Rotor winding short detection

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Indexing terms: *Turbogenerators, Nondestructive testing, Plant machine monitoring*

Abstract: The paper presents a review of four techniques which are used for detecting, and in some instances locating, short-circuited turns in the rotors of large turbogenerators. The information is supplemented by experience with some of the techniques gained in a manufacturing establishment. The four techniques described are airgap search coil, recurrent surge oscillograph (RSO), circulating stator current, and rotor shaft current.

1 Introduction

For many years the occurrence of a short-circuited turn in a rotor was considered acceptable until it resulted in an operational problem such as a change in vibration level due to thermal unbalance. Many rotors of lower power ratings (30 to 120 MW) have run for decades with short-circuited turns, some of them undiscovered until recent overhauls when the employment of the rotor short-circuited-turn detection techniques discussed below revealed their presence.

On todays base load generators with 500 to 800 MW ratings, the detection and repair of rotor short-circuited turns is regarded as of increasing importance, because the economic conditions prevailing over the last decade mean that unreliable machines incur high cost penalties due to the lack of efficient spare capacity in the UK. Experience has shown that in some instances a short-circuited turn can become dormant; i.e. not all short-circuited turns develop until generator operation is affected. However, the higher operating conditions possibly lead to a greater likelihood of a serious fault developing from a shorted turn.

Due to the importance attached to rotor short-circuit detection, the techniques are being used in the manufacture, testing and operation of generators. The principles of the techniques described are established but the methods are being developed so that the maximum use can be made of them in the three above regions. Fig. 1 represents the present region of application of each technique. This point is discussed further in the appropriate sections of the paper.

The information presented in the paper has been obtained from a range of generators from 60 MW to 800 MW in size, but mainly from the larger units. Figs. 2 and 3 show the typical winding arrangements for slots and coils, respectively, to be found in modern two pole generators of the types investigated.

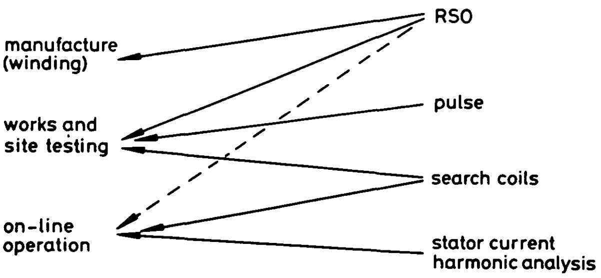

Fig. 1 *Applicability of rotor shorted-turn detection techniques*
——— existing practice
– – – – possible future development

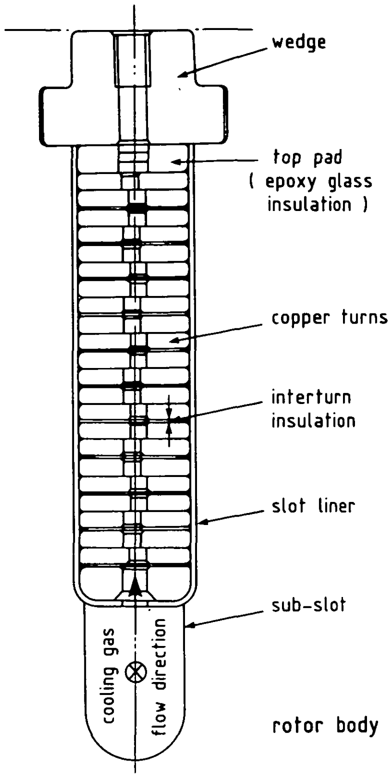

Fig. 2A *Radially cooled rotor slot*

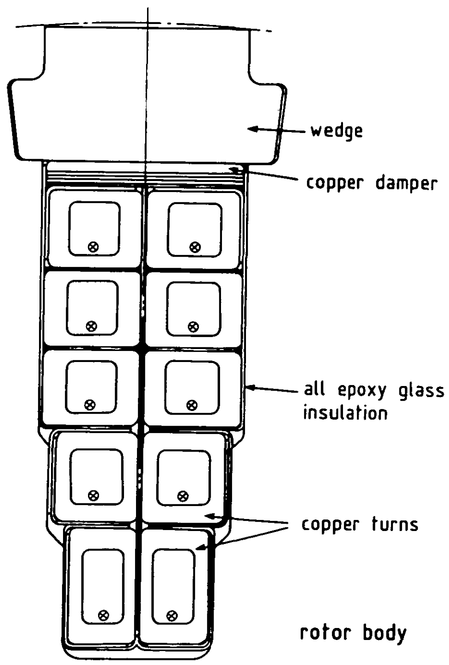

Fig. 2B *Axially cooled rotor slot*
⊗ direction of cooling gas flow

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2 Airgap search coils

This technique [1–3] was first described by Albright [1] in 1971. The principle is illustrated in Fig. 3 where coil

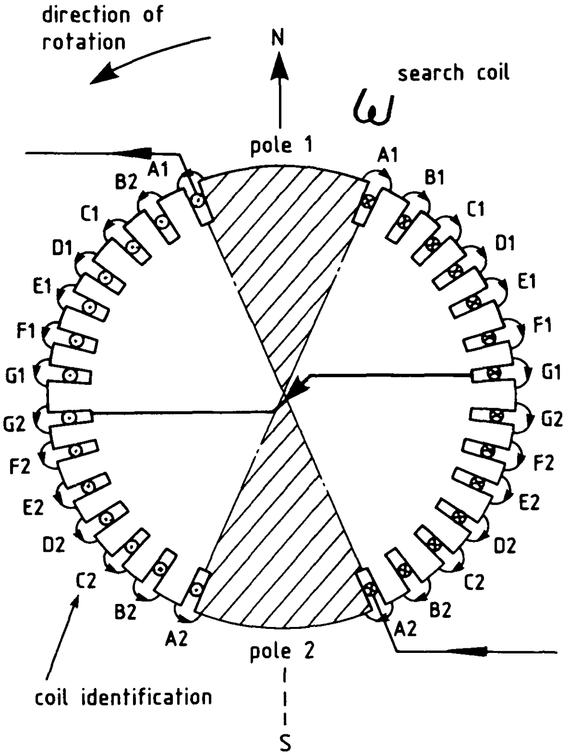

Fig. 3 *Airgap search coil principle and slot identification*

identification is also shown. A search coil is positioned near the rotor surface and, as the rotor rotates, a voltage is induced in the coil by the passage of the leakage flux from each conductor slot. The voltage amplitude is directly proportional to the ampere turns in the slot, and consequently a reduced voltage is observed when shorts occur in a coil.

Due to the requirement of a rotating rotor this technique cannot be employed during the winding of a rotor.

