Electricity Distribution

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Company Directive

STANDARD TECHNIQUE: TP21AA

Earthing Design Fundamentals
Part A
Safety Limits For Touch & Step Voltages

Summary
This Standard Technique defines the safety limits for touch and step voltages when designing earthing systems which are to be owned or adopted by Western Power Distribution.

Author: **Graham Brewster**

Implementation Date: **December 2020**

Approved by

Carl Ketley-Lowe
Engineering Policy Manager

Date: **11th December 2020**

Target Staff Group	**Network Services Teams & ICPs**
Impact of Change	**AMBER - The changes have an impact of current working practices that are not safety critical – Communication at next team meeting or as part of a retraining programme**
Planned Assurance Checks	**None**

All references to Western Power Distribution or WPD must be read as National Grid Electricity Distribution or NGED

IMPLEMENTATION PLAN

Introduction

This Standard Technique defines the safety limits for touch and step voltages when designing earthing systems which are to be owned or adopted by Western Power Distribution.

Main Changes

This is a revision of ST: TP21A and has been re-numbered as ST: TP21AA.

Impact of Changes

This Standard Technique is relevant to staff, Contractors and Independent Connection Providers involved with the design / assessment of earthing systems for safe touch and step voltage.

Implementation Actions

Managers should notify relevant staff that this Standard Technique has been published.

There are no retrospective actions.

Implementation Timetable

This ST shall be implemented with immediate effect.

REVISION HISTORY

Document Revision & Review Table		
Date	**Comments**	**Author**
December 2020	• Initial issue	Graham Brewster

Contents

1.0 INTRODUCTION

This Standard Technique defines the safety limits for touch and step voltages when designing / assessing earthing systems which are to be owned or adopted by Western Power Distribution.

The safety limits for touch and step voltages are described in tabular form, and the data is based on BS EN 50522, ENA TS 41-24 and the underlying assumptions.

The rise of earth potential associated with current passing through an earthing system under fault conditions can present an electric shock hazard. A potential difference across parts of the human body causes current to flow. There is a risk of fatal electric shock if the current flows for sufficient time to cause ventricular fibrillation of the heart. IEC 60479-1 defines a series of time-current curves for judging whether this will occur. These curves are used to derive the permissible touch and step voltages.

2.0 DEFINITIONS

For the purpose of this document the following definitions are employed:

TERM	DEFINITION
Step Voltage	The potential difference between a person's feet which are 1m apart
Touch Voltage	The potential difference between a person's hands and feet when standing 1m away from the object they are touching
Ventricular Fibrillation	A state of the heart in which the lower chambers (ventricles) twitch randomly (fibrillate) instead of contacting in a co-ordinated fashion, resulting in an inability to pump blood. Considered to be the main mechanism of death in fatal electrical accidents

3.0 REFERENCES

This document makes reference to, or should be read in conjunction with, the documents listed below. The issue and date of the documents listed below shall be those applicable at the date of issue of this document, unless stated otherwise.

3.1 IEC Standards

NUMBER	TITLE
IEC 60479-1	Effects of current on human beings and livestock - Part 1: General aspects

3.2 British Standards

NUMBER	TITLE
BS EN 50552	Earthing of power installations exceeding 1 kV a.c.

3.3 Energy Networks Association

NUMBER	TITLE
ENA TS 41-24	Guidelines for the design, installation, testing and maintenance of main earthing systems in substations

4.0 REQUIREMENTS

4.1 Maximum Touch & Step Voltages For Shoes On Soil Or Outdoor Concrete

Fault Clearance Time (s)	Touch Voltage Limit (V)	Step Voltage Limit (V)
0.1	2070	A
0.15	1808	A
0.2	1570	A
0.3	1179	A
0.4	837	A
0.5	578	A
0.6	420	A
0.7	332	A
0.8	281	21608
0.9	250	19067
1.0	233	17571
1.1	219	16460
1.2	209	15575
1.3	200	14839
1.4	193	14267
1.5	188	13826
2	173	12629
3	162	11727
5	156	11250
≥ 10	153	11012

A = Potentials in excess of 25kV and which cannot foreseeably be exceeded.

