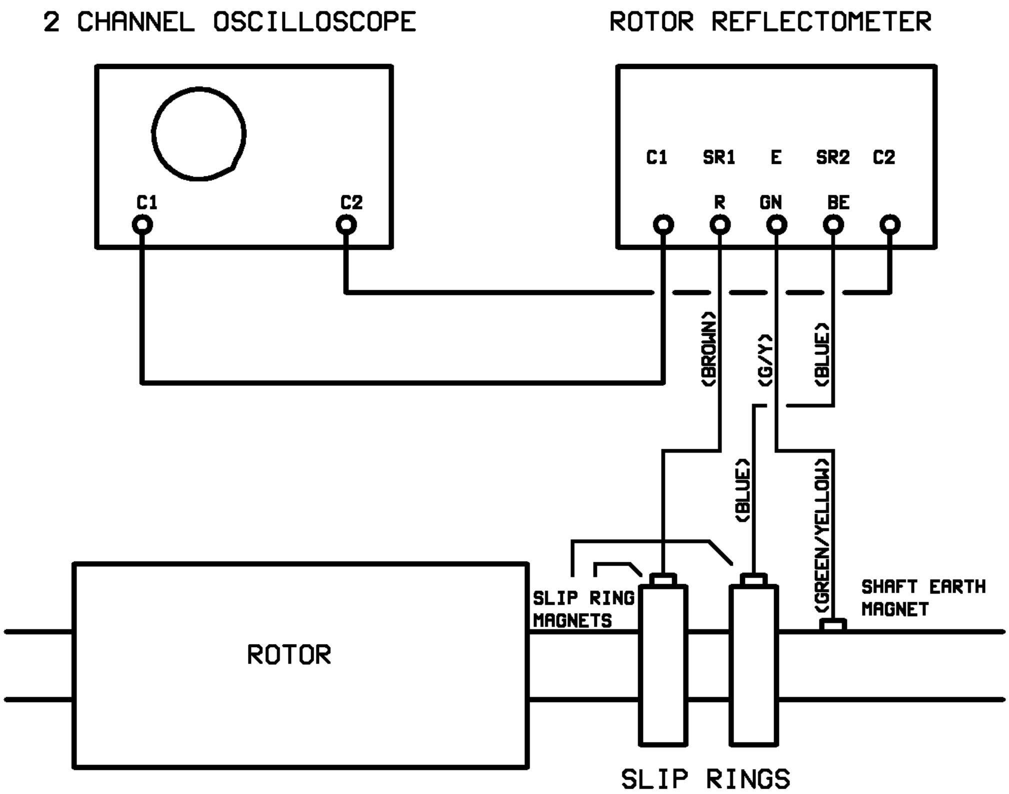
2) Testing rotor at speed in generator.

3) Testing rotor when removed from generator.

The most straightforward case is when the rotor is at rest in the generator and the test method for this will be described in detail. The other test modes are based on this technique with suitable modifications. The measurement system connection diagram is shown in Figure 2.1 and assumes the use of a basic two channel analogue oscilloscope, although a single channel instrument will suffice if a 2-channel oscilloscope is not available. Suitable low-cost instruments are listed in section 7.

Note that it is also possible to use a digital oscilloscope under some circumstances and the use of this type of oscilloscope is described in section 5.

* Please refer to Appendix 1 for additional information about the use of the TDR100RB unit which contains internal rechargable batteries.



Note that the colours in parentheses eg (BROWN) refer to the connecting leads, while the abbreviated colours eg R (RED) etc. refer to the 4mm banana plugs and terminals.

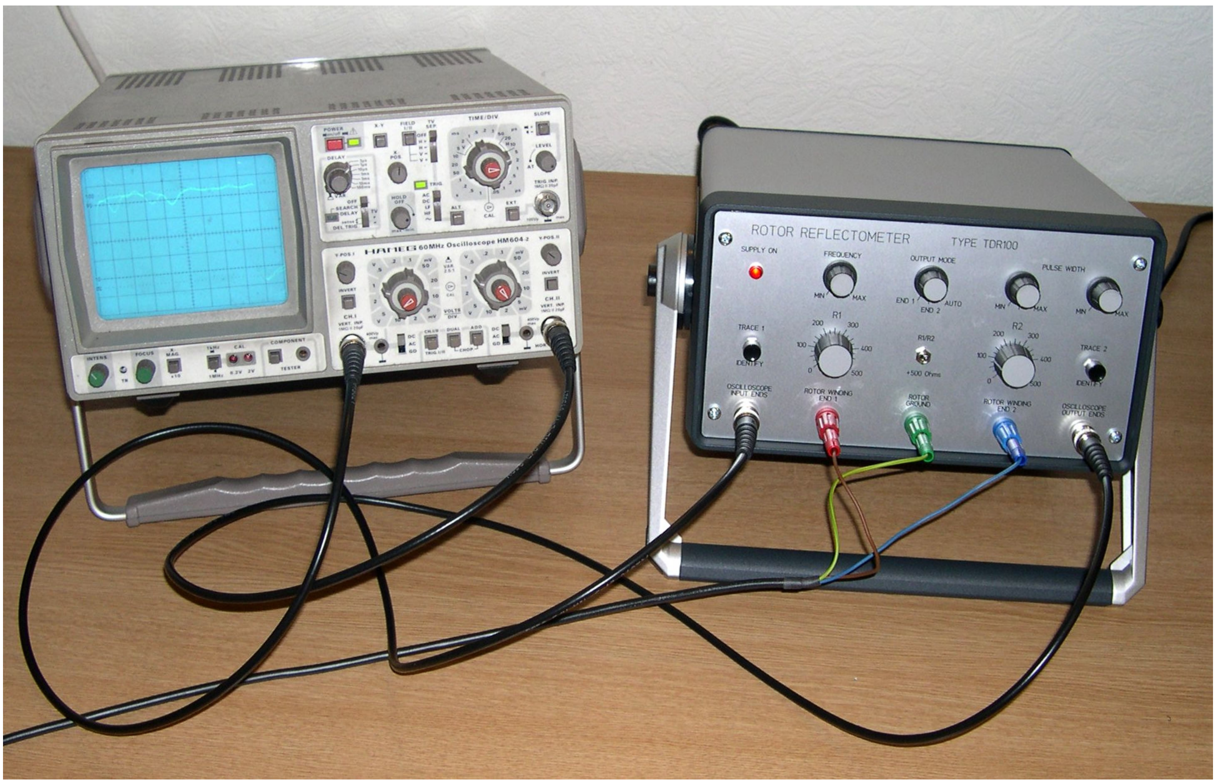


Figure 2.1 Measurement system connection diagram and image

2.3 METHOD FOR TESTING A ROTOR AT REST WHILE INSTALLED IN THE GENERATOR

SAFETY WARNING

The use of this equipment on a rotor installed in an operational generator must be carried out with the explicit permission and under the supervision of the local plant operator. All local safety rules and procedures must be complied with.

In particular, the equipment must only be connected to the generator rotor after the field supply has been disconnected and isolated in accordance with local safety regulations. Failure to comply with this instruction will damage the equipment and may endanger both the the plant and the operator.

2.3.1 Rotor Winding Connection Module and test leads

The connections between the **Reflectometer** and the **Generator rotor winding** are made using the **3-core 5m Rotor test lead** and **Connection module** supplied with the equipment. This lead has **4mm insulated banana plugs** at the **Reflectometer end** and a **Connection module** terminated in **4mm insulated terminals** at the **rotor end.** Three 3m insulated single core leads connect this module to the rotor winding. The **Connection module** and **test leads** are shown in figure **figure 2.2** below**.**

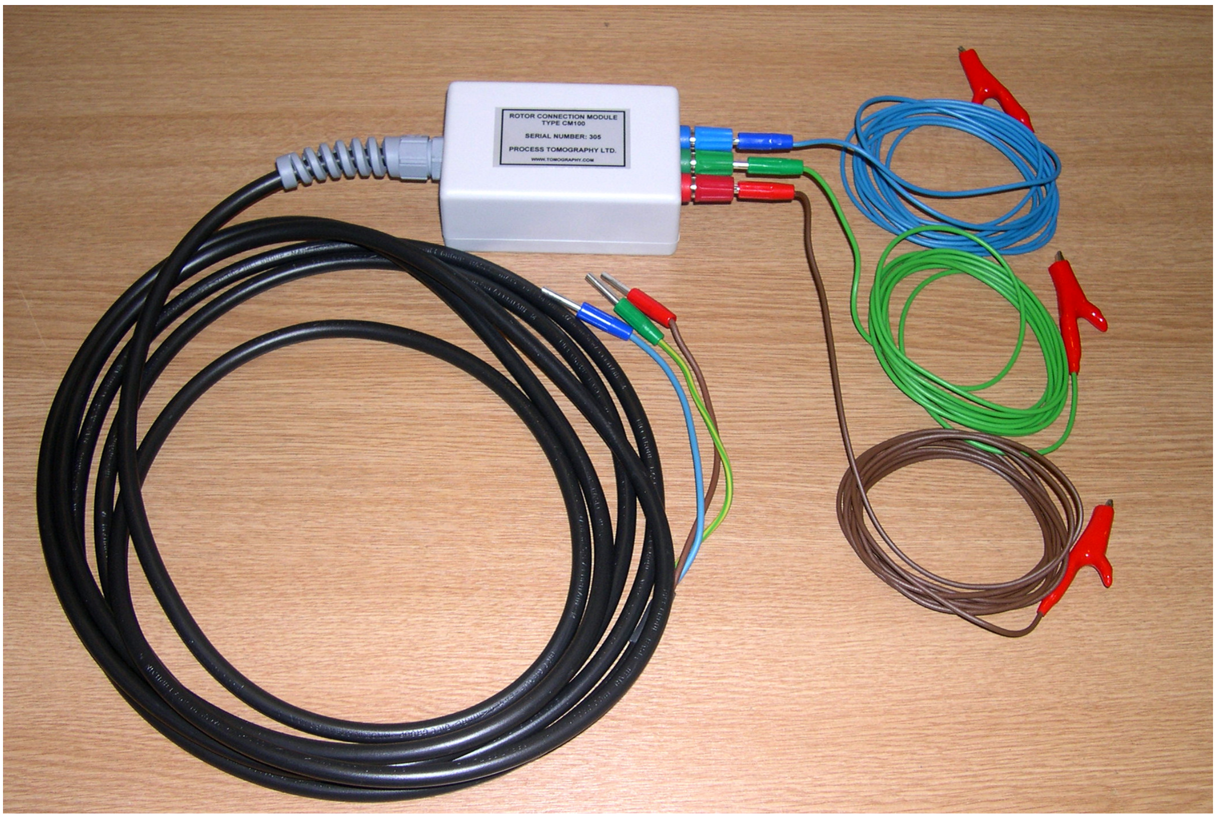


Figure 2.2 Rotor test leads and connection module

Note: The connection module provides simple 1:1 connectivity between the banana plugs at the **reflectometer end** and the **output terminals** on the module. This arrangement has been used to allow connections to be made to the rotor windings of large generators, where there may be significant distances between the slip rings and the rotor shaft earthing point. It also allows damaged connecting leads to be repaired or replaced easily on-site, or for customers to use their own connecting leads if preferred.

The connections to the rotor slip rings and earthed shaft can be made using the contact magnets supplied and shown in figure 2.3.

Figure 2.3 Contact magnets and keepers.

2.3.2 Setting up the test equipment

1. Isolate and make safe the generator stator winding.

2. Either isolate the field brushgear from the field supply (both sets of brushes), or remove all of the brushes from each brushgear cage, ensuring that none of the brushes touch the slip rings. For a brushless generator, isolate the generator field winding from the rotating rectifier unit (both leads).

3. Connect the banana plugs of the individual 3m leads to the output terminals of the Connection Module. Match the plug and terminal colours (red to red etc.). **At this stage, do not connect the other end of the 5m test lead to the Reflectometer terminals**.

4. Clean an area of rotor shaft adjacent to the slip rings with emery cloth, followed by a degreasing solvent and wipe off with a clean rag. Remove the magnetic keeper and attach one of the terminal magnets supplied (see figure 2.2) to the shaft at this point.

5. Connect the crocodile clip of the **green** conductor of the **3m Green test lead** to the screw stud on this magnet.

6. Attach the crocodile clips of the **brown** and **blue 3m test leads** to each end of the rotor field winding as follows:

> i) If it has been possible to isolate the brushgear cages from the field supply, then simply connect these leads to each brushgear cage assembly (clip the crocodile clip on to one of the brush braids).
>
> ii) If the brushes have been removed, clean a small area on each slip ring with degreasing solvent and attach the two remaining magnets to the slip rings. Attach the **brown** and **blue** leads to the terminal studs on these magnets using the crocodile clips.
>
> iii) For the case of a brushless generator, clip the **brown** and **blue** leads directly to the up-shaft field winding leads after the isolating links have been removed.

Note: **Do not connect the other end of the 5m lead to the Reflectometer at this stage**.

7. Using an electrical test meter, measure the **rotor winding resistance** between the **red** and **blue banana plugs** at the **Reflectometer end** of the 5m rotor test lead. This should be typically less than one ohm, including the resistance of the leads. If the measured resistance is greater than one ohm, check the contact resistance between the clip ends of the **brown** and **blue** leads and the field winding. If magnets are being used, remove them and reclean the slip ring and magnet faces if necessary. Record the measured winding resistance.