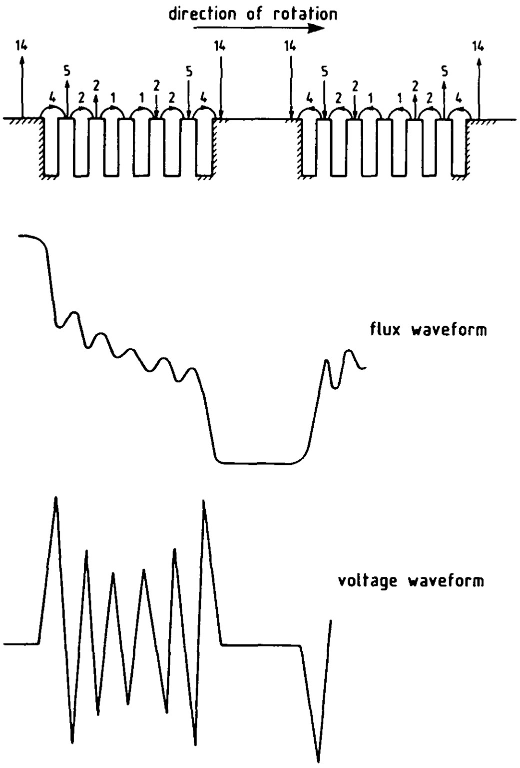

Fig. 4 *Radial flux and voltage waveforms on open circuit*

However, search coils are used on the test bed in NEI Parsons' Works, and most 500 MW and 660 MW sets in the UK, and some overseas machines, have them permanently fitted.

2.1 *Theory*

The voltage induced in a search coil positioned in the airgap is a function of the rate of change of the flux threading it. The flux consists of the main flux and slot leakage flux. The waveforms induced are illustrated in Fig. 4 for the case of open circuit for a coil positioned to measure the radial component of leakage flux, and in Fig. 5 for the

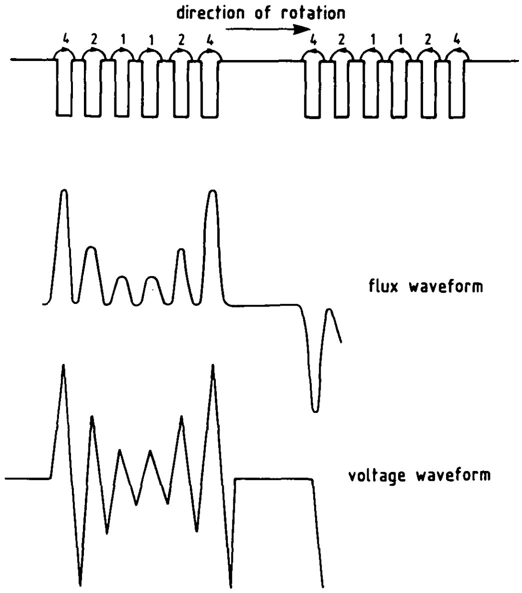

Fig. 5 *Circumferential flux and voltage waveforms on open circuit*

circumferentially placed coil, for fictitious values of flux. Note that there is one more positive peak than there are negative peaks on the radial coil voltage. Although on open circuit this does not present a major problem, under load conditions the voltage waveforms are more difficult to interpret and possible confusion can occur. This confusion is not present when circumferential rotor slot leakage flux is measured.

With open circuit, a gradual increase in voltage amplitude is observed starting at the quadrature axis and reaching a peak for the coil next to the pole. This arises from a distortion factor [1]. Under short-circuit conditions there is a symmetrical flux pattern set up in the air gap. Any component of the main magnetic field in the airgap which may add to the rotor slot leakage flux will therefore do so to the same extent over each coil side of a given coil. Under load conditions this is no longer so, because the resultant magnetic field due to the rotor and stator no longer has its axis of symmetry through the rotor poles. However, diametrically opposite slots will still have the rotor slot leakage flux modified by the main flux in the same way, and therefore comparison of the voltage peaks due to those slots could be made. To eliminate asymmetry it is usual to add together the voltages of both coil sides of a coil and compare with the voltage peaks of the same coil position in the other pole. This method is described in this paper.

2.2 *Apparatus*

Search coils can be either cylindrical or rectangular, and their diameter or width for radial flux sensing coils is determined by the width of the rotor tooth tips. The product of their area and turns should be such as to provide adequate sensitivity. Typical coils will have approximately 750 turns of 0.0508 mm diameter wire wound on a 9.5 mm diameter former. Coils are positioned to measure radial and circumferential components of the slot leakage flux to aid interpretation. Fig. 6 shows a section of a typical search coil probe assembly containing 2 radial and 2 circumferential coils.

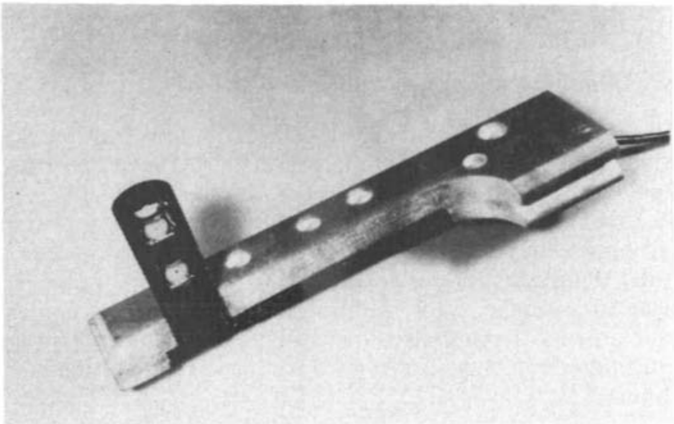

Fig. 6 *Section of an airgap search coil*

Probe security in a generator is important. Fig. 7 shows one arrangement in which the probe holder slides into a retaining dovetailed slot created by modified stator conductor bar slot wedges. The whole assembly is manufactured from epoxy glass laminate. It is preferable to fit the probe assembly without removing the rotor from its bearings and this can often be done. In some instances, however, the probe dimensions required, proximity to the rotor, position of the rotor fan, and the machine airgap are such that the device needs to be fitted when the rotor is being threaded. For these latter machines, if already in service, further time and expense is involved.