Shoe resistance = 4kΩ per shoe
Standing surface resistivity = 100Ωm
Standing surface resistance = 3 x standing surface resistivity = 300Ω
Total additional resistance - touch = 2,150Ω
Total additional resistance - step = 8,600Ω

4.2 Maximum Touch & Step Voltages For Shoes On 75mm Chippings

Fault Clearance Time (s)	Touch Voltage Limit (V)	Step Voltage Limit (V)
0.1	2341	A
0.15	2043	A
0.2	1773	A
0.3	1331	A
0.4	944	A
0.5	650	A
0.6	471	A
0.7	371	A
0.8	314	24906
0.9	279	21976
1.0	259	20253
1.1	244	18971
1.2	232	17951
1.3	223	17103
1.4	215	16445
1.5	209	15936
2	192	14557
3	180	13517
5	173	12967
≥ 10	170	12692

A = Potentials in excess of 25kV and which cannot foreseeably be exceeded.

Shoe resistance = 4kΩ per shoe
Standing surface resistivity = 333Ωm
Standing surface resistance = 3 x standing surface resistivity = 1,000Ω
Total additional resistance - touch = 2,500Ω
Total additional resistance - step = 10,000Ω

4.3 Maximum Touch & Step Voltages For Shoes On 150mm Chippings Or Indoor Concrete

Fault Clearance Time (s)	Touch Voltage Limit (V)	Step Voltage Limit (V)
0.1	2728	A
0.15	2379	A
0.2	2064	A
0.3	1548	A
0.4	1095	A
0.5	753	A
0.6	544	A
0.7	428	A
0.8	361	A
0.9	321	A
1.0	298	24083
1.1	280	22559
1.2	266	21347
1.3	255	20338
1.4	246	19555
1.5	239	18951
2	220	17311
3	205	16074
5	198	15420
≥ 10	194	15092

A = Potentials in excess of 25kV and which cannot foreseeably be exceeded.

Shoe resistance = 4kΩ per shoe
Standing surface resistivity = 667Ωm
Standing surface resistance = 3 x standing surface resistivity = 2,000Ω
Total additional resistance - touch = 3,000Ω
Total additional resistance - step = 12,000Ω

4.4 Maximum Touch & Step Voltages For Shoes On 100mm Tarmac / Asphalt / Bitmac

Fault Clearance Time (s)	Touch Voltage Limit (V)	Step Voltage Limit (V)
0.1	13579	A
0.15	11761	A
0.2	10202	A
0.3	7622	A
0.4	5376	A
0.5	3656	A
0.6	2614	A
0.7	2012	A
0.8	1710	A
0.9	1523	A
1.0	1376	A
1.1	1288	A
1.2	1220	A
1.3	1167	A
1.4	1117	A
1.5	1191	A
2	992	A
3	919	A
5	897	A
≥ 10	884	A

A = Potentials in excess of 25kV and which cannot foreseeably be exceeded.

Shoe resistance = 4kΩ per shoe
Standing surface resistivity = 10,000Ωm
Standing surface resistance = 3 x standing surface resistivity = 30,000Ω
Total additional resistance - touch = 17000Ω
Total additional resistance - step = 68,000Ω

4.5 Maximum Hand-To-Hand Touch Voltages

Fault Clearance Time (s)	Touch Voltage Limit (V)
0.1	1114
0.15	968
0.2	836
0.3	639
0.4	484
0.5	368
0.6	276
0.7	221
0.8	191
0.9	172
1.0	161
1.1	152
1.2	146
1.3	141
1.4	137
1.5	134
2	125
3	119
5	115
≥ 10	114

4.6 Permissible Touch & Step Potentials For Personnel Outside Substations For Typical Fault Clearance Times

In the UK National Annex to BS EN 50552 there is additional information (provided by the Health & Safety Executive) to assist with the application of the requirements.

It advises that permissible touch and step voltages within a substation where the public are excluded should be based on a typical minimum value for footwear resistance of 4kΩ per foot.

It also advises that touch and step voltage scenarios outside enclosed substations might require adoption of other values of footwear resistance, and neglecting additional resistances due to chippings.