8. Check the **contact resistance** of the earth magnet to the rotor shaft by measuring the resistance between the **green banana plug** at the **Reflectometer end** and a **point on the rotor shaft** near the magnet. If the resistance exceeds one ohm, reclean the shaft and the magnet face and repeat until a low contact resistance is obtained.

9. Using an electrical test meter, measure the **insulation resistance** of the rotor between either one of the the red or blue banana plugs and the green banana plug. A healthy rotor will have an insulation resistance in excess of 1MΩ, although if the winding is damp, this may be reduced to 10KΩ or less. Record the insulation resistance.

10 Now connect the **red and blue** plugs of the **5m test lead** to the same colour terminals on the **Reflectometer front panel** (slip ring 1 and 2 terminals) and connect the **green** plug to the **green** earth terminal on the Reflectometer (see figure 2.4).

Figure 2.4 Reflectometer front panel controls (TDR100RB)

11. Connect the coaxial **BNC leads** to the oscilloscope input channels

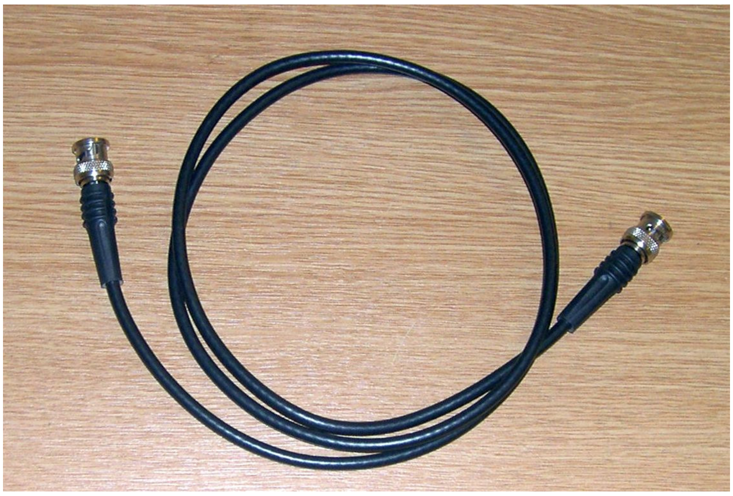


Figure 2.5. Oscilloscope Lead

12. Connect the coaxial **BNC Oscilloscope leads,** shown in figure **figure 2.5** from the **oscilloscope input channel type BNC terminals** to the **reflectometer osciloscope BNC terminals** as follows:

Connect one coaxial lead between the **oscilloscope channel 1 input** and the **reflectometer oscilloscope input ends connector**. Turn the BNC connector on the coaxial lead clockwise to lock it into position.

Similarly, connect the other coaxial lead between the **oscilloscope channel 2 input** and the **reflectometer oscilloscope output ends connector**.

The system connectivity should now be as shown in figures 2.1 and 2.6.

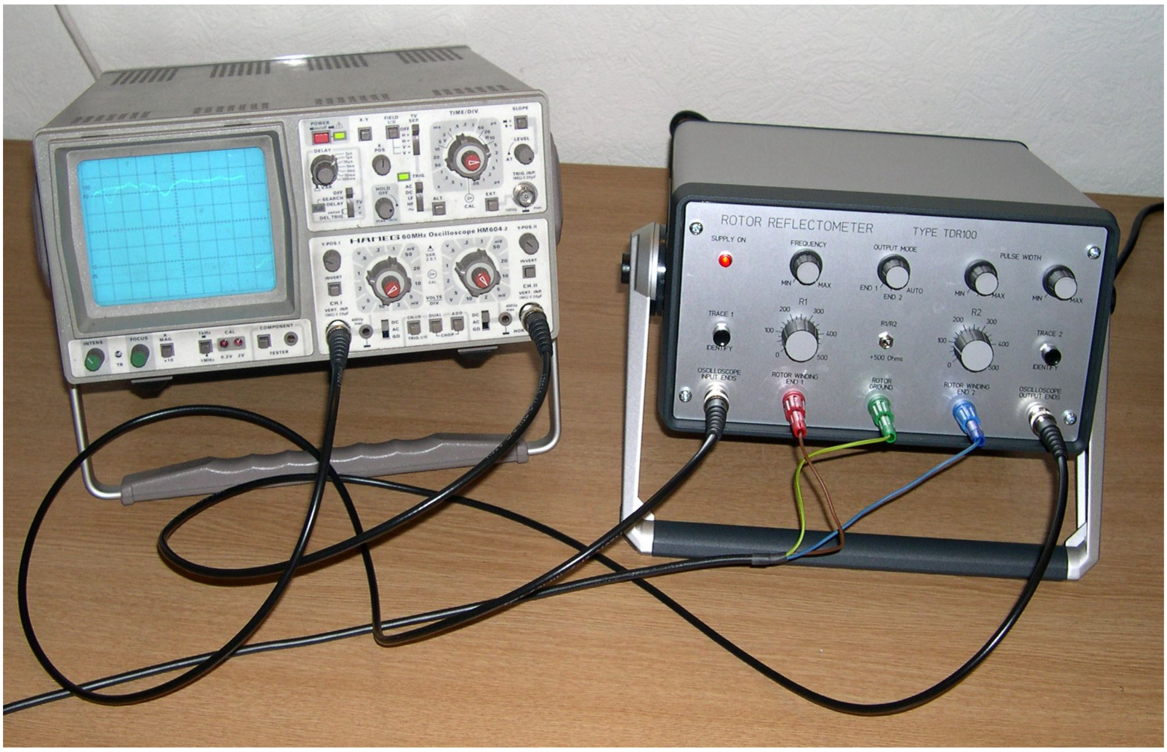


Figure 2.6. Measurement system connectivity

2.3.2 Testing the rotor winding

1. Set the controls on the **Reflectometer** initially as follows:

   R1= R2 = 100Ω

PULSE FREQUENCY	: Fully clockwise
PULSE WIDTH SWITCH	: Centre position
PULSE WIDTH POTENTIOMETER	: Mid scale
PULSE OUTPUT SWITCH	: Auto
R1/2 TOGGLE SWITCH	: Up (0 - 500 Ohms)

2. Set the oscilloscope controls initially as follows:

DISPLAY	: Channel 1
VERTICAL SENSITIVITY	: 2V/CM (Both channels)
TRIGGER CONTROLS	
- MODE	: Normal
- SOURCE	: Channel 1
- LEVEL	: Positive
- SLOPE	: Positive
- COUPLING	: D.C.
- TIME BASE	: 20 μsec/CM

3. Switch on the **Oscilloscope** and the **Reflectometer**. Adjust the oscilloscope trace position and triggering controls until a stable voltage step is displayed on the oscilloscope screen. This is the waveform at the input ends of the rotor winding and should resemble one of the traces shown in Fig. 2.7 (a) to (c).

Further detailed information about these waveforms is given in section 3.

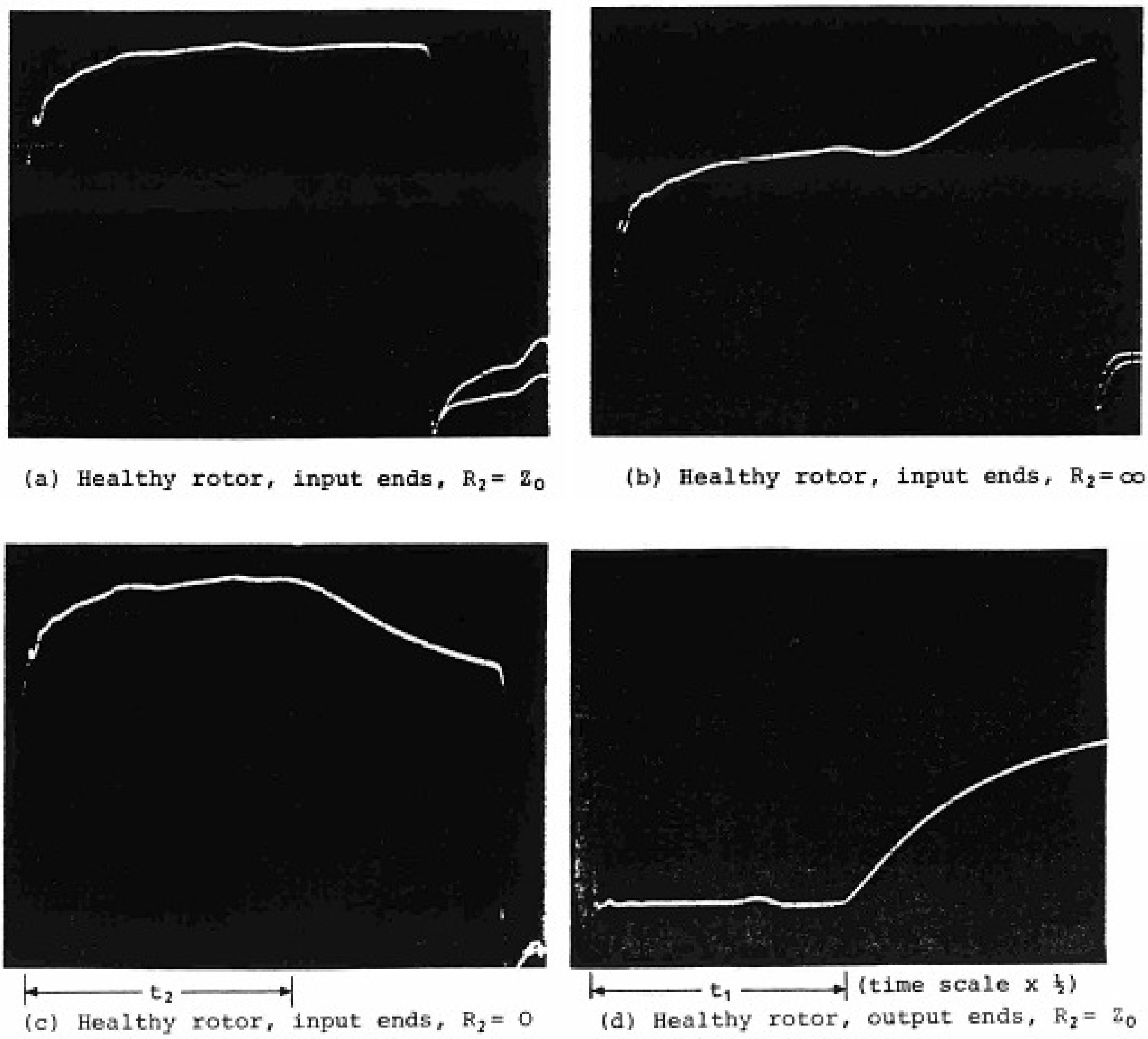


Figure 2.7 Typical oscilloscope waveforms

4. Switch the **oscilloscope to display channel 2** or, if a single channel oscilloscope only is available, connect the oscilloscope input lead to the '**OSCILLOSCOPE OUTPUT END**' terminal of the **Reflectometer**. Adjust the oscilloscope controls until a trace similar to that shown in Fig. 2.7(d) is obtained. This trace shows the voltage step received at **each remote end** of the rotor winding. Adjust the oscilloscope timebase switch (and, if necessary, the Reflectometer pulse width controls) until the single pass transit time [t_1 in Fig. 3.1 (d)] occupies less than half of the trace width. Record this transit time in micro-seconds.

5. Switch the oscilloscope back to **display channel 1** and adjust the **pulse width controls** on the Reflectometer unit so that the trailing edge of the voltage step can be seen at the far right of the trace as shown in Figs. 2.7 (a) to (c). This is a convenient way of displaying the **zero voltage level**. Now **adjust R2** so that there is no reflected signal from the ends of the winding.

Fig. 2.7 shows three cases:

a) R2 matched (no reflection)

b) R2 too large (positive reflection)

c) R2 too small (negative reflection)

The reflection is seen at the input ends t_2 seconds after the start of the voltage step where t_2 is approximately twice the single pass transit time (t_1).

Note that the range of the **Matching Resistors R1 and R2** can be increased using the **R1**/**R2** switch.

If the switch is in the **UP** position, the range is 0 - 500 Ohms.

If the switch is in the **DOWN** position, the range is 500 - 1000 Ohms.

If the toggle switch is down when correctly matched, add 500Ω to the dial reading to obtain the value of R1/R2.

6. Having matched the output ends correctly, **note the value of R2** (adding 500Ω if necessary), which is the average **characteristic wave impedance** of the rotor winding. **Now set R1 = R2 to complete the matching at the input ends**. This eliminates the possibility of multiple reflections from one end of the rotor to the other. It may now be necessary to adjust the oscilloscope vertical sensitivity controls to optimise the trace size relative to that of the oscilloscope screen.

7. If the rotor winding is perfect, **two perfectly superimposed traces** will be displayed on the screen. If this occurs then the rotor winding can be safely assumed to be fault-free. To verify the existence of the two traces, push one of the **trace identifier** buttons, when one of the traces should be displaced vertically towards the zero voltage level, showing the two traces. If only one trace is displayed check that the **PULSE OUTPUT** mode switch is in the **AUTO** position.

8. If two perfectly superimposed traces are not obtained, there may be a fault in the rotor winding. Section 3 explains in detail the trace shapes to be expected for various types of faults.

9. Record the traces by photographing the oscilloscope display using a digital camera (with the flash turned off), then edit the image using an image editing program such as the freeware **Irfanview**, available from: **http://www.irfanview.com/**

An example of a screenshot obtained using this method is shown below.