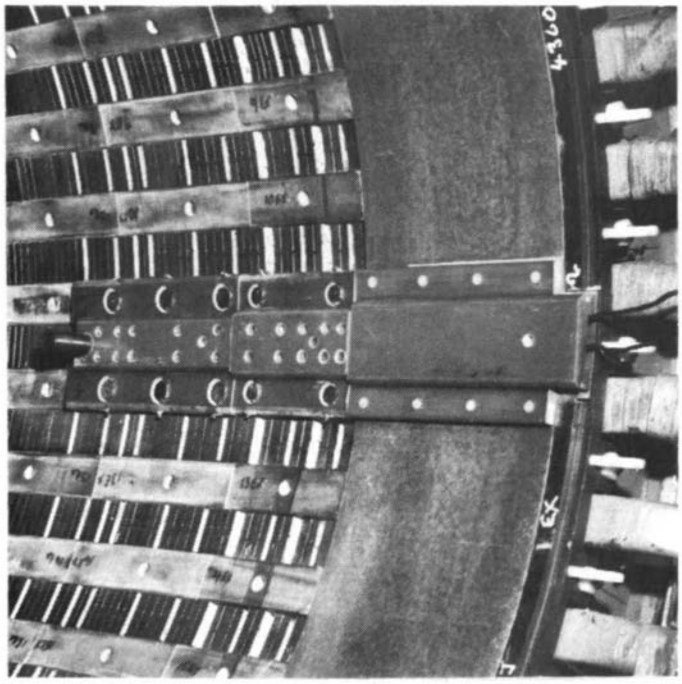

Fig. 7 *Airgap search coil clamping arrangement*

Experience has shown that the spacing between search coil and rotor surface is not critical, and a distance of between 40% and 60% of the airgap length gives adequate sensitivity.

The leads from a coil are noninductively wound and brought out to a socket on the stator casing. The search coil voltages may be displayed on an oscilloscope and photographed to obtain a permanent record for analysis. An alternative method has been described by Byars [2], in which an analogue delay line is used to delay one half of the waveform, Fig. 8, so that the differential voltage between diametrically opposite slots is obtained, which can be displayed on an oscilloscope. An instrument, a Rotor Flux Monitor, is commercially available to do this.

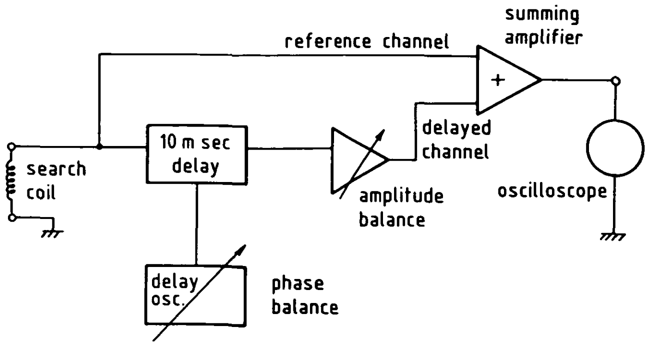

Fig. 8 *Principle of rotor flux monitor*

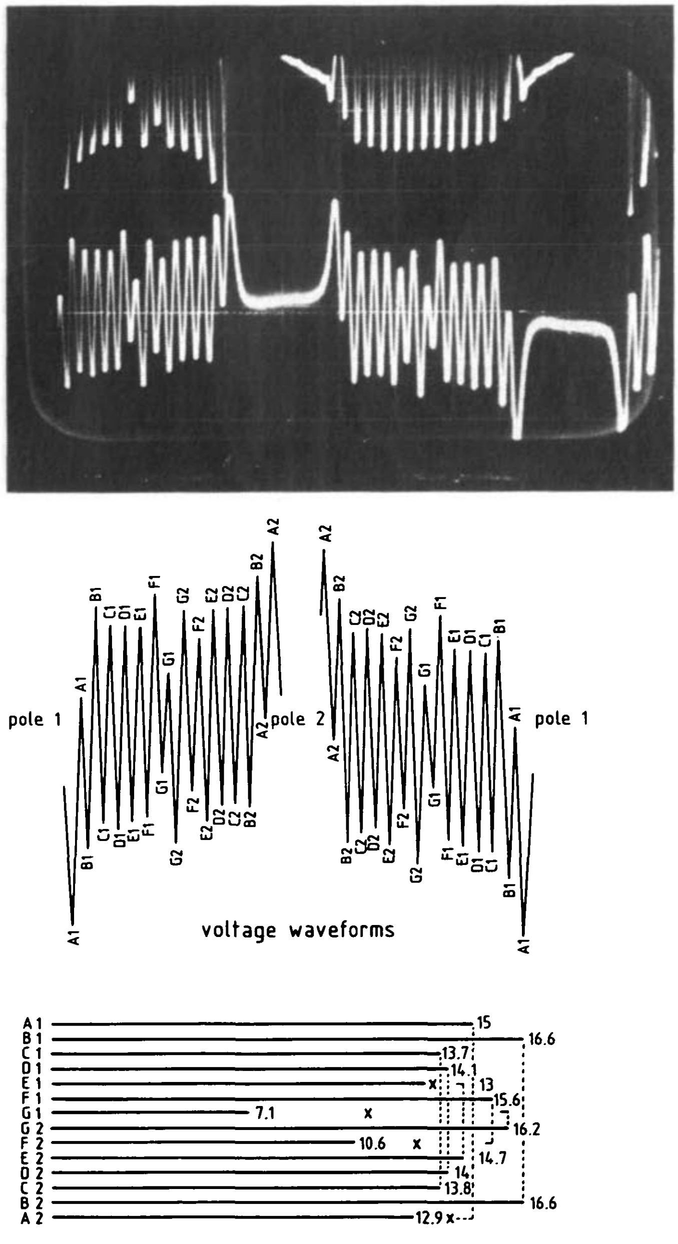

Fig. 9 *Airgap search coil voltage analysts*

× indicates positions of possible faults

NEI Parsons has developed a method in which the search coil voltage is digitised and the results analysed using a computer program.

2.3 Results

As an illustration of the results obtainable, values from the probe shown in Fig. 6 in a 500 MW machine are given. The positions and identification of each of the four coils in the probe are detailed in Table 1. Fig. 9 is an example of the output from No. 4 coil under short-circuit conditions. Also shown are the sums of the peak-to-peak voltages. A 5% difference is taken as a guide as to whether or not a short exists. Table 2 compares the percentage differences from the same coil under open- and short-circuit conditions. Table 3 shows the values obtained for each of the four coils with 20 MW load on the generator.