Normally, a footwear resistance of 4kΩ per foot should be assumed for all locations, however when deemed appropriate, the touch and step voltage limits in the following tables shall be applied.

4.6.1 Maximum Touch & Step Voltages For Old Wet Shoes On Soil

Fault Clearance Time (s)	Touch Voltage Limit (V)	Step Voltage Limit (V)
0.1	1295	A
0.15	1132	A
0.2	984	A
0.3	748	A
0.4	536	A
0.5	364	24557
0.6	276	17478
0.7	207	13514
0.8	189	11305
0.9	169	9958
1.0	156	9228
1.1	147	8644
1.2	141	8159
1.3	135	7797
1.4	131	7462
1.5	127	7261
2	118	6618
3	111	6148
5	108	5985
≥ 10	107	5889

A = Potentials in excess of 25kV and which cannot foreseeably be exceeded.

Shoe resistance = 2kΩ per shoe
Standing surface resistivity = 100Ωm
Standing surface resistance = 3 x standing surface resistivity = 300Ω
Total additional resistance - touch = 1,150Ω
Total additional resistance - step = 4,600Ω

4.6.2 Maximum Touch & Step Voltages For Bare Feet On Soil

Fault Clearance Time (s)	Touch Voltage Limit (V)	Step Voltage Limit (V)
0.1	521	22753
0.15	462	19763
0.2	407	17077
0.3	313	12715
0.4	231	8905
0.5	166	6044
0.6	128	4290
0.7	106	3320
0.8	92	2770
0.9	84	2434
1.0	80	2249
1.1	76	2098
1.2	73	1992
1.3	71	1897
1.4	69	1823
1.5	67	1771
2	63	1616
3	60	1503
5	58	1442
≥ 10	57	1412

Standing surface resistivity = 100Ωm
Standing surface resistance = 3 x standing surface resistivity = 300Ω
Total additional resistance - touch = 150Ω
Total additional resistance - step = 600Ω

5.0 BACKGROUND INFORMATION

5.1 Effects on the Human Body of 50Hz Alternating Current

This section describes the effects of 50Hz sinusoidal alternating current passing through the human body.

5.1.1 Threshold of Perception

The threshold of perception is the minimum value of current which causes any sensation for the person through which it is flowing.

The threshold depends on several parameters, such as the contact surface area, the conditions of contact (dry, wet, contact pressure), and also on the physiological characteristics of the individual. It will be less than the threshold of reaction.

5.1.2 Threshold of Reaction

The threshold of reaction is the minimum value of current which causes involuntary muscular contraction for the person through which it is flowing.

The threshold depends on the same factors as per the threshold of perception. The IEC Standard uses a value of 0.5mA for the threshold of reaction when touching a conductive surface.

5.1.3 Threshold Of Ventricular Fibrillation

Ventricular fibrillation is a state of the heart in which the lower chambers (ventricles) twitch randomly (fibrillate) instead of contacting in a co-ordinated fashion, resulting in an inability to pump blood. It is considered to be the main mechanism of death in fatal electrical accidents.

The threshold of ventricular fibrillation is the minimum value of current through the body which causes ventricular fibrillation.