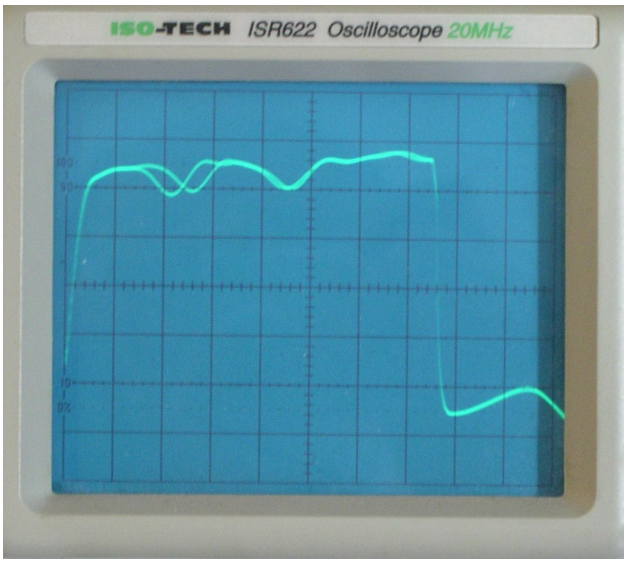


Figure 2.8 Screenshot of traces for Delay line with simulated interturn fault.

2.3.2 ADDITIONAL OPERATING MODES

In addition to operation in **Auto mode**, it is possible to apply pulses to either slip ring 1 or slip ring 2 only. This option can be useful when using a digital oscilloscope to monitor the traces as described in section 5. The operating mode is controlled by the 3-way **Pulse Operation switch** as follows:

Position 'END1' - pulses are injected into slip ring 1 only.

Position 'END2' - pulses are injected into slip ring 2 only.

Position 'AUTO' - normal operating mode.

NOTES

1. Mode switch

For normal rotor testing ensure that the switch is in the '**AUTO**' position, as the single trace produced when the switch is in the **'END1**' of **'END2**' position will not indicate a winding fault.

When in the **'AUTO**' position always check that two traces are present by using the '**Trace Identify**' buttons. If only one trace is shown when one button is pressed, check and adjust the triggering of the oscilloscope (particularly when using a digital oscilloscope).

2. Operation of the case handle.

The case handle can be rotated by pushing in the black buttons at each handle pivot point as shown below:

Figure 2.9 Handle pivot buttons (one on each side)

Depress both buttons to allow rotation of handle

2.4 METHOD FOR TESTING ROTOR AT SPEED

CAUTION

Any testing carried out on a rotating rotor must be carried out with extreme care and with the explicit permission and under the supervision of the local plant operator. All local safety rules and procedures must be complied with.

1. The **Reflectometer** may be used to test an unexcited rotor at speed. This is particularly useful for detecting and locating faults that are **speed-dependent**.

The most useful information is obtained if the test is conducted either while the rotor is being run up to speed from rest, or while it is run down to rest from synchronous speed. The method is essentially the same as for testing a stationary rotor except of course that it is necessary to make contact with moving slip rings and shaft earth connections.

2. If the brushgear cages can be isolated from the field supply, then connections can be made to the slip rings via the brushgear. However, in most cases it is not possible to isolate the cages. In these circumstances it is necessary to remove all of the brushes from the cage and install some insulated brushes that have been previously prepared. In anticipation of the test, three brushes per slip ring should be removed from the cages and marked so that they may be reinserted in the positions from which they have been removed. The brushes should be machined undersize, and strips of Tufnol or other suitable insulating material glued to the faces of the brushes using an epoxy resin adhesive. The insulated brushes should then be re-machined down to the correct size for reinsertion.

Experience has shown that it is necessary to use brushes that have been in service in the machine and which have been passing current. This technique does not work if new brushes are used because these give very poor contact with the slipring. The insulated brushes are installed in the machine prior to the test, and the brushes in each cage are commoned taking care not to let the brush braids touch the cage assembly. Connections are then made from these insulated brushes to the Reflectometer.

3. It is necessary to make a separate earth connection to the rotor shaft. The most effective method appears to be to clean an area of the shaft and to hold a short length of heavy duty stranded earthing cable against the shaft. This may be done by stripping off the last few centimetres of insulation from the cable and taping the cable to a short length of dowel so that the temporary earth brush may be held safely in contact with the shaft. It has been found by experience that it is not satisfactory to use an existing shaft earth brush for this test because of the large amount of electrical noise generated by these devices.

4. With the modifications mentioned above, the test may be carried out as the rotor speed is increased or decreased. The equipment should be set to monitor the traces at the input ends of the rotor and should be watched carefully for any changes in one trace which will indicate a speed dependent fault.

2.5 METHOD FOR TESTING ROTOR WHEN REMOVED FROM GENERATOR

1. The test method is basically the same as that outlined in Section A. However, with the rotor removed from the machine, further tests may be possible.

2. If the rotor end rings are removed, the shape of the traces obtained may differ considerably from that for a rotor with the end rings in-situ. Moreover, because the windings can expand radially in the absence of the end ring, two slightly different traces may be obtained for a rotor that is known to be fault-free, because the expansion of the end region windings may not be uniform. In general, the effect of removing the end rings increases the characteristic impedance of the rotor considerably.

3. If a winding fault has been detected in the rotor, and the end rings have been removed, it is possible to find the approximate location of the fault by putting a similar fault onto the other half winding of the rotor and moving the position of this deliberate fault until two identical traces are obtained. This may be done by using insulated probes.

If an earth fault is suspected, then one of the probes should be earthed to the rotor body using a short flexible lead, and the end winding should be probed until the application of this fault causes similar traces to appear. The faulted coil may be found by touching the probe onto the outer turn of each coil in the end region of the winding. When the coil which causes the traces to almost coincide has been located, the faulted turn may be located by moving the probe radially down this coil in the end winding region and making contact with the sides of the conductors, which are not usually insulated. When the turn has been located which causes the traces to coincide (or nearly so) its coil number and turn number (found by counting turns down from the outside of the winding) should be noted. The fault lies in the equivalent coil in the other half winding.

4. It is possible to use this same technique without removing the end rings if the rotor contains radial cooling holes that run next to the conductor slots. In this case, the winding may be probed directly.

5. The position of an inter-turn fault may be located by using two probes connected via a length of flexible lead. In this case, adjacent turns of the opposite half-winding are shorted together to locate the fault. An alternative method is to make up a special two-pronged probe to apply the shorts between adjacent turns. An example of this type of probe is shown below.

LENGTH OF INSULATED BRASS WELDING ROD

A short lengths of welding rod brazed to main section

P = pitch between adjacent turns of rotor winding

Figure 2.10 Probe for locating shorted turns

3. INTERPRETATION OF RESULTS

3.1 Fault-free, Healthy Rotor Winding

Fig. 3.1 shows the results to be expected when a healthy rotor is tested.

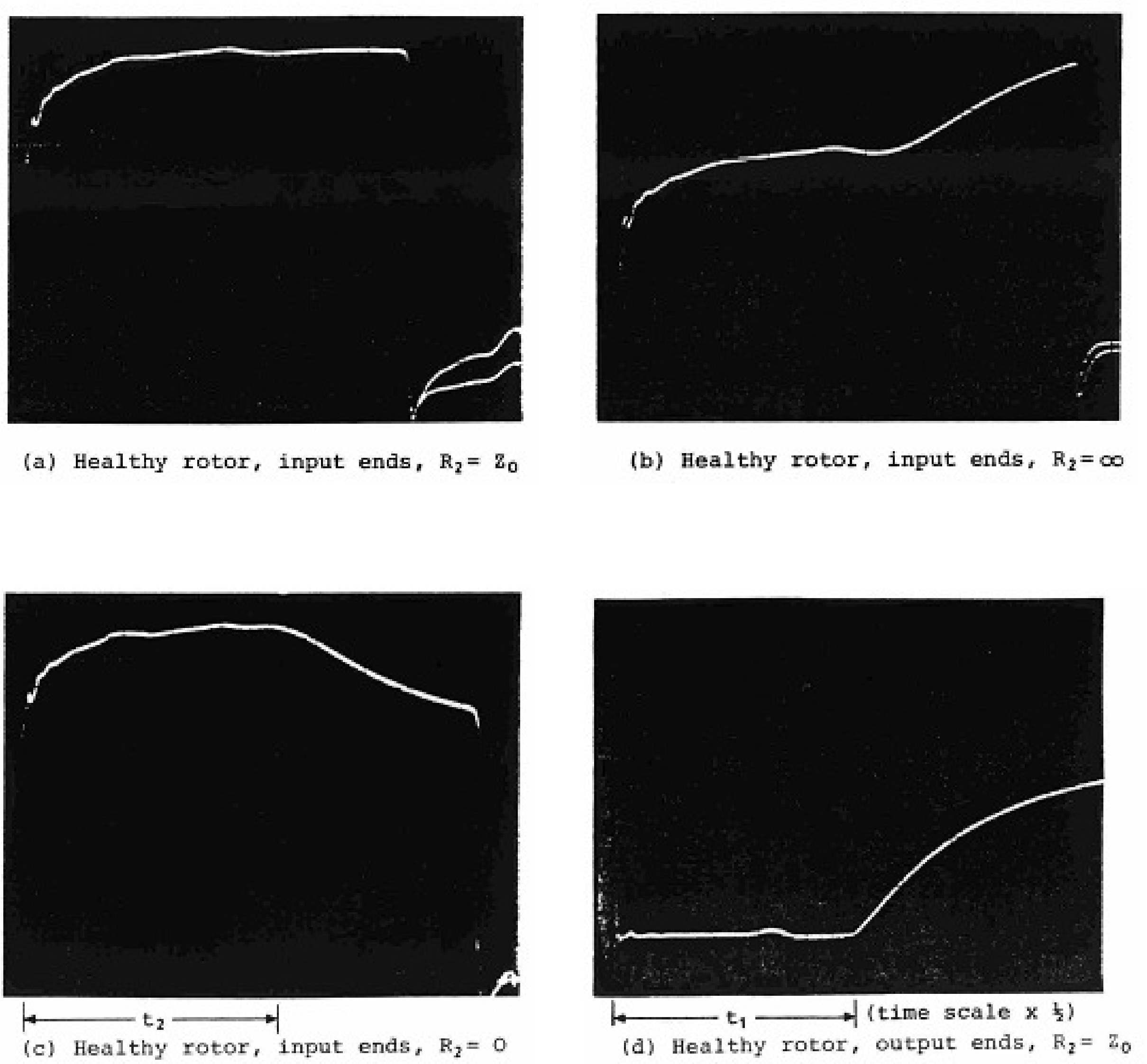


Figure 3.1. Typical waveforms for a fault-free rotor winding

Fig. 3.1 (d) shows the voltage step received at the far end of the rotor, and t_1 is the time for it to propagate through the rotor. This is termed the single pass transit time and is typically 20-100μS.

Fig. 3.1 (a) shows the traces at the input ends of the rotor and displays two perfectly superimposed traces (except in the region after the end of the voltage step, which is of no relevance to the test). This indicates a healthy rotor winding.

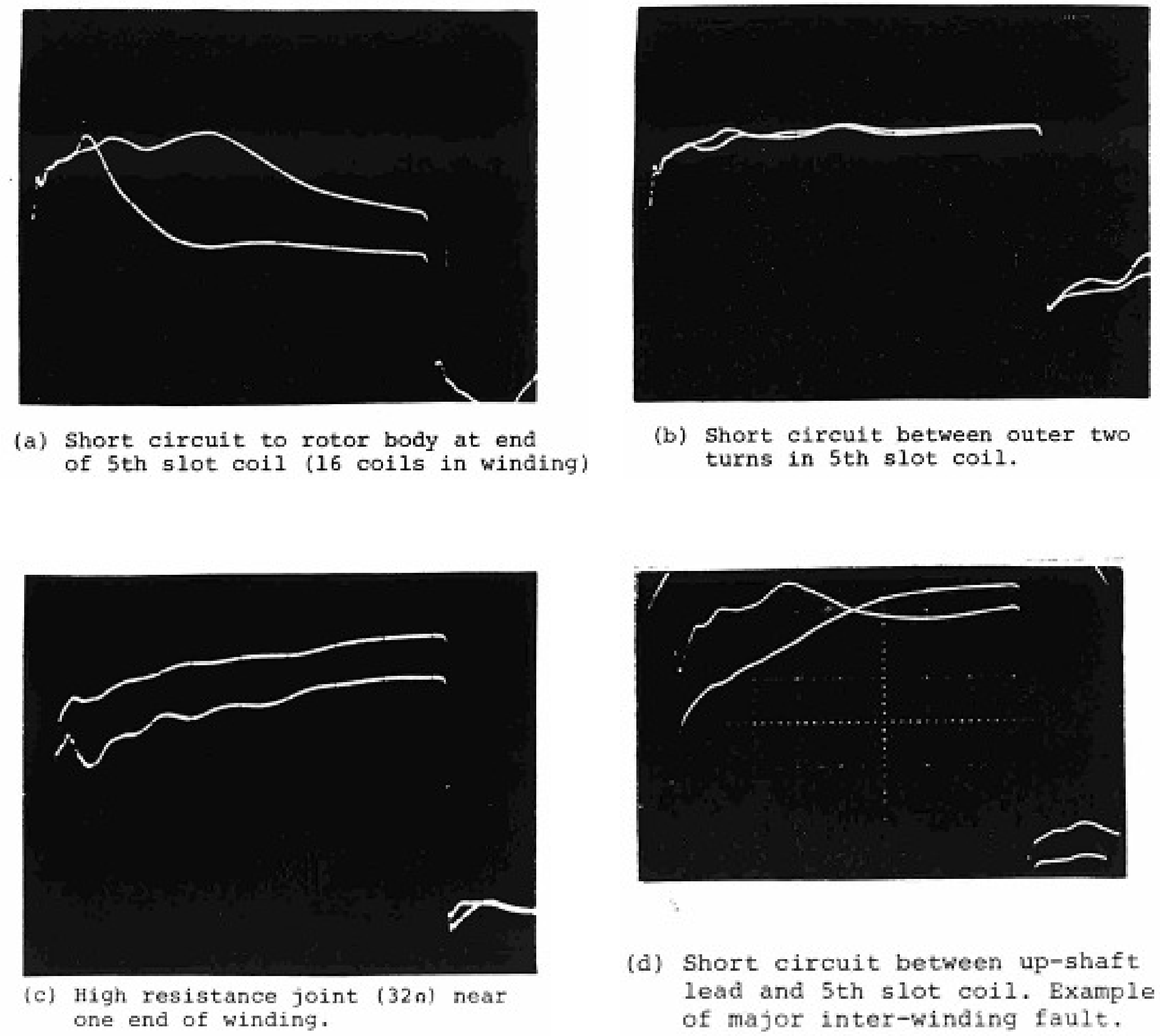
Fig. 3.1 (c) shows the input end traces when the output ends are terminated in a near short circuit (R2 = O). The top of the voltage step is seen to start to decrease in amplitude after a time t_2 seconds, which is the time for the pulse to pass through the winding once and then back again.