Table 1: Spacing of coils from rotor surface

Coil number	1	2	3	4
Distance of coil centre to rotor surface, mm	20	28.5	36.5	45
Type	radial	circumferential	radial	circumferential

Table 2: Search coil voltages for coil 4 under open- and short-circuit machine conditions

	Open circuit % difference	Short circuit % difference
A	25.0	14
B	0.7	0.0
C	1.6	0.7
D	0.9	0.7
E	5.1	11.6
F	22.0	32.0
G	32.5	56.0

Table 3: Comparison of search coil voltages from radial and circumferential coils

	Percentage difference			
	Coil 1	Coil 2	Coil 3	Coil 4
A	6.1	20.5	23.7	32.2
B	1.3	0.6	1.0	0.8
C	0.0	1.3	0.9	1.4
D	0.9	1.5	0.0	0.7
E	2.1	7.5	6.5	8.1
F	7.3	16.7	14.1	25.7
G	19.1	35.0	30.8	46.7

2.4 Comments on the technique

There are variations between rotors which make it difficult to recommend definite experimental details. The best results appear to be obtained from a short-circuit test, and meaningful results have been obtained with loads up to 50 MW on a 500 MW generator. Radial search coils may give better results with short circuit and circumferential with open circuit, but it is usual to fit both types. A short-circuit test is possible at site by short-circuiting the transformer HV side.

Under optimum conditions the technique is capable of detecting single turn short-circuits, the sensitivity being greatest for quadrature positions.

Slotted pole faces and magnetic slot wedges cause problems of interpretation. In older machines, magnetic balance weights were sometimes used, and these affect the indication if they are within 5 cm either side of a search coil.

The above technique does not give good results on line at full load. Connolly *et al.* [3] have tried to overcome this limitation and that imposed by the variety of coil and coil position available to them. They have developed an on-line monitor which will detect the change in the search coil voltage from the start or growth of an interturn fault. If a fault develops even harmonic components are produced in the voltage waveform. The on-line monitor measures the sum of the first four even harmonics. Further details are not available at present.

3 Recurrent surge oscillograph (RSO)

The RSO technique was developed for use on transformer windings to enable the estimation of the voltage distribution resulting from the application of a lightning surge (1/50 μs wave), and thereby enable the correct design of the insulation strength. In the rotor short-circuited-turn detection technique, however, a fast-fronted step pulse is injected into the rotor winding, which acts in a similar manner to a transmission line, and reflections occurring at impedance changes resulting from short-circuited turns are sought.

The technique is used by NEI Parsons Works personnel during the winding of a rotor and its subsequent testing. It may be used at standstill or with the rotor rotating. Normally, site testing is undertaken by the utility. To the authors' knowledge no one uses the technique on-line with the rotor excited, but in principle this would appear to be possible.

3.1 Theory

The response of a winding to a step pulse has been treated by Makin [4]. A simplified analysis is given in Appendix 8.1. It is shown that only frequencies below a critical frequency propagate as part of a travelling wave. In the RSO technique, as applied to a rotor winding, rise times of approximately 50 ns are used, and the frequencies contained in the front of the pulse are very much higher than the critical frequency. The result is that the travelling wave which propagates through the winding has a much slower rise time than the applied pulse, typically 20 μs. A rotor winding is a complex shape and must contain regions of changing impedance which cause reflections themselves. The result is that the terminal voltage has a characteristic waveshape in the absence of short-circuited turns. However, the presence of a short-circuited turn produces a relatively large reflection. The manner in which the reflection occurs has been described by Grant†. Appendix 8.2 summarises this analysis. As rotor windings are symmetrical, each end of the winding is pulsed in turn and the waveforms compared; in the absence of short-circuited turns the waveforms are identical for practical purposes, provided the correct experiment arrangement is used.

3.2 Apparatus

The circuit used for an RSO test is shown in Fig. 10. NEI Parsons uses a commercially available pulse generator which applies a pulse alternately to each slipring. The rise time of the applied pulse is 75 ns, and the repetition rate is variable from 30 to 275 pps. Although only relatively low frequencies propagate through the winding with low attenuation, supercritical frequencies do travel short distances, and these produce usable reflections from any shorted turns in the first few coils. Consequently the oscilloscope used to display the terminal voltage waveforms should have a bandwidth of 20 MHz at least. Matched lengths of screened cable to connect from the RSO pulse generator to the rotor are preferable, and earthing should be a central point to prevent earth loops.

† GRANT, A.E.: Private communication.

3.3 Results

Fig. 11*a* shows the typical superimposed traces of the terminal (slipring) voltages to earth for a rotor with no

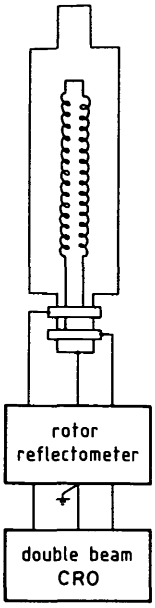

Fig. 10 *Test arrangement using rotor reflectometer*

short-circuited turns. The upper trace shows the input voltages and the lower trace the transmitted pulses. This display is achieved by switching the input point and recording channels together each time an RSO test pulse is applied. The lower trace, Fig. 11*a*, shows the arrival of the

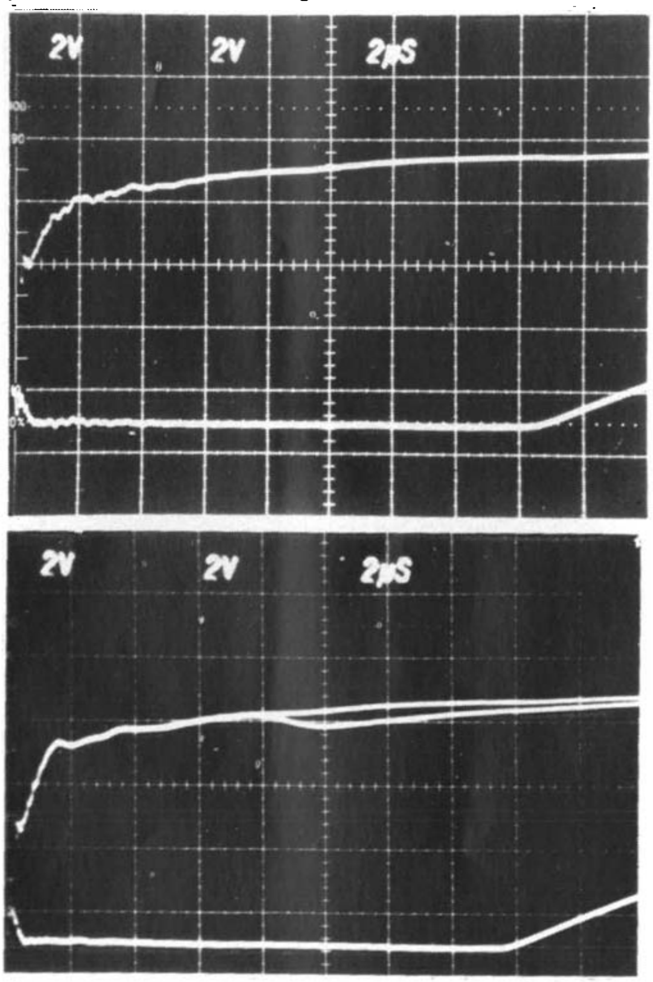

Fig. 11 *Simulated rotor short-circuited on a 500 MW radially cooled rotor*

a Unfaulted winding
b Fault in 'E' coil (short-circuited turn)

transmitted pulse from which the single pass transit time (SPTT) can be measured.