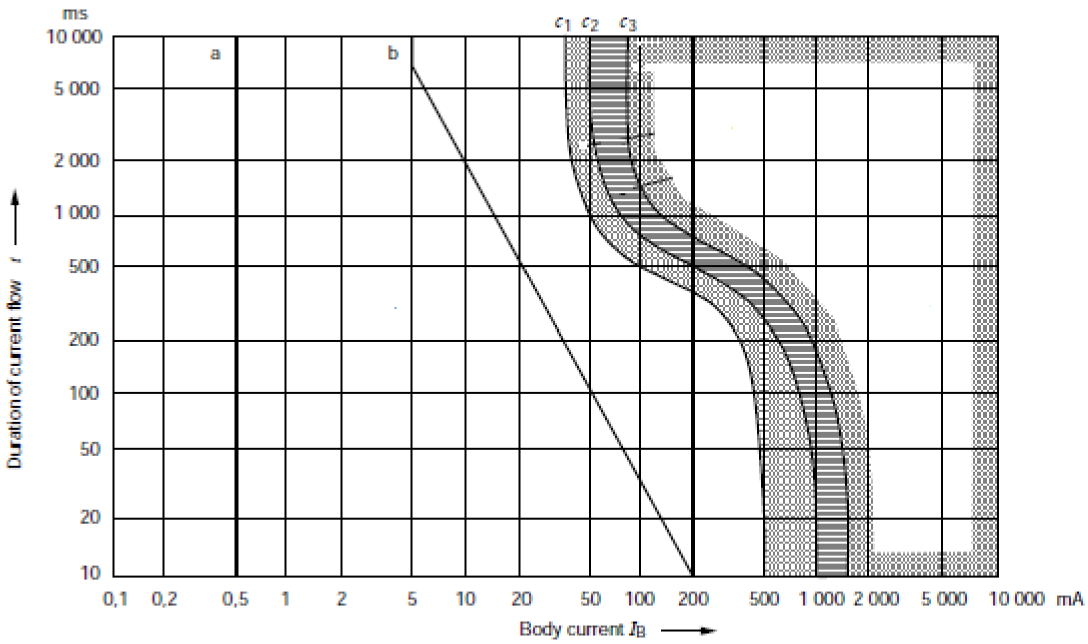
The threshold depends on physiological parameters (anatomy of the body, state of cardiac function, etc.) as well as on electrical parameters (duration and pathway of current flow, etc.).

5.1.4 Time-Current Curves

IEC 60479-1 provides time-current curves for a left hand to both feet current path, where the probability of ventricular fibrillation occurring in a population is 0%, 5% and 50%.

The diagram below shows the time-current curves for the human body for 50Hz alternating current.

Up to a	= threshold of perception
a to b	= involuntary muscular contractions
b to c	= Strong involuntary muscular contractions
c1	= Limit of 0% probability of ventricular fibrillation
c2	= Limit of 5% probability of ventricular fibrillation
c3	= Limit of 50% probability of ventricular fibrillation



5.1.5 Body Current Limit

The time-current curve used in the UK for earthing system design is the C_2 curve i.e. where the probability of ventricular fibrillation occurring in a population is 5%.

The Body Current Limit for the left hand to both feet current path (i.e. C_2 time-current curve) in tabular form is shown below:

Duration of Current Flow (s)	Body Current Limit (mA)
0.05	950
0.1	750
0.15	672
0.2	600
0.3	432
0.4	299
0.5	200
0.6	144
0.7	111
0.8	91
0.9	81
1.0	80
1.1	71
1.2	67
1.3	64
1.4	68
1.5	66
2	60
3	54
5	51
≥ 10	50

5.1.6 Heart Current Factor

A ‘heart-current factor’ is utilised in order to calculate the body current limit (i.e. threshold of ventricular fibrillation) for current paths other than left hand to both feet.

$$Body\ Current\ Limit_{other\ current\ path} = \frac{Body\ Current\ Limit\ _{left\ hand\ to\ feet}}{Heart\ Current\ Factor}$$

Current Path	Heart Current Factor
Left hand to left foot, right foot or both feet	1.0
Both hands to both feet	1.0
Left hand to right hand	0.4
Right hand to left foot, right foot or to both feet	0.8
Back to right hand	0.3
Back to left hand	0.7
Chest to right hand	1.3
Chest to left hand	1.5
Seat to left hand, right hand or to both hands	0.7
Left foot to right foot	0.04

For example, the hand to hand current that has the same likelihood of producing ventricular fibrillation as a current of 80 mA left hand to both feet is:

$$I = \frac{80mA}{0.4} = 200mA$$

5.2 Electrical Impedance Of The Human Body

From an earthing design perspective, it is more convenient to refer to body voltages rather than body current, and this requires an understanding of the electrical impedance of the human body.