Similarly Fig. 3.1 (b) shows the input end traces when the output ends are terminated in an open circuit. In this case, the top of the voltage step starts to increase after t_2 seconds.

It will be seen that the input and output matching resistors have no effect on the individual traces apart from changing their shape. It is not possible to produce two different traces for a healthy rotor by maladjustment of the Reflectometer or oscilloscope controls and hence the possibility of misinterpreting traces caused by operator error is greatly reduced. Always check for two traces by pressing the trace identify switches.

3.2 Trace indicates a Faulty Winding

There are several basic modes of failure of a rotor winding and some example traces are shown in figure 3.2.



(a) Short circuit to rotor body at end of 5th slot coil (16 coils in winding)

(b) Short circuit between outer two turns in 5th slot coil.

(c) High resistance joint (32Ω) near one end of winding.

(d) Short circuit between up-shaft lead and 5th slot coil. Example of major inter-winding fault.

Figure 3.2 Typical Traces for various winding faults

a) **Fault between winding and rotor body (earth fault)**

A full or partial fault may occur between the winding and the rotor body. An example of the type of trace obtained in this case is shown in Fig. 3.2 (a). The voltage step which is injected from the end nearest the fault is seen to increase to a peak at the fault and then to decay rapidly. The voltage step injected from the end furthest from the fault increases and decays some time later, as the voltage step injected from the remote end takes a longer time to reach the position of the fault. It should be noted that the sharpness and rate of decay of the second peak is considerably less than that for the first peak. This is an example of the general rule that the resolution of the measurement for this test is greatest near the point of injection of the voltage step (i.e. at the slip rings) and decreases as the position of the fault moves further into the winding.

The approximate location of the fault may be found by comparing the time from the start of the voltage step to the peak of the trace with that to the end of the winding when R2 is set equal to zero as shown in Fig. 3.2 (c). This must have been done prior to the fault occurring and highlights the need to record the traces of 3 (a) and 3 (b) for the rotor while it is in a fault-free state (ideally when it is first commissioned) to act as a reference 'fingerprint' for future use. See also the note in paragraph 3.2(f) on the next page.

b) **Interturn Fault**

Fig. 3.2 (b) shows the type of trace obtained when a short circuit between adjacent turns occurs. The trace corresponding to the end nearest the fault increases slightly then decreases and finally increases to meet up again with the trace injected from the other slip ring end. The faulty trace is that which gives rise to the lower part of the first major loop shown in Fig. 3.2 (b). The approximate location of the fault may be found by similar means to that described for the earth fault case. It should be noted that the test is particularly sensitive and will detect a relatively high resistance (a few ohms) interturn fault that may, in practice, not carry current in an operational state. Further tests involving measuring the voltage drop across adjacent turns by passing a large direct current through the total winding must be carried out to determine whether the fault is current-carrying or not.

c) **High resistance joint in rotor**

The effect of a high resistance joint on the winding is shown in Fig. 3.2 (c). The apparent characteristic impedance of the end of the winding nearest the fault is increased relative to that of the other end of the winding. Hence the upper trace shown in Fig. 3.2 (c) corresponds to the end of the winding nearest the fault. It is possible that the fault may be caused by a high resistance joint at one slip ring. In this case, the fault may be confirmed by placing a variable 0 - 500Ω resistor in series with the lead to the other slip ring and adjusting this variable resistor. If it is possible to make the traces coincide by these means, then the fault occurs very close to the first slip ring.

d) **Interwinding fault**

It is possible for faults to occur between rotor slot coils and the upshaft leads which connect the slip rings to the ends of the rotor winding. Fig. 3.2 (d) shows an example of a fault of this type, in which the upshaft lead had shorted to the fifth coil in the winding, effectively shorting out the first five coils in a total winding of sixteen coils. The lower trace corresponds to the slip ring nearest the shorted coils.

e) **Other causes of non-identical traces**

Apart from these common faults, there are circumstances where, in applying the test, problems occur which may indicate that a good rotor is faulty. These may be caused by:

i) Poor contact between the slip rings and the test leads. If this occurs, the traces will resemble Fig. 3.2 (c), the difference between the traces being dependent on the magnitude of the contact resistance. If this occurs, re-check the contact between the test leads and the slip rings before assuming that the rotor winding is faulty.

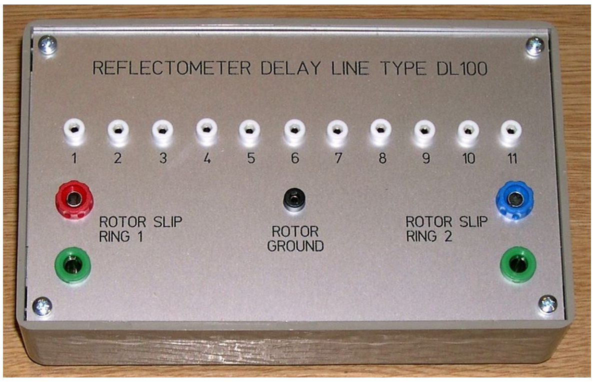
ii) Poor contact between the earth lead and the rotor shaft. Again, the cure is to re-check the contact resistance.

iii) The characteristic impedance of both rotor half windings are not identical. On the face of it, this seems most improbable. However, it may be caused by a previous repair to one half winding using insulation different from that used during manufacture. Moreover, when the end rings are removed, the end windings expand radially in a non-uniform manner, causing the impedances to differ. Consequently, two slightly different traces are nearly always obtained when one or both end rings are removed.

f) **Method for deriving the time/distance curve for the rotor**

A more accurate method for determining the location of the fault is decribed in Appendix 4. This method shows how an approximate relationship between the measured transit times and the distance from the slip-rings or winding ends can be derived using the single and double-pass transit times..

4. USE OF REFLECTOMETER DELAY LINE TEST UNIT



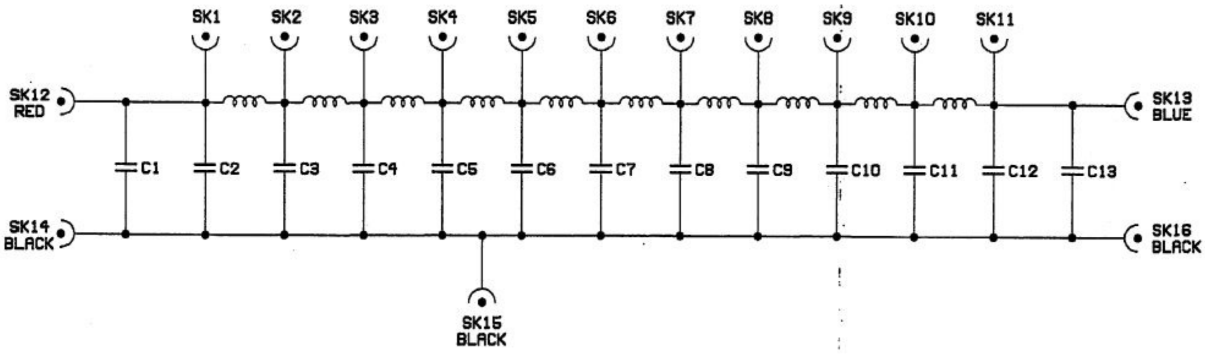


Figure 4.1 Delay line type DL100

The delay line unit is used to check that the Reflectometer is operating correctly and is also an aid to demonstrating and understanding the test method. The unit consists of a 10 section lumped component delay line. The characteristic impedance of the delay line is 100Ω and the propagation time for a single pass through the unit is 11µS. The junctions between each section of the delay line are connected to a series of 2mm sockets, enabling external connection to these points. The input and output ends of the unit are connected to 4mm sockets.

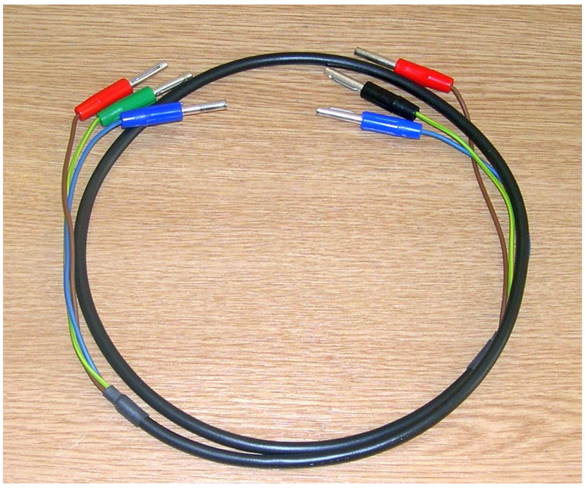


Figure 4.2 1m delay line connection lead

In use, the **Delay line** is connected to the **Reflectometer** using the **1m 3-core test lead** supplied and shown above in figure 4.2. At the **Delay line** end, the **red banana plug** is connected to the **red input terminal** on the delay line, the **blue banana plug** is connected to the **blue output terminal** and the **green banana plug** is connected to the **green common terminal**.

At the **Reflectometer end**, the **red banana plug** is connected to the **red (Rotor slip ring 1)** input terminal on the front panel, the **blue banana plug** is connected to the **blue (Rotor slip ring 2)** output terminal and the **green banana plug** is connected to the **green** ground terminal. The overall connection arrangement is shown below.

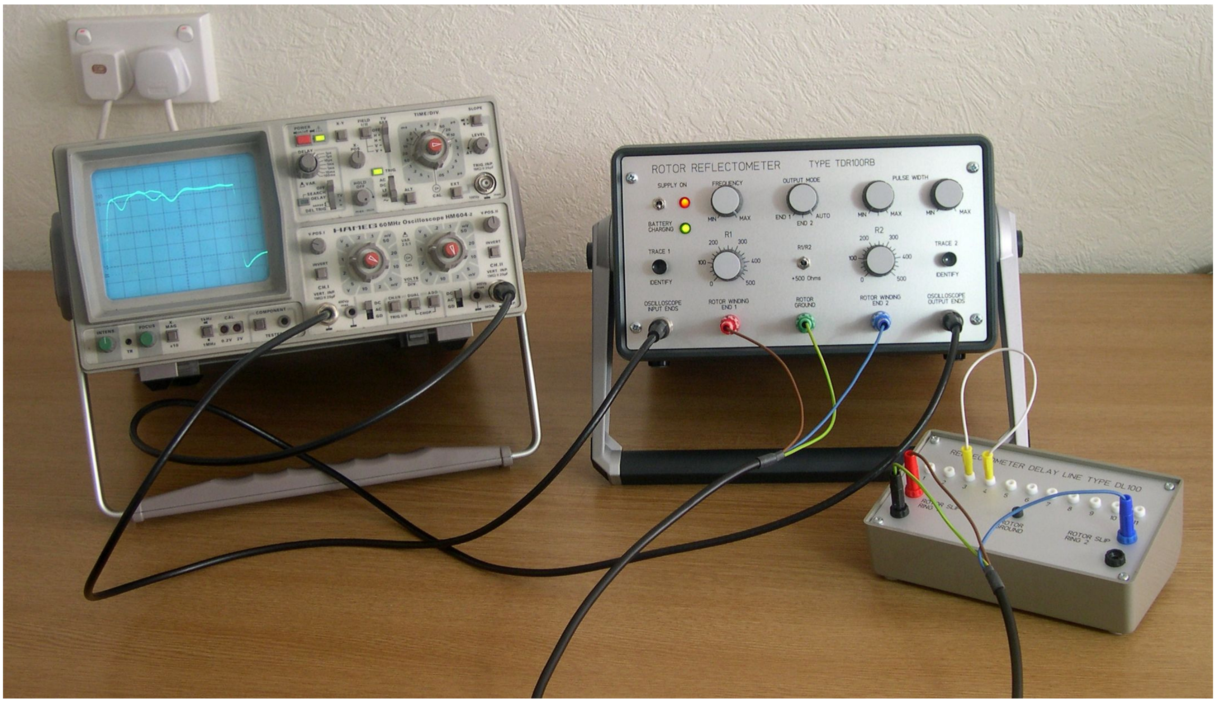


Figure 4.3 Use of Delay line test unit *

The oscilloscope controls should be set up as described in Section 2 of this manual. Set the oscilloscope vertical sensitivity to 1V/cm, the horizontal sensitivity to 5µS/cm and both Reflectometer matching resistors to 100Ω.