Fig. 11*b* shows an example of a rotor to which a single artificial short has been applied to E coil of a seven coil rotor. The position of the short-circuited turn in time related to the position of the short-circuited in the winding.

The relationship between the first trace deviation and the position in the winding of the short-circuited is not generally linear and has to be derived by experiment for each design of machine, Fig. 12. Errors in position in

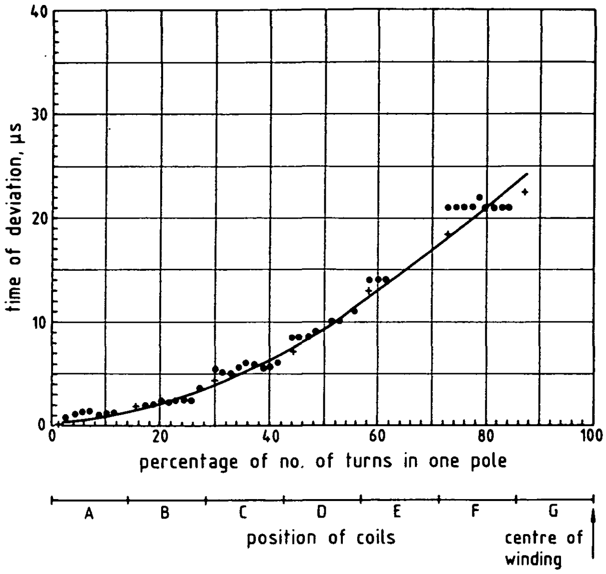

Fig. 12 *Time of deviation resulting from an artificial short at various positions*

• single turn short circuits
+ full coil short circuits

excess of one coil can arise if estimations are based on a linear relationship.

Variations in transit time from machine to machine of the same design and in the same condition are within approximately 5%. The effect of end caps is significant, up to 150%, as is the difference in design for a given winding length (as the inductance and capacitance of the winding vary). For this reason a technique termed 'complementary shorting' is adopted where access is available to the winding. Fig. 13 shows a fault oscillogram and the effect of introducing the same fault in the other half of the winding.

The technique is sensitive enough to enable single shorted turns to be detected. Experiments on a 500 MW axially cooled rotor showed that a 10 Ω short-circuited was just detectable in an A coil and a 3 Ω short-circuited in the G coil.

The above examples were obtained from rotors at standstill but similar results are obtained from rotating rotors. It is important to be able to test rotors at speed because centrifugal loading can induce short-circuited turns. Two major problems have been found in testing rotors up to 3000 rev/min, and these are illustrated in Fig. 14. Brush noise can make it impossible to distinguish the oscilloscope trace, Fig. 14*b*. Experience has shown that improvements to the method of earthing the rotor shaft can remove this effect. The best results have been obtained with a brass brush clamped firmly onto the shaft and bedded in. Carbon brushes give the poorest earth. Copper loaded carbon brushes are being evaluated.

Multiple triggering, Fig. 14*c*, makes the recording of oscilloscope traces extremely difficult. This is an effect which occurs on the manufacturer's test bed but has not been reported from site. This phenomenon is caused by

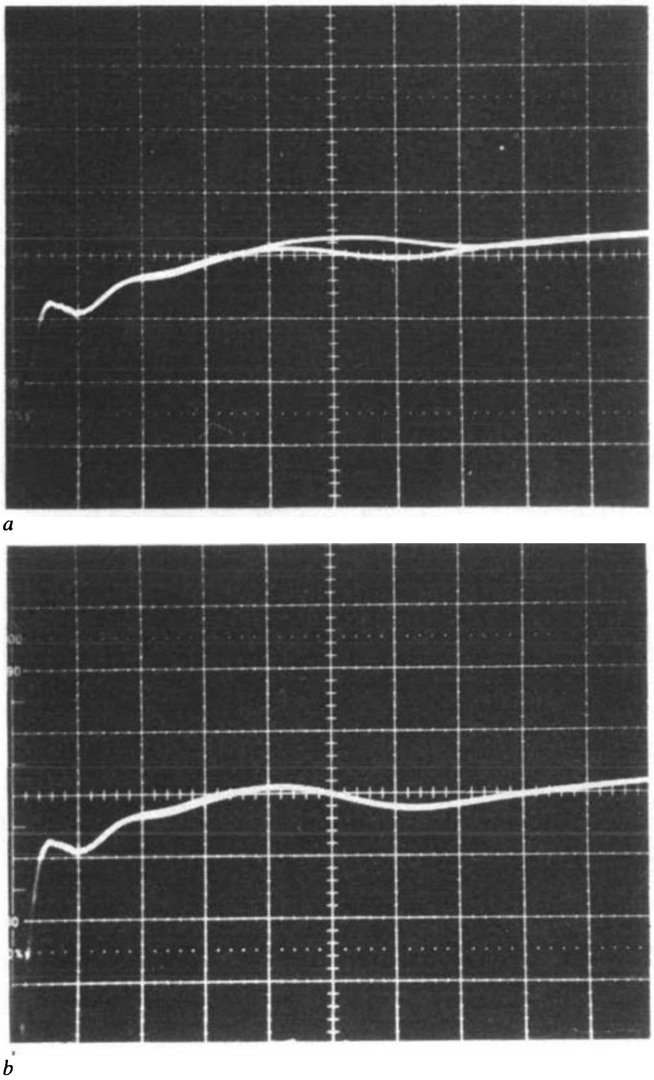

Fig. 13 *Location of a fault in a 500 MW axially cooled rotor by a 'complementary short-circuit' technique*
a Fault in 'G' coil; pole 1 *b* Artificial complementary short circuit in 'G' coil; pole 2

stray magnetic fields in the test area, external to the rotor, which induce a sinusoidal voltage in the rotor winding. As the speed of the rotor is increased, the induced voltage and the RSO test pulse repetition rate produce a beat effect. It is of interest to record RSO traces at any speed from standstill to overspeed in order to study the commencement of a shorted condition. This can be achieved by varying the RSO test pulse repetition rate until it corresponds to the induced voltage frequency and a stationary trace is obtained. The commercially available equipment requires a small modification to permit the pulse repetition rate to be swept over the full range required.

3.4 Comments on the technique

The technique is sensitive enough to detect single short-circuited turns, but to locate their position accurately will require a previous calibration, e.g. Fig. 12, which often is not available, unless the 'complementary short' technique can be employed.