With the oscilloscope monitoring the input ends of the delay line, adjust the pulse width so that the display resembles that shown in Fig. 4.4 (a). The effect of mismatching the output ends of the delay line may now be demonstrated by changing the output matching resistor, R2 on the Reflectometer. Fig. 4.4 (c) shows the traces obtained when R2=0. The double pass transit time is seen to be 22µS and Fig. 4.4 (d) shows the traces obtained with R2=500Ω.

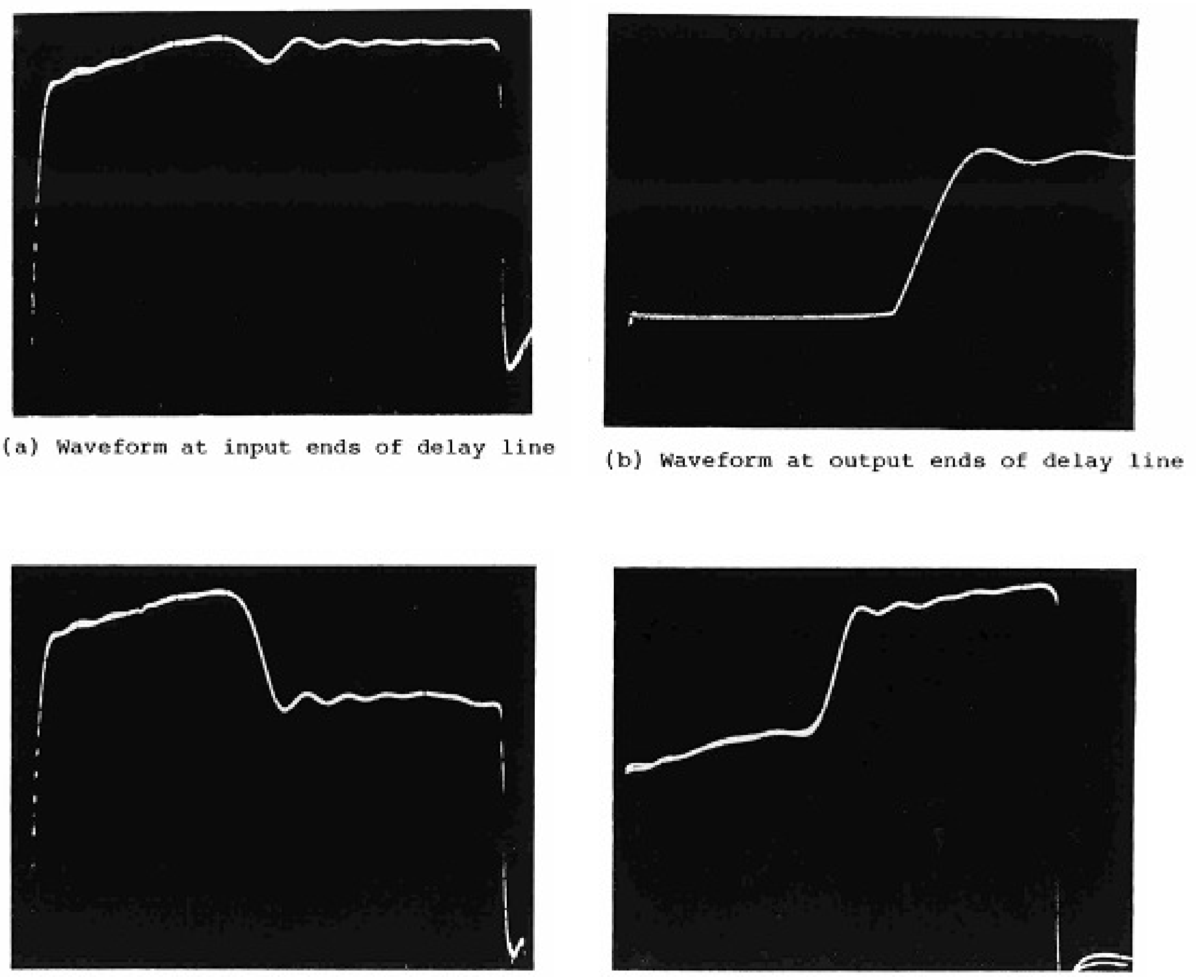
The effect of a simulated earth fault may be demonstrated by shorting one of the delay line junctions to earth using the 2mm plug lead supplied.. Fig. 4.5 (a) shows the result of shorting junction 4 to earth.

Similarly the effect of a shorted turn may be demonstrated by shorting out one or more delay line sections as shown in Fig. 4.5 (b).

NOTES

The impedance and single pass transit time of the unit supplied may vary from the figures quoted above.

* The delay line common terminals and the common lead plug are now **GREEN** instead of black.



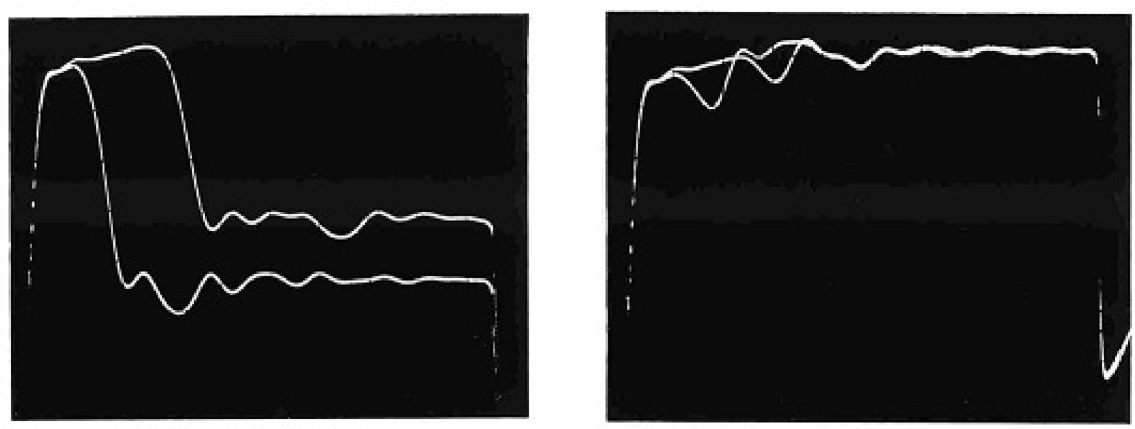
(a) Waveform at input ends of delay line

(b) Waveform at output ends of delay line

(c) Waveform at input ends, R2=0

(d) Waveform at input ends, R2=500n

Figure 4.4 Delay line oscilloscope traces with no faults applied



(a) Waveform at input ends.
Short circuit to earth at '4'

(b) Waveform at input ends.
Short circuit between '4' and '5'

Figure 4.5 Typical delay line traces with faults applied

5. USE OF A DIGITAL OSCILLOSCOPE

In principle, it is possible to use a digital oscilloscope instead of an analogue instrument to display the reflectometer waveforms. However, most budget digital oscilloscopes have limitations which may prevent them from being used effectively with the **TDR100** range of reflectometers. This section describes some possible ways for coping with these limitations.

5.1 OVERVIEW

One of the main uses of the **TDR100** measurement system is to display live waveforms during a winding repair, so that the winding state can be monitored continuously and the onset or clearance of faults seen immediately. To do this, the oscilloscope must display simultaneously the two waveforms corresponding to pulse injection from each end of the rotor winding.

The **TDR100** produces alternating waveforms at the input to one oscilloscope channel corresponding to the pulses injected from each end of the rotor winding. To view them correctly, the oscilloscope must trigger on the leading edge of each alternating pulse waveform. Most analogue oscilloscopes can do this routinely. However, many digital oscilloscopes have difficulty displaying signals where successive waveforms are different.

Digital oscilloscopes often use some form of waveform averaging to reduce the noise on the displayed traces but if this is used, only one of the waveforms can be shown at any single time. Although averaging can usually be turned off, the result is waveforms with a high level of superimposed noise. Even with averaging disabled, the osciloscope triggering may still be unable to track the alternating waveforms produced by the **TDR100** equipment.

A number of options are available to overcome some of these problems and these are described in the following sections.

The instructions given are based on the use of the Tektronix TDS 1000/2000 oscilloscope equipment range and should be modified accordingly for other oscilloscope models.

5.2 OPTION 1. USE OF AUTO MODE

It may be possible to use the **TDR100 Auto mode** in the same way as described for an **analogue oscilloscope**, by careful adjustment of the **Frequency** control on the **TDR100** unit. We suggest that familiarity with the technique is gained using the demonstration **delay line** initially, as described below:

Apply a shorting link between terminals 5 and 6 of the delay line to simulate an interturn fault and connect the delay line to the **TDR100** system as described in section 4.

Connect **channel 1** of the oscilloscope to the **TDR100 input end oscilloscope BNC connector** and set the **reflectometer controls** as described in section 4. Then set **channel 1** to display the input end waveforms, as shown in figure 5.1.

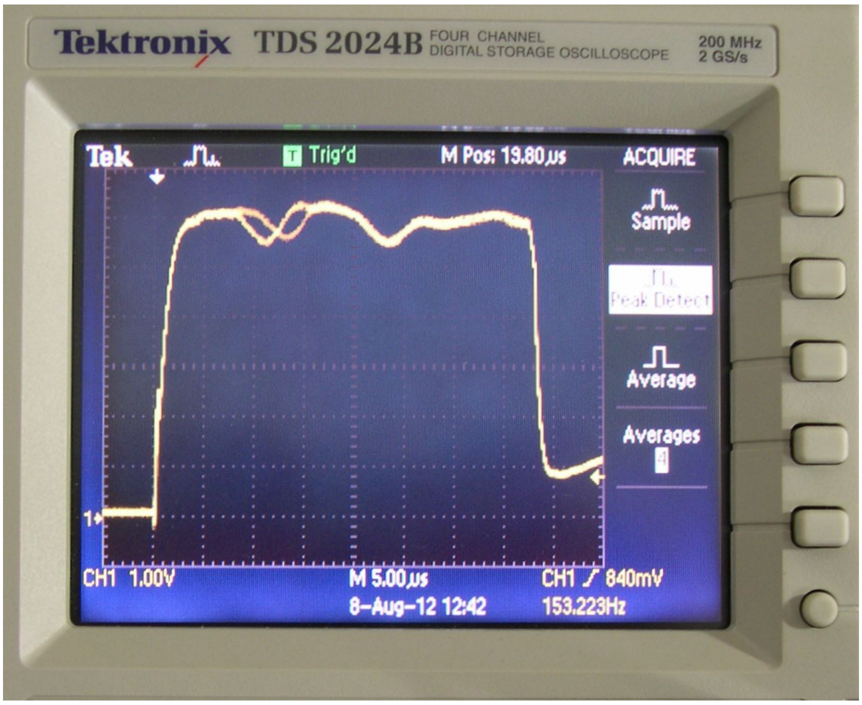


Figure 5.1 Digital oscilloscope waveforms at input ends using delay line with simulated inter-turn fault

The following comments (applicable to Tektronix TDS 1000/2000 series) may be helpful in setting up the oscilloscope initially:

Press the **Acquire** button and select **Sample** from the **ACQUIRE**screen.

If necessary, disable all other channels by pressing the appropriate **channel select buttons** until all traces other than that for **channel 1** are no longer displayed.

Press the **Trig Menu** button and set the **trigger controls** as follows:

Type: edge

Source: CH1

Slope: rising

Mode: normal

Coupling: DC

Now adjust the **trigger level** control until reliable triggerring occurs.

Move the **channel 1 baseline** to +1 horizontal graticule line from the bottom of the screen using the **channel 1 offset control knob**.

Adjust the **maximum waveform amplitude** to + 7 graticule lines from the bottom of the screen using the **channel 1 gain control knob**.

Expand the **horizontal time scale** to show all of the waveform using the **horizontal sec/div control knob**.

Move the **start of the waveform** to the +1 vetrical graticule line using the **horizontal position control knob**.

Adjust the **frequency control** on the **TDR 100** unit until 2 waveforms are displayed as shown above.

Using this technique, the 2 input end waveforms can be displayed and compared directly and continuously. However, in the case of the TDS oscilloscope range, these 2 waveforms cannot be saved directly, as the **save image** function apears to save one of the individual waveforms, not the displayed image. It is also not possible to reduce the image noise by averaging in this option.

5.3 OPTION 2. USING THE SINGLE END INJECTION MODE TO CAPTURE THE WAVEFORMS

Overview

As an alternative to **alternating end pulse injection**, the **TDR100** unit can inject pulses at one end of the rotor winding only.

If this is done sequentially at each slip ring, it is then possible to use the digital oscilloscope to capture and store these two waveforms in internal memory and then compare them.

The advantage of this method is that it is possible to save the two measured waveforms as .bmp files directly to a USB memory stick. It is also possible to reduce the noise levels in the images using the averaging option

This can be carried out as follows:

Equipment Set-up

Connect the **TDR oscilloscope input ends lead** to the **Oscilloscope input channel 1**.

Press the **ACQUIRE** button on the oscilloscope and set the screen options to Average 16 samples.

Capture and save the Slip ring 1 waveforms

Set the **TDR100 mode switch** to **END1** (Inject pulse at slip ring 1 only).

Press the **SAVE/RECALL** button on the oscilloscope and set the screen options to:

Action: **Save waveform**
Save to: **Ref**
Source: **Channel 1**
To: **Ref A**

Press the (on-screen) **Save** button

The slip ring 1 end input waveform will be saved to **Reference A** in the oscilloscope memory.

Capture and save the Slip ring 2 waveforms

Set the **TDR100 mode switch** to **END2** (Inject pulse at slip ring 2 only).

Press the **SAVE/RECALL** button on the oscilloscope and set the screen options to:

Action: **Save waveform**
Save to: **Ref**
Source: **Channel 1**
To: **Ref B**

Press the (on-screen) **Save** button

The slip ring 2 end input waveform will be saved to **Reference B** in the oscilloscope memory.

View the 2 waveforms

Press the **Channel 1 menu button** to switch off the live channel 1 display.

Press the (white) **REF MENU** button on the oscilloscope

Use the (on-screen) buttons to turn on (display) the stored **Ref A** and **Ref B waveforms** as shown in the figure below:.

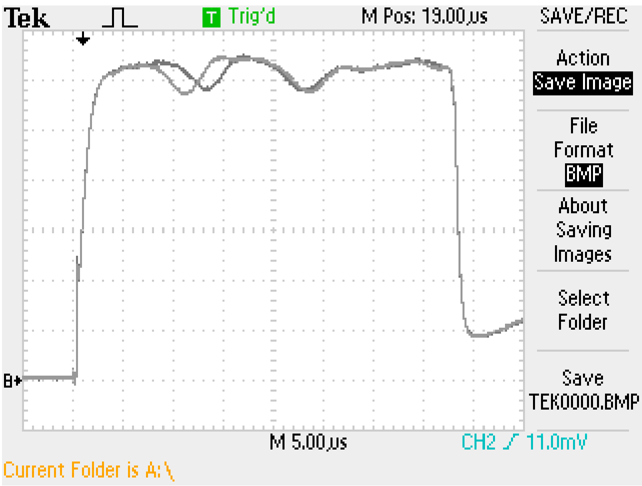


Figure 5.2 Captured Screen image showing the two reference waveforms.

Save the waveforms

Press the **SAVE/RECALL** button and select the **Save image** option using the on-screen button.

Insert a **USB memory stick** into the oscilloscope **USB socket**.

Press the (on-screen) **Save** button to store the image as a bit-map (.bmp) file.

6. REFERENCES

Additional information on testing generator rotors can be found in the following documents:

1. **Turbo-Generator Winding Fault Detection by a Recurrent Surge Method**, Grant, A.E. , UK Central Electricity Generating Board Technical Disclosure Bulletin 201, 1973. (See Appendix 3 of this manual)

2. **Rotor winding short detection**, Wood, J.W. and Hindmarch, R.T., IEE Proceedings, Vol 133, Pt. B, No. 3, May 1986, pp 181-190.

3. **GE Generator Rotor Design, Operational Issue, and Refurbishment Options**, Ronald J. Zawoysky, Karl C. Tornroos, GER 4212, 08/01, GE Power Systems. Schenectady, NY

Copies of all of these papers are included on the documentation CD supplied with the equipment.

7. NOTE ON ANALOGUE OSCILLOSCOPES

The following model has been tested with the TDR100 unit

Isotech ISR 622 (20MHz)

A similar higher performance mode (with a brighter trace) is also suitable

Isotech ISR 6051 (50MHz)

However, almost any analogue oscilloscope with a bandwidth of 20MHz or more should work satisfactorily with the TDR100 unit.

8. FUSE RATINGS (Please contact Rowtest before replacing any fuses.)

EXTERNAL FUSES

IEC mains input module (including spare): 1A 20mm
Battery fuse (round item with screwdriver access): 1A 20mm

INTERNAL FUSES

In-line battery fuse: 2A 20mm
PCB fuse: 1A 20mm

APPENDIX 1

TDR100RB OPERATION

The **TDR100RB** is similar in operation to the **TDR100**. The main difference is that the **TDR100RB** contains a maintenance-free 12 volt 2.0 AH rechargeable NiMH battery pack, giving over 15 hours continuous use under average operating conditions. There is also an additional switch on the front panel to turn on the instrument for both battery and mains operation. Note that the equipment can be used while the battery is being recharged.

To recharge the battery, connect the **Reflectometer** to a suitable 240V or 110V 50Hz mains supply via the rear mounted IEC socket and turn on the **Mains switch** on the rear panel. The green '**CHARGE**' indicator on the front panel will light showing that the unit is on charge.

To turn on the instrument to carry out a rotor test, switch on the **Supply ON** switch on the front panel. The red **Supply ON** indicator will light showing that the unit is in operational mode. The **TDR100B** unit can be operated either on its internal batteries only, or with a mains supply connected to the instrument.

With the front panel **'SUPPLY**' switch set to the '**OFF**' position the battery can be fully charged from a fully discharged state in 20 hours.

NOTES ON BATTERY MAINTENANCE

The internal battery pack may be damaged if it is allowed to discharge fully. If the unit is not used for long periods, we suggest it is given an overnight charge once per month..

The internal battery-charging circuit operates as a trickle charger and should not damage the battery if the **Reflectometer** is left connected to a mains power supply for long periods. However, to maximise battery life, the mains supply should be disconnecetd from the unit after a maximum charging period of no more than 24 hours.

APPENDIX 2

USE OF PADDED CASE

The **TDR100** units are supplied with a padded case containing pouches for the instruction manual, leads, magnets and oscilloscope adapters.

The case can be used in one of 2 modes, **transit** and **storage.**

In **transit** mode, the unit is inserted into the case with the handle vertical and the top cover passed through the handle and attached to the velcro fastening as shown in figures A3.1 a and b below. The unit can then be carried by the handle. Alternatively, a pair of carrying handles on the case can be used.

(a) Handle vertical

(b) Cover passed through handle

Figure A2.1 Padded case in transit mode

For storage purposes, the handle can be tilted forwards and the cover passed over it, as shown in figure A3.2 below. This protects the handle from knocks.

(a) Handle forwards

(b) Cover over handle

Figure A2.2 Padded case in storage mode

APPENDIX 3

TURBO-GENERATOR WINDING FAULT DETECTION BY A RECURRENT SURGE METHOD

CEGB TECHNICAL DISCLOSURE BULLETIN 201

A. E. GRANT 1973

This is a copy of the first paper describing the use of the RSO method for detecting winding faults in turbo-generator rotors. It was written by A.E. Grant of the UK Central Electricity Generating Board (CEGB) in 1973.

Please accept our apologies for the print quality of this important document, and also the paper in Appendix 4. If anyone has better copies, please send them to enquiries@rowtest.com. Many thanks in advance.

TURBO-GENERATOR ROTOR WINDING FAULT DETECTION BY A RECURRENT SURGE METHOD

A.E. Grant
Central Electricity Generating Board
South Eastern Region
Scientific Services Department
West Farm Place
Chalk Lane
Cockfosters

Summary:

Short circuited turns in rotor windings may give rise to excessive vibration and to shaft magnetisation. They are not easy to detect in situ by conventional methods. A method of fault detection and location, based on the recurrent surge oscillograph, is described. It is quick and easy to apply.

Introduction

Recurrent surge methods have been used for several years by manufacturers of high voltage power transformers to determine the distribution of surge voltages through the windings (Refs.1,2).

The recurrent surge technique has potential for in situ testing of the security of rotor winding interturn insulation of turbo-generators without modifying or dismantling the machine.

The presence of a short circuited turn may cause vibration due to magnetic unbalance and uneven heating of the rotor (Ref.3),

July 1973

and shaft magnetisation due to magnetic unbalance (Ref. 4). In the latter case homopolar generation may occur, giving rise to excessive shaft voltages and bearing corrosion, and also to enormous circulating currents if the electric circuit is completed.

Recurrent Surge Generators

The circuit diagram of a simple battery operated recurrent surge generator (RSG) is given in Figure 1. The e.m.f. source is a capacitor of high value (100 μF to 1,000 μF) charged from a primary cell via a current limiting resistor so that for several microseconds it has virtually zero impedance The effective source impedance may then be adjusted to any desired value by external connection of non-inductive resistors.

The surge is generated by a mercury-wetted contact relay, which has a constant low impedance across closed contacts of less than 40 milliohms, and gives clean makes and breaks at currents of up to 5 A at 500 V. The relay is driven at a nominal 50 Hz by a multi-vibrator circuit and the output of the RSG is a nominal square wave with a very fast (20 ns) rise time. The output waveform can be adjusted to give the usual surge waveforms by external differentiating and integrating circuits (Ref. 1). The RSG may be used for this application with most wide-band oscilloscopes. A suitable method of connection is given in Figure 2.

The Rotor Winding as a Transmission Line

The recurrent surge method depends on the fact that the rotor winding approximates to a transmission line, when a surge is applied between one slip ring and the rotor body as in Figure 2.

The surge performance of an ideal line is adequately described by two parameters viz, surge impedance (Zo) and velocity of propagation (v) (Ref. 5).

It is usual to consider the response of the line to a steep fronted surge; that is, a surge whose rise-time is a very small fraction of the time required for the surge to travel from one end of the line to the other, as the reflections and refractions of the surge at changes of surge impedance are then well developed. The basic principle of the recurrent surge method is shown in Figure 3. In an ideal line, the surge impedance has dimensions of resistance. When switch S is closed, the amplitude of the surge entering the line is determined by the source impedance R and the surge impedance of the line Zo. The surge reaches the far end of the line after a delay (T) determined by the length and propagation velocity of the line, and is there reflected, its magnitude depending on reflection factor k. For an open-circuited line k = +1 and for a short-circulated line k = -1. The reflected surge returns to the source and if the source impedance equals the surge impedance of the line (the reflection factor k = 0), it is absorbed without further reflection (Figure 4). The rotor winding of a turbo-generator approximates to a transmission line. As each coil of a concentric winding is in a pair of slots and is independent of the others, a surge launched between one slip ring and the rotor body will not cause mutual effects between slot windings.

Mutual effects will occur between end windings, but those form only a small proportion of the total winding. The propagation of the surge will be mainly between conductor and slot and the velocity will be determined principally by the permittivity of the insulation, and the permeability of the rotor iron.

Rotor windings have a surge impedance which, depending on size and construction, may lie between 20 and 300 ohms.

Application of Recurrent Surge Method

The surge is applied between one slip ring and earth and the other slip ring may be earthed or earth free. The signal may be applied through the brushgear but the exciter connections must be disconnected as they give rise to confusing reflections.

The rise time of the surge will affect the sensitivity of the method. This must be less than the propagation time for the wave front through a single turn for sharp reflections to occur. With slower rise times the sensitivity will be reduced.

The preferred method is to apply a square wave with a rise time of the order of 20 ns, with the remote slip ring earth free (Figure 2). A source voltage of between 10 and 100 V is used. A higher surge voltage is undesirable as a large proportion of it will appear across interturn insulation particularly near to the slip rings, and may overstress aging or weak insulation. Oscillograms are made for each slip ring individually and superimposed (Figures 7,8). Faults are indicated on the oscillograms by deviation of the superimposed traces. Both the source voltage and the response at the slip ring are displayed on a two channel oscilloscope, with both channels set to the same sensitivity. The measurements are standardised by making the source voltage produce full scale deflection of the oscilloscope, and by adjusting the series resistance (R in Figure 2) so that the initial step of the response is approximately half full scale deflection. The source is then matched to the surge impedance of the winding so that spurious reflections are minimised. In this way, repeatability of results is ensured in future tests.

From the oscillograms the winding end reflection point is determined (Figure 6). Faults may then be approximately located by taking the ratio of times for reflections from the fault and from the end of the winding. The velocity of propagation varies with time and the variation may be estimated by measurement of the times for a single and double passage through the winding as in Figures 5 and 6. This will improve the accuracy of estimation of fault location.

The surge tends to separate into two modes:

(a) between conductors,

(b) between conductors and rotor body.

These travel at slightly differing velocities. Mode (b) predominates and should be used for calculations. The maximum amount of information can be obtained if recurrent surge oscillograms (RSO) can be made on machines immediately after they are taken off load.

The generator is isolated, the field is de-energised and exciter connections are disconnected. RSO's are made with the machine still running at rated speed. The machine is then allowed to slow down to barring speed and RSO's are again taken and repeated after an interval of about 1 hour. There is at present no convenient way of making RSO's on excited machines.

Faults which are present when the machine is at speed sometimes disappear at standstill or barring and vice versa. Movement of the rotor winding occurs during barring, under the influence of centrifugal and gravitational forces, and sometimes produces periodic variation in the RSO during rotation, which may be due to intermittent faults.

When oscillograms are made with the rotor spinning, contact to the rotor body is made via the shaft earth brush and this is not always effective. Random noise on RSO's taken at rated speed and during the run down is caused by intermittent earth brush contact. In this case a temporary brush of copper braid provides an effective earth connection to the rotor shaft.

The recurrent surge method may also be used to obtain an approximate location of open-circuit faults. The fault location is given by the ratio of the times of reflections from the fault, measured at both slip rings. Earth faults of low resistance may also be located by this method.

The method is sensitive enough to detect single turn faults and faults having a contact resistance of several ohms. Such faults may have no apparent effect on the running of the machine and may be undetectable by other test methods.

Conclusions

1. The recurrent surge oscillograph is a very sensitive method of detecting interturn faults in the turbo-generator rotor windings.

2. It indicates the location of the faults. The results are not significantly affected by the temperature of the winding.