High resistance shorts (several ohms), which might not affect rotor operation significantly, can be detected. Consequently, due consideration must be given to the interpretation of results.

4 Other techniques

There are other techniques used to detect or confirm the presence of rotor short-circuited turns. Their applicability

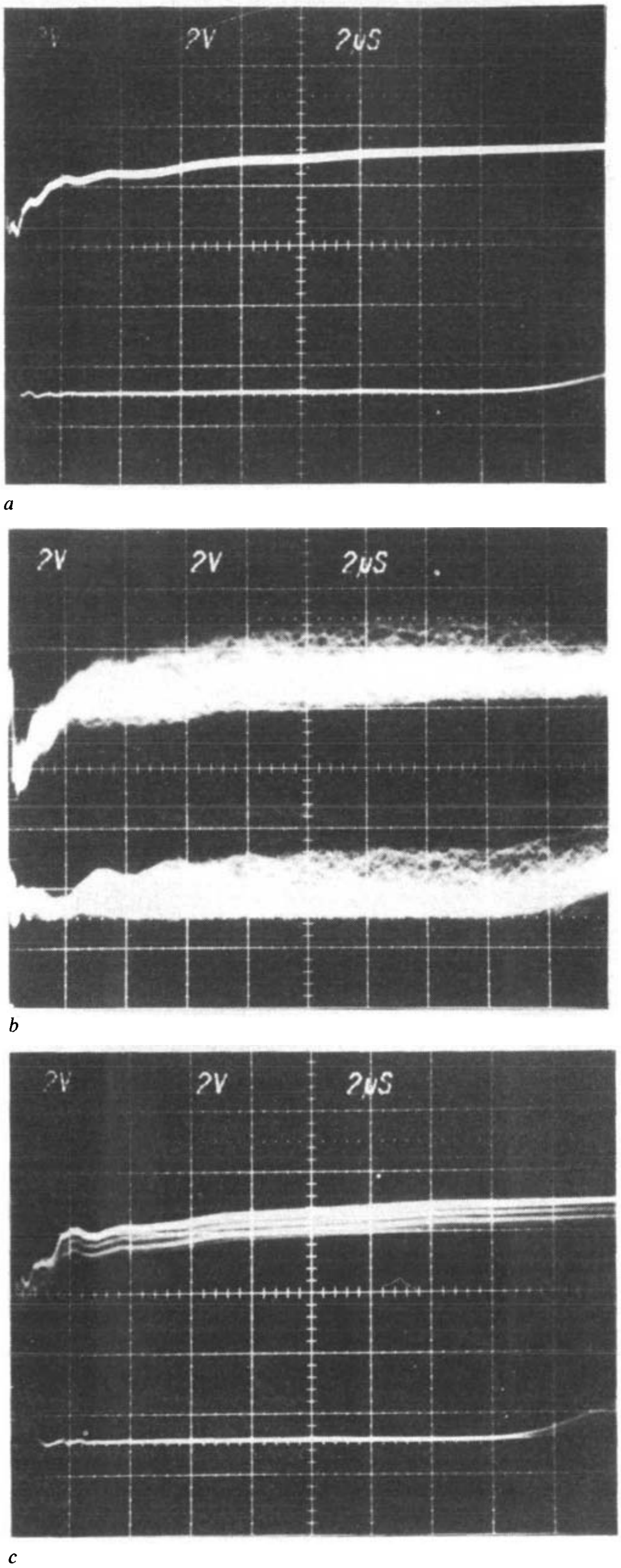

Fig. 14 *Examples of brush noise and multiple triggering*
a Rotor stationary *b* Brush noise at 3000 rev/min
c Multiple triggering at 3000 rev/min

depends on the condition of the rotor. If the rotor is in the process of being wound, a 'drop test' can reveal the presence of a short-circuited turn. Such a test involves applying a direct voltage across the rotor winding and measuring the voltage at selected positions.

On a fully assembled rotor a 'Hall' probe technique may be used to detect variations in the field from slot to slot. In this technique the field is measured against the derivative of the field with a search coil technique, making the method less sensitive. However, the cost of running the rotor is avoided.

Two further techniques are discussed in more detail below.

4.1 Measurement of circulating stator currents

Mulhaus *et al.* [5] have described a technique for detecting the presence of rotor shorted turns with the machine on-line. Their technique relies on the windings of each phase of the generator being divided into two half phases connected in parallel. When a short-circuited turn is present on a rotor there is no longer a symmetry between the flux distribution of the two pole faces, and the airgap flux density will contain even harmonics [6]. Hence equal and opposite even harmonic voltages are induced across the phase windings, so that circulating even harmonic currents flow round the parallel half phase. The method used for detecting these currents is shown in Fig. 15. Fig. 16 shows

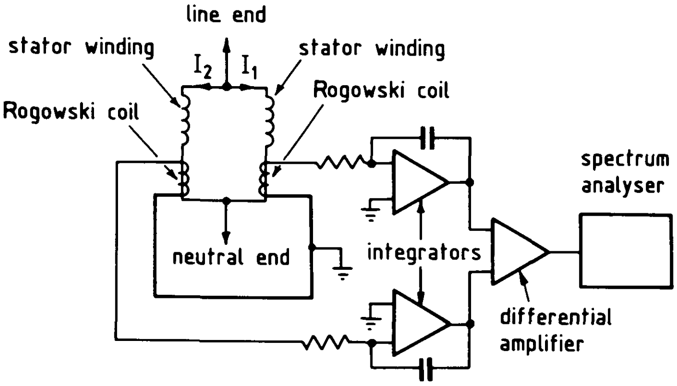

Fig. 15 *Schematic arrangement for measuring stator circulating harmonic currents*

Note: stator output current = $I_1 + I_2$
stator circulating current = $\frac{1}{2}(I_1 - I_2)$

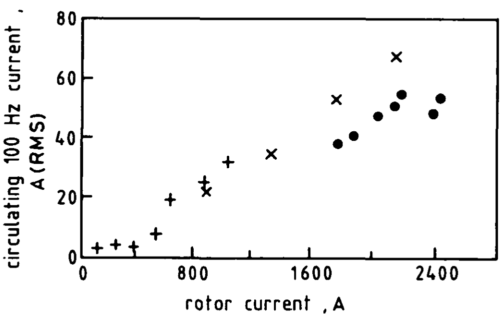

Fig. 16 *Circulating 100 Hz current for a generator thought to have a rotor short circuit*

+ open circuit
× short circuit
● on load

the circulating 100 Hz current measured under different conditions on a generator suspected of having short-circuited turns. The conclusion reached was that these currents are much larger than would be expected from a generator with a rotor having no short-circuited turns (5 A was measured) and confirmed the presence of a rotor fault. The method based on 100 Hz current measurement does not, however, provide information on the exact location of the short-circuited turns, but the authors are investigating other information (4th harmonic) which may give supportive evidence.