3. It is very quick and easy to apply as it requires only the disconnection of the exciter connections to the brushgear.

4. The method is suitable for use as a routine method for periodic checking of rotor windings for deterioration.

5. When used with other methods of fault detection it is a convenient way of checking the security of the winding in situ.

References

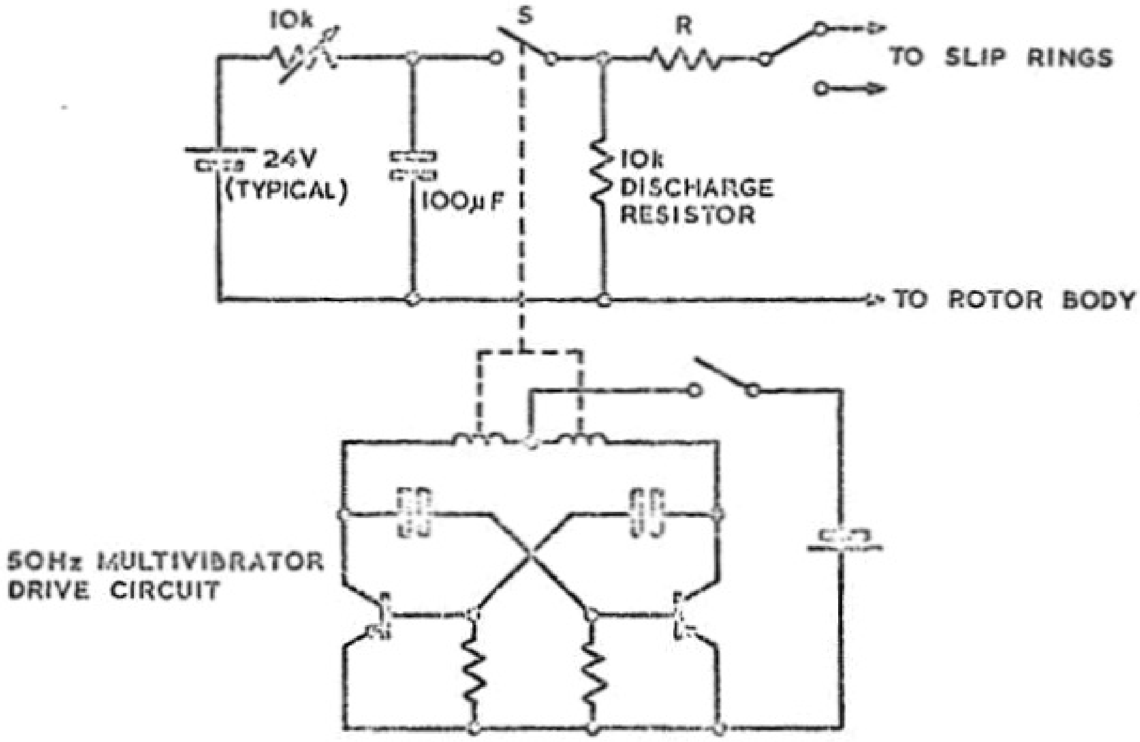
1. "Recurrent surge oscillographs and their application to short time transient phenomena", K.J.R. Wilkinson, J. Institution of Electrical Engineers, Vol. 83, pp. 663-672 (1938).

2. "The recurrent surge oscillograph and its application to the study of surge phenomena in transformers", E.L. White and W. Nethercot, Proc. Institution of Electrical Engineers, Vol. 96, Pt II, pp. 269-275 (April 1949).

3. "Effect of turn short-circuits in a turbogenerator rotor on its state of vibrations", K.A. Khudabashev, Elektricheskie Stantsii, No. 7, pp. 40-45 (July 1961).

4. "Shaft voltages and bearing currents - a survey of published work", P. von Kaehne, ERA Report No. 5030 (1964).

5. "Travelling waves on transmission systems", L.V. Bewley; New York : Dover publ. (1963) 543 pp.



NOTES

1. 'S' IS A MERCURY WETTED CONTACT RELAY, RATING 5A 500V SUCH AS CLARE TYPE HG, OR ELLIOT TYPE E8.
2. SOURCE VOLTAGE & RESISTANCE 'R' MUST BE SELECTED SO THAT RELAY RATING IS NOT EXCEEDED.

FIG. 1. RECURRENT SURGE GENERATOR

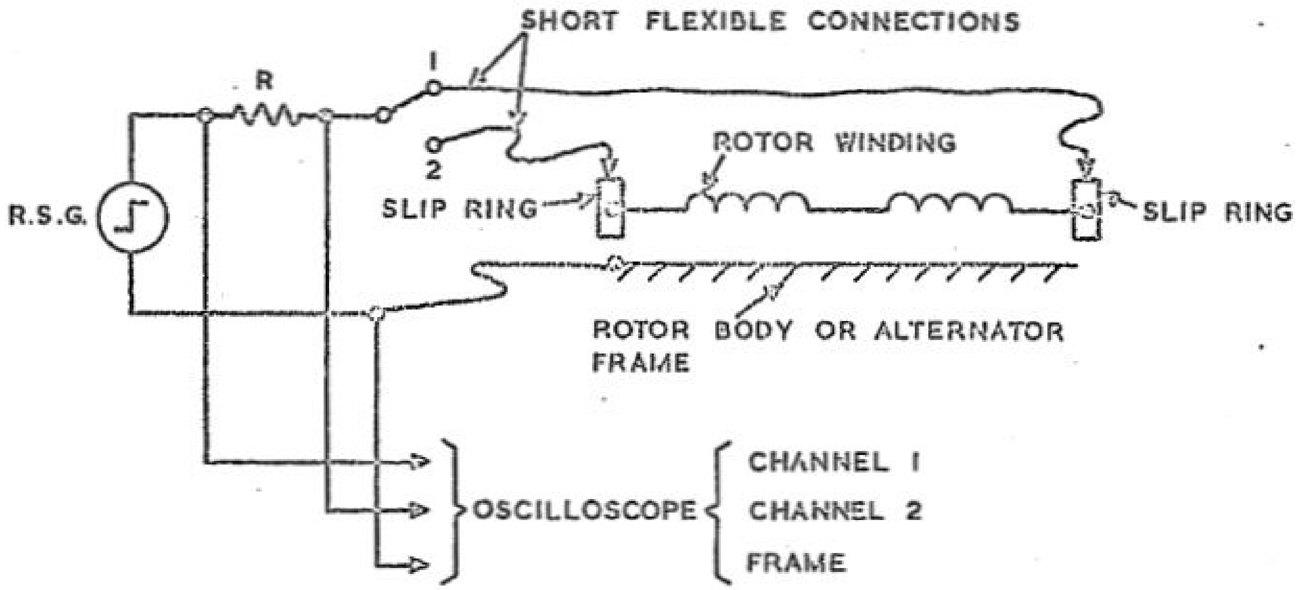


FIG. 2. CONNECTION OF R.S.G. TO ROTOR WINDING

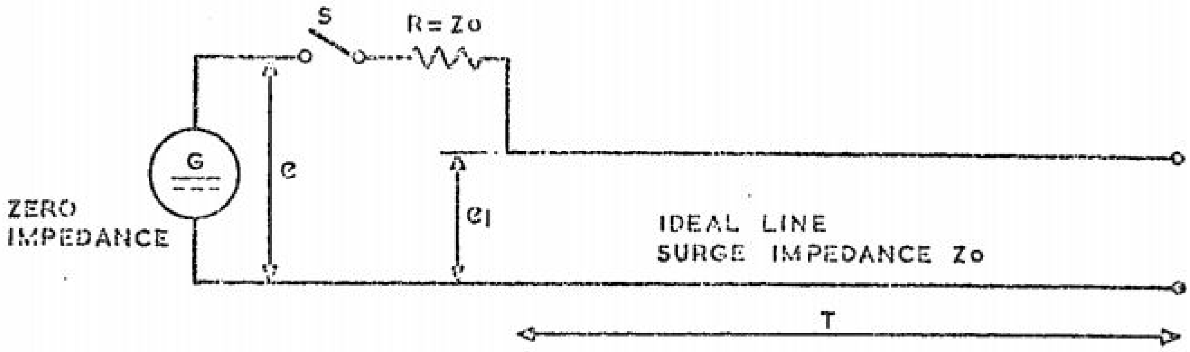


FIG. 3. RECURRENT SURGE GENERATOR AS A REFLECTOMETER

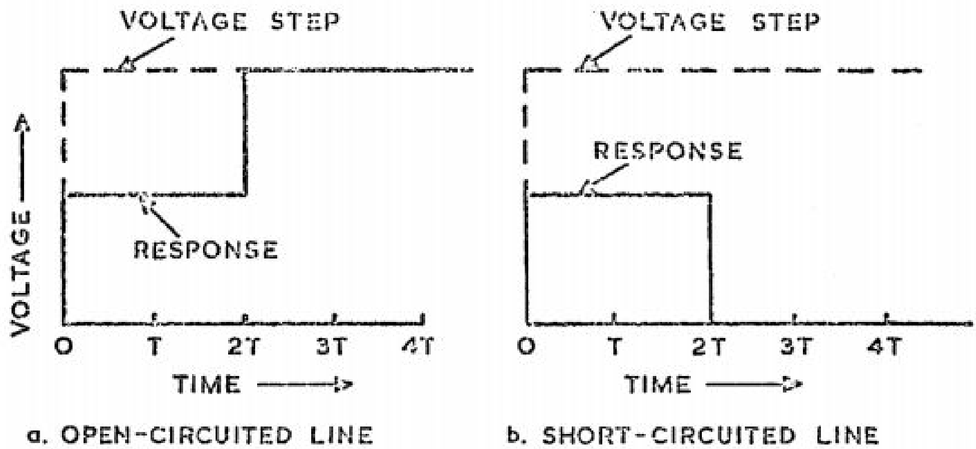


FIG. 4. RESPONSE AT START OF AN IDEAL LINE

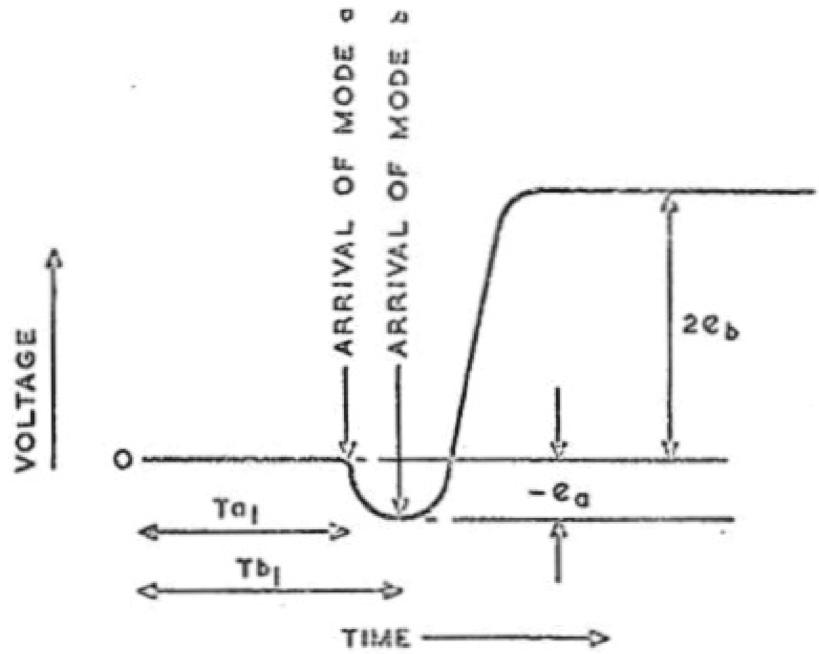


FIG. 5. VOLTAGE Vs. TIME FOR SURGE ARRIVING AT END OF WINDING

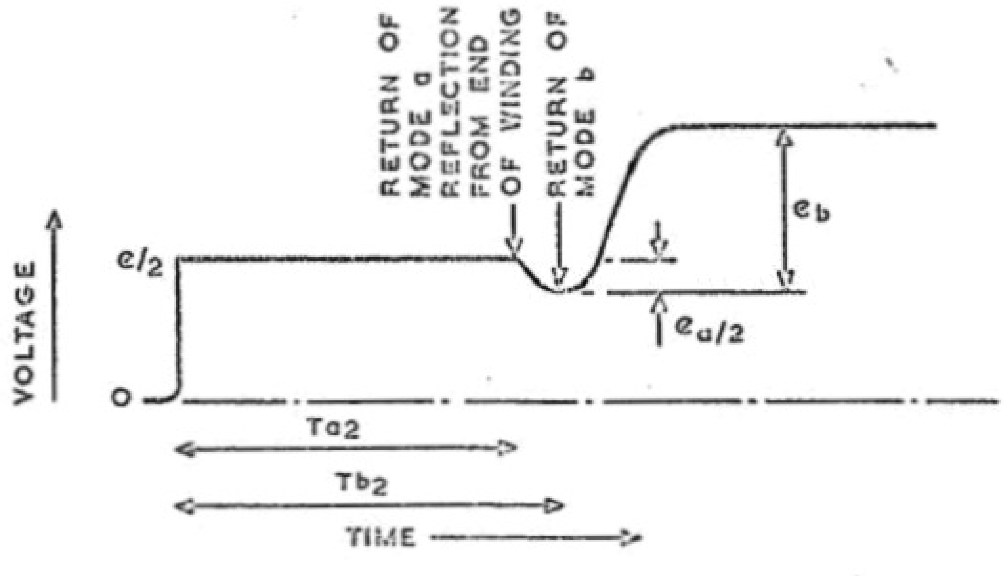


FIG. 6. VOLTAGE Vs. TIME FOR SURGE RETURNING TO START OF WINDING

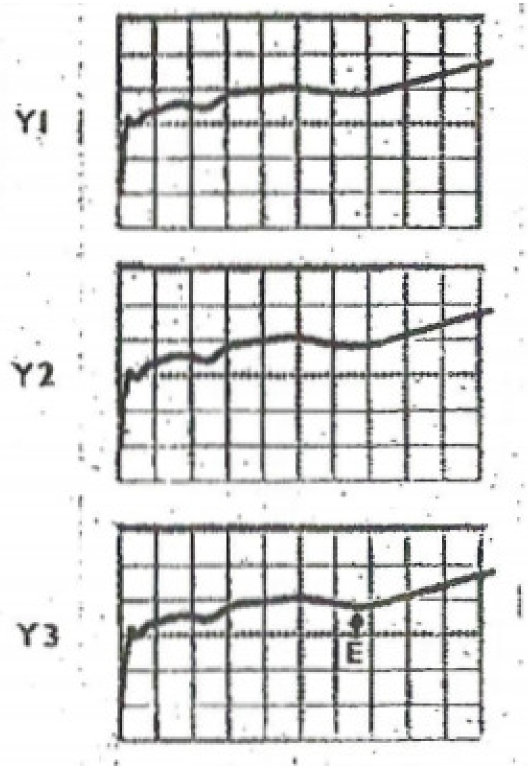


FIG. 7

X = 10µs/DIV.
Y1 SLIP RING 3 TO EARTH
Y2 SLIP RING 4 TO EARTH
Y3 Y1 AND Y2 SUPERIMPOSED
E START OF REFLECTION FROM WINDING END (OPEN CIRCUITED)
F START OF REFLECTION FROM FAULT
SPEED 0 RPM
WINDING TYPE : PROGRESSIVE