4.2 Rotor shaft current

The necessity of a rotor interturn voltage test for rotors having thyristor excitation was considered by Richardson *et al.* [7]. Although the conclusion reached was that it was not necessary, customers requested that a test on large rotors having thyristor excitation be undertaken. It was consequently necessary to devise a method of detecting the presence or the occurrence, caused by the applied voltage, of a shorted turn. Thyristor excitation pulses were found to be well represented by a 10 μs rise-time 3 ms decay-time pulse. Pulses of amplitude up to 3.2 kV peak (depending on thyristor excitation voltage) were applied to rotors of up to 800 MW generators. The test circuit used, Fig. 17,

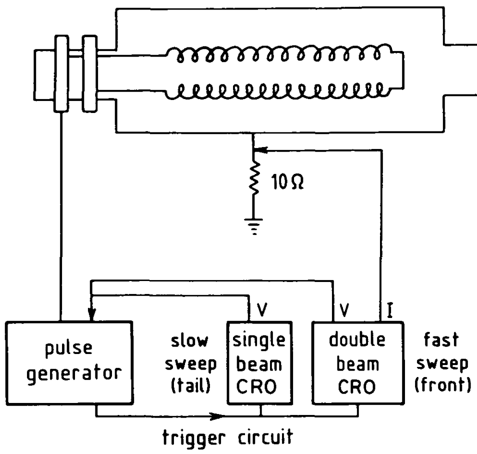

Fig. 17 *Circuit arrangements for pulse tests*

was similar to that for an RSO test, but single pulses were applied and rotor shaft current measured. Fig. 18 shows the shape of the rotor shaft current measured, and Fig. 19 the current change produced by a deliberately introduced shorted turn. Fig. 20 shows the relationship between time delay to the first peak of current change and the shorted-turn position corresponding to Fig. 19. This technique can

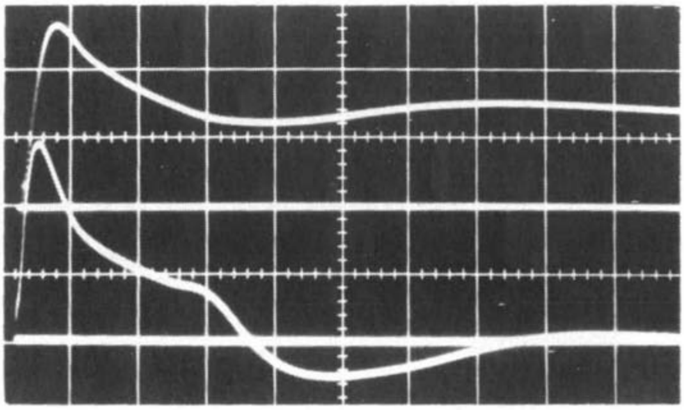

Fig. 18 *Rotor shaft current during a pulse test*
a Applied voltage = 1 kV/div
b Rotor shaft current = 20 A/div
Sweep = 20 μs/div

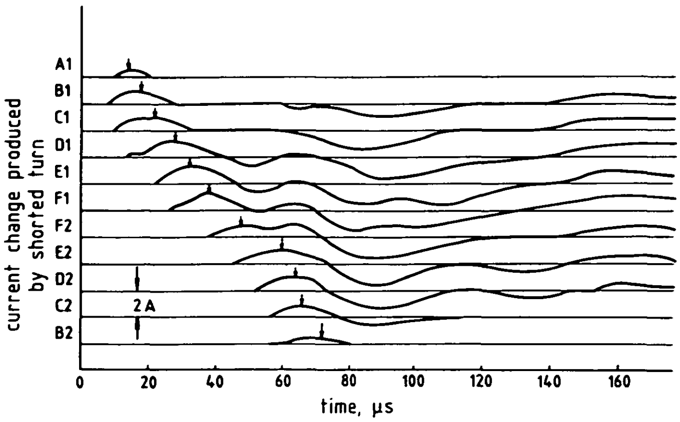

Fig. 19 *Current change due to a short-circuited turn*

therefore be used to detect and locate the presence of short-circuited turns in a rotor.

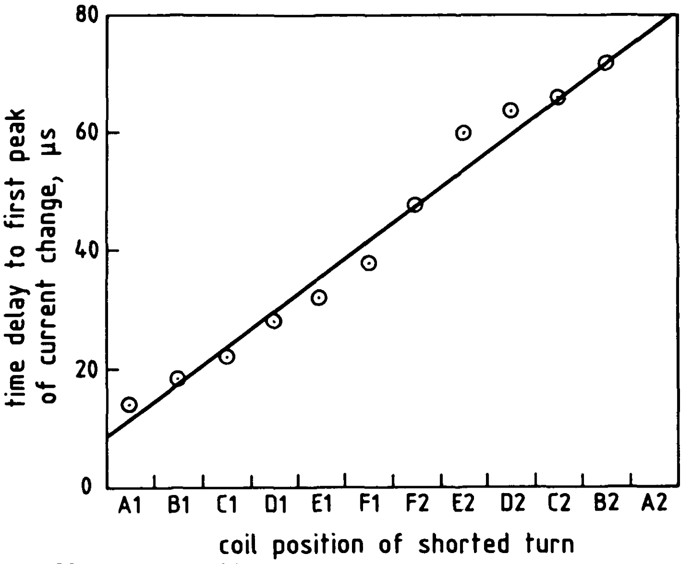

Fig. 20 *Variation of first peak in current with position of short-circuited turn*

5 Summary

Various methods of rotor short-circuited-turn detection have been described which show that detection and location techniques are available for use during the winding and Works, and site testing of the generator. The methods of measuring search-coil harmonic voltages and stator harmonic circulating current are two new means of detecting the presence of rotor short-circuited turns with the generator on-line, and their recent development illustrates the present sensible trend of extending surveillance techniques to the continuous monitoring of power equipment where this is economically justifiable.