FIG. 7 RSO FOR HEALTHY ROTOR WINDING

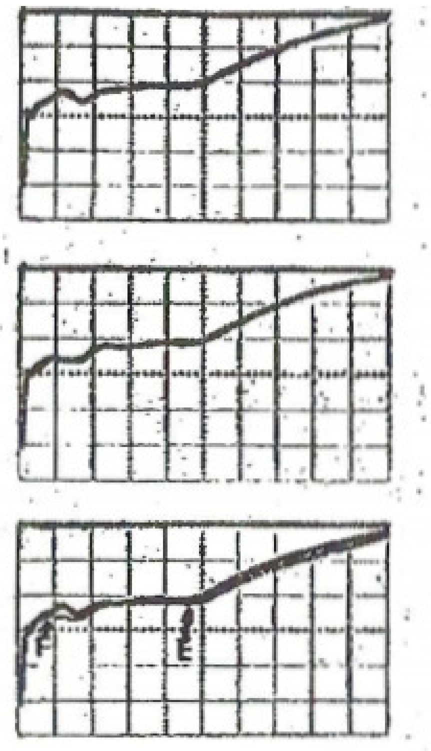


FIG. 8a

X = 10µs/DIV.
Y1 SLIP RING 1 TO EARTH
Y2 SLIP RING 2 TO EARTH
Y3 Y1 AND Y2 SUPERIMPOSED

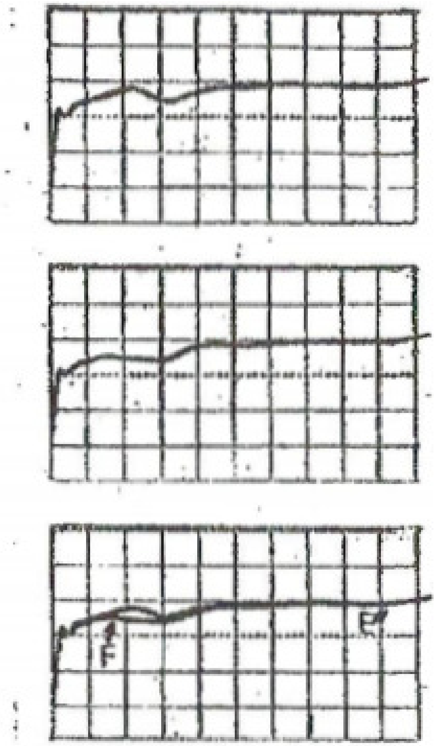


FIG. 8b

X = 5µs/DIV.
DITTO

FIG. 8. RSO FOR FAULTED ROTOR WINDING

APPENDIX 4

A STANDARD APPROACH TO RSO INTERPRETATION

G.A. Elsworth 1986

This is an editted copy of a note describing how rotor winding faults can be identified and located using the RSO test. It was written by G.A. Elsworth of the UK Central Electricity Generating Board (CEGB) in 1986 and refers to the short-pulse excitation method as well as the long-pulse method used by Grant (and also by Rowtest). In particular, it explains how the location of a winding fault can be estimated using an approximate pulse propagation algorithm.

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1. Introduction.

This note is intended to provide the means of standardising and simplifying Recurrent Surge Oscillograph interpretation within the Generator Group. To fully interpret RSO traces it is necessary to know the pulse transit times through the winding for the single pass and double pass case, which will then allow a curve of transit time against distance to be plotted which can be used for subsequent fault investigations.

Slight differences between rotor winding pulse propagation characteristics for rotors of the same family and different RSO techniques exclude the possibility of a standard curve being used to represent a family of rotors without the introduction of errors, which could provide misleading interpretations. Therefore, to provide an accurate data base of information it will be necessary to assess each rotor and RSO technique on an individual basis.

Although the RSO technique has to some extent been superseded by the air gap search coil technique, which allows on load rotor interturn fault detection, it is still a valuable technique for off load testing of rotors for the detection of winding interturn and/or earth faults and is invaluable for repair monitoring and quality assurance tests during repair/manufacture.

2. RSO Interpretation.

The minimum information required to allow an interturn fault to be located from an RSO trace is the single pass transit time of the pulse through the winding and the time to the fault indication on the trace. This will allow an approximate analysis to be made by time scaling, but is based on the assumption that pulse propagation is linear. However, in reality the pulse velocity (and amplitude) is attenuated as it travels through the winding and therefore its velocity follows a non-linear law. To achieve a more accurate analysis it is necessary to find the characteristic relationship which the pulse follows for a particular rotor. This relationship in standard form is :-

$$t = Ad + Bd^2$$

Where t and d are the time and distance respectively travelled by the pulse from the point of injection and A and B are constants for a particular rotor.

This characteristic equation can be obtained for a given rotor if its single and double pass transit times are known. The single pass transit time can be obtained by recording the injected and received pulses at each end of the winding and measuring the time between them and the double pass transit time can be obtained by measuring the time for the pulse to travel back to the injection point from an open ended winding.

With knowledge of these two times, then two simultaneous equations are obtained which can be solved to find A and B to give the constants for the winding. With these characteristics and a given time t, a quadratic equation is formed which can be solved for the unknown, d, to find the distance travelled by the pulse in that time. This will allow a time/distance curve to be plotted for any rotor to aid future fault investigations. This technique is demonstrated in appendix 1.

3. Rotor Fingerprinting.

It is important that rotor fingerprinting is carried out when the rotor winding is in a fault free condition to enable a characteristic curve to be obtained. This will provide the most accurate means of analysis. If data is only available for the faulted condition then the accuracy is reduced as the single pass and double pass transit times are altered by the fault condition. Single pass transit times in the faulted condition can be used, with the fingerprint characteristics, to find the percentage or per unit reduction in winding length due to the winding fault.

Once a characteristic fingerprint curve for any particular rotor has been obtained, any future RSO fault indications on that rotor can quickly be interpreted in a standard form to give the approximate location and size. This technique is demonstrated in appendix 2.

In addition to the RSO characteristics which are required for detailed analysis it is important that full winding details are also available. Such details for all 500MW and 660MW generator rotors currently operational within the CEGB are attached to this note as appendix 3.

4. Conclusions.

If the standard data of single pass and double pass transit times can be obtained for individual rotors then it will be possible to set up a data base of fingerprint curves for RSO interpretation.

This method should reduce the possibility of introducing further errors during the interpretation of RSO results.

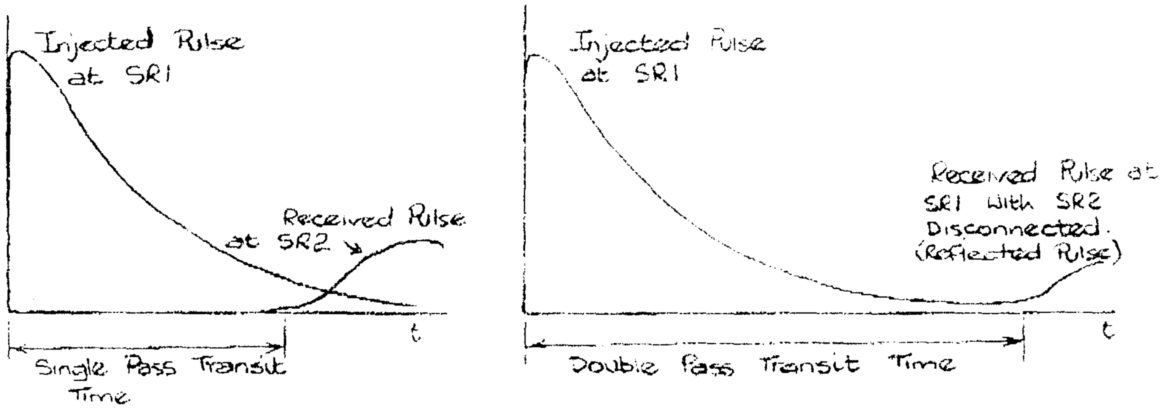
The data base will have to be very comprehensive to take account of not only individual rotor differences but also to cover the number of RSO techniques currently in use within the CEGB and in manufacturers works.

Appendix 1.

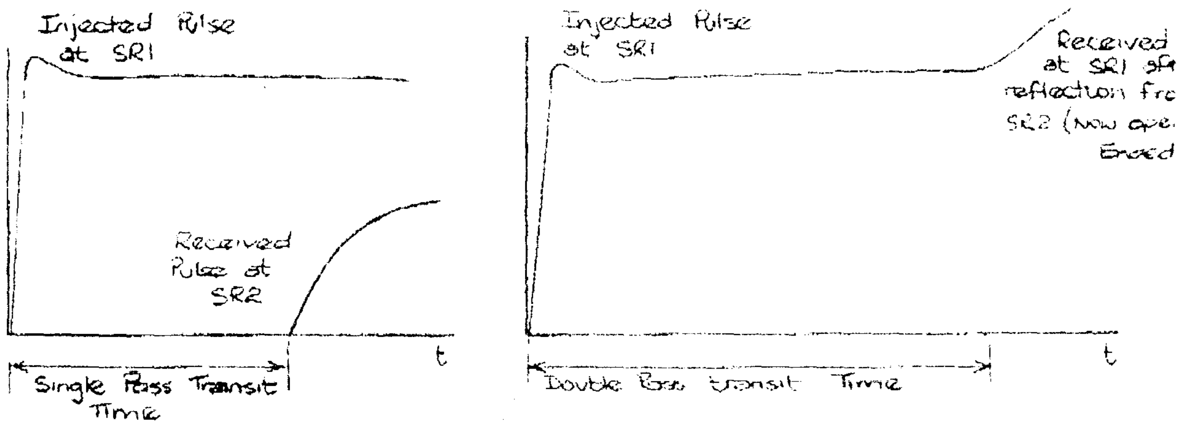
Data Acquisition from RSO Traces.

The various transit times which are required for RSO analysis are shown for the following types of RSO test;-

a). Smith - Moat



b). Byars - Armin (also applicable to Grant).

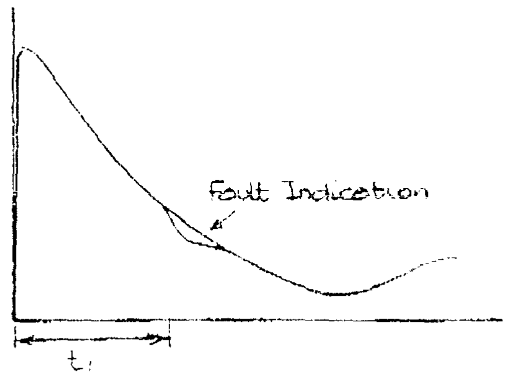


SR1 - Injection Slipring
SR2 - Receive Slipring

Appendix 2.

Fault Interpretation.

Using the data of appendix 1 the following fault interpretation technique can be used;-



Smith-Moat trace for the typical 500MW generotor rotor used in Appendix 1

For a fault indication at time t_1, which can be read directly from the RSO trace, the location can be identified using the fingerprint curve (for the particular rotor in unfaulted condition) of figure A1

For example if t_1 is 15.5µsec then from figure A1 this corresponds to a fault 0.8 p.u into the pole or 0.4 p.u into the whole winding, which places the fault in the 7^{th} coil. Which pole the fault lies in can only be determined at the time of carrying out the test.

The single pass transit time for this faulted condition will now be less than for the unfaulted condition by an amount corresponding to the number of turns involved in the fault.
for example;-

If single pass transit time for faulted rotor is 19µsec
& single pass transit time for unfaulted rotor is 19.6µsec

Then number of turns short = (1 - (19/19.7))x(total No. of turns)
= 0.036 x 128
approximately = 5 turns.