6 Acknowledgments

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8 Appendix

8.1 Response of a rotor winding to a step pulse

For a simple single-layer winding, having capacitance to earth per unit length c, capacitance between turns per unit length k, and inductance per unit length l, Makin [4] derives the following differential equations:

$$\frac{\partial^2 V}{\partial x^2} - lc\,\frac{\partial^2 V}{\partial t^2} + lkw^2\,\frac{\partial^4 V}{\partial t^2 \partial x^2} = 0 \tag{1}$$

where V is voltage and w mean turn length. This is satisfied by the harmonic wave equation

$$V = V_0\, e^{j\omega(t - x/v)} \tag{2}$$

provided a certain relationship exists between w and wave velocity v

$$v = \pm\sqrt{\frac{1}{lc} - \frac{k}{c}\,w^2\omega^2} \tag{3}$$

From this simplified equation it can be seen that there should exist an angular frequency, $\nu(= 2f_\nu)$, such that the velocity is zero; i.e. when

$$\nu = \frac{1}{w\sqrt{lk}} \tag{4}$$

For frequencies below f_ν the velocity will be real, whereas for high values it will become imaginary. f_ν has therefore been termed the critical frequency. Further simplified analysis shows that all frequencies greater than the critical value form an attenuated exponential distribution along the winding. Makin [4] shows that if nonlinear inductive effects are taken into account (due to eddy currents the magnetic flux will not be the same for all frequencies), all frequencies are passed by the winding, but those of a higher value than f_ν have such a small velocity compared with the vast majority of the lower frequencies that they are soon left behind and may be considered as cutoff.

The application of a step pulse to a winding involves applying an infinite series of harmonic waves, the magnitude of each varying inversely with frequency. Only those of frequency below f_ν propagate, so in a simplified approach it may be seen that if

$$\frac{2}{\pi}V\int_0^\infty \frac{\sin\omega t\, d\omega}{\omega} = 1$$

which represents a step pulse

$$\frac{2}{\pi}V\int_0^\nu \frac{\sin\omega t\, d\omega}{\omega}$$

represents the wave propagated along the winding. The function

$$\int_0^\nu \frac{\sin\omega t\, d\omega}{\omega}$$

is a well-known mathematical function called the sine integral Si (νt) and tables of it are published; Fig. 21 shows its form.

8.2 Simplified analysis of the effect of a short-circuited turn on a travelling wave

The effect of a short-circuited turn may be determined by assuming that the rotor winding behaves as an ideal transmission line. At the short-circuited turn, Fig. 22, there is a junction of four transmission lines of equal surge impedance Z_0. A wave of amplitude V arriving at the fault after t microseconds produces a reflected wave of amplitude,

$$V_T = \left(\frac{Z_0/3 - Z_0}{Z_0/3 + Z_0}\right)V = -\frac{V}{2} \tag{5}$$

from transmission-line theory. Equal amplitude waves propagate in each limb of the short-circuited turn and along

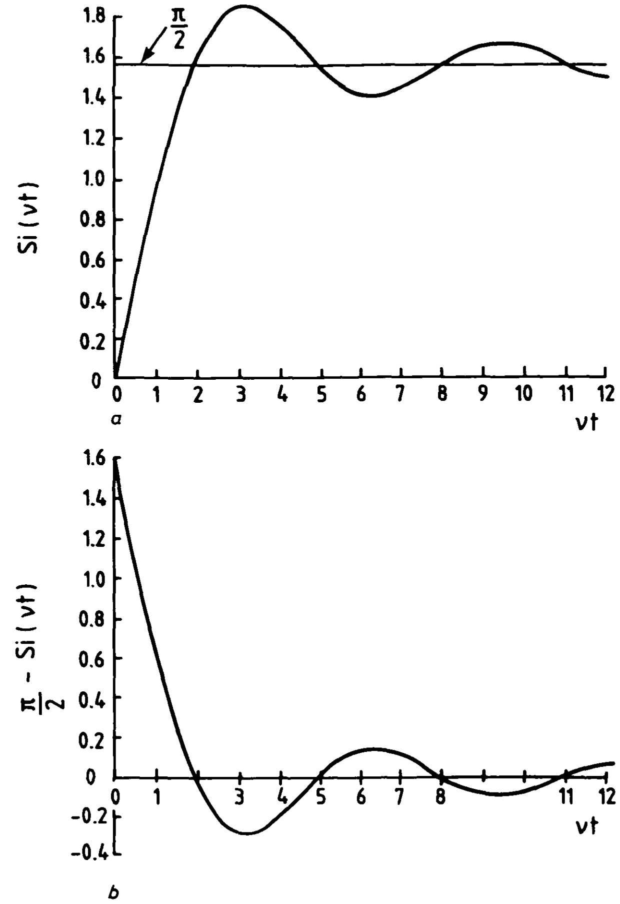

Fig. 21 *Step-pulse response of an idealised winding*
a Sine integral (transmitted pulse)
b Summation of supercritical frequencies (attenuated components)

the winding, as shown in Fig. 23*a*. If T is the SPTT in microseconds, and n is the number of turns in the winding, then the waves propagating in the short-circuited turn will reach the short circuit again after T/n microseconds, producing the conditions shown in Fig. 23*b*. As a consequence, the idealised response of the winding will be as shown in Fig. 24, assuming the far end of the winding is effectively open circuit.

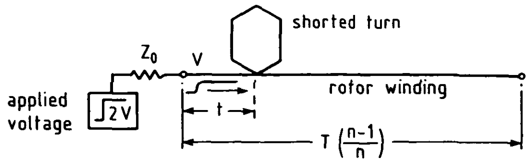

Fig. 22 *Schematic diagram of a short-circuited turn in a rotor winding*

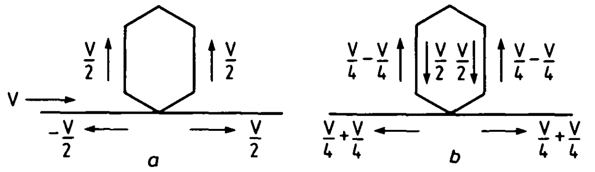

Fig. 23 *Conditions in a short-circuited turn*
a On arrival of wave
b After delay $\frac{T}{n}$

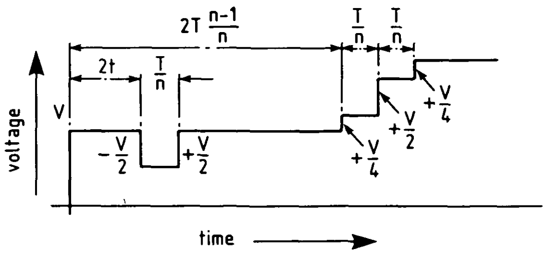

Fig. 24 *Idealised response of a faulted winding (single short-circuited turn)*

Ideally, if n_s is the number of short-circuited turns, then the duration of the reflected pulse, $n_s T/n$ microseconds, enables the number of turns short-circuited to be determined; the position of the start of the fault is given by $t/T\ n$.

Normally the step pulse is applied to a winding through a variable resistor set to Z_0 to ensure that repeatable test conditions can be obtained for future comparisons. This produces an applied voltage to the rotor of one half of the pulse generator output voltage.