The electrical impedance of the body depends on a number of factors, including the:

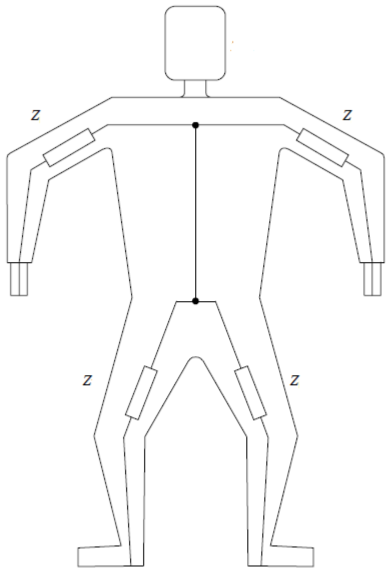
- Magnitude of the touch voltage
- Path of the current through the body
- Duration of current flow
- Degree of moisture of the skin
- Surface area of contact
- Contact pressure exerted

5.2.1 Impedance Of The Skin

The impedance of the skin is mostly resistive. Its value depends on the magnitude of the touch voltage, duration of the current flow, surface area of contact, pressure of contact, and the degree of moisture of the skin.

5.2.2 Internal Impedance Of Human Body

The internal impedance of the human body is mostly resistive. The internal impedances are mainly located in the limbs (arms and legs), and a simplified schematic diagram for the internal impedances of the human body is shown in the diagram below.



If Z is the internal impedance of an arm or a leg, then the hand to hand internal impedance is 2Z, as is the one hand to one foot internal impedance.

It is apparent that the internal impedance from one hand to both feet is 1.5Z, or 75 % of the hand to hand impedance. Likewise, the impedance from both hands to both feet is Z, or 50 % of the hand to hand impedance.

5.2.3 Body Impedance

IEC 60479-1 includes tables of the total impedance of the human body for a hand-to-hand current path and a range of touch voltages, for large, medium and small surface areas of contact, and for dry, water-wet and saltwater-wet conditions. Values are provided for total body impedances that are not exceeded for 5%, 50% and 95% of the population.

The UK Government (via the Health & Safety Executive) has decreed that in the UK, earthing systems shall be designed assuming large surface area of contact, dry conditions, and body impedances not exceeded by 5% of the population.

The body impedance for these conditions (from IEC 60479-1) is shown in the table below:

Body Voltage (V)	Body Impedance (Ω)
25	1750
50	1375
75	1125
100	990
125	900
150	850
175	825
200	800
225	775
400	700
500	625
700	575
1000	575

5.2.4 Body Factor

A ‘body factor’ is utilised in order to calculate the body impedance for current paths other than hand to hand (see section 5.2.2).

$$Body\ Impedance_{other\ current\ path} = Body\ Impedance_{hand\ to\ hand} \times Body\ Factor$$

The following table shows the Body Factor for a range of current paths.

Current Path	Body Factor
Left hand to right hand	1.0
Left hand to left foot or right foot	1.0
Right hand to left foot or right foot	1.0
Left hand to both feet	0.75
Right hand to both feet	0.75
Both hands to both feet	0.5

For example, the left hand to both feet body impedance where the hand-to-hand body impedance is 800Ω is:

$$Body\ Impedance = 800\Omega \times 0.75 = 600\Omega$$

5.3 **Additional Resistances**

Additional resistances include that presented by gloves, footwear and the type of standing surface covering.

5.3.1 Additional Resistance - Feet

In the UK National Annex to BS EN 50552, the Health & Safety Executive has advised that permissible touch and step voltages for typical fault clearance times should be based on a typical minimum value for footwear resistance of 4kΩ per foot within a substation where the public are excluded. It has also advised that touch and step voltage scenarios outside enclosed substations might require adoption of other values of footwear resistance.

The resistance of the standing surface, for each foot, is calculated using the formula:

$$Resistance_{standing\ surface} = 3 \times \rho$$

Where ρ is the electrical resistivity of the standing surface, and the following values are assumed:

Surface	Resistivity (Ωm^{-1})	Resistance $_{standing\ surface}$ (for each foot) (Ω)
Soil	100	300
75mm Chippings	333	1,000
150mm Chippings	666	2,000
Tarmac / Bitmac / Asphalt	10,000	30,000

Touch potentials are normally assessed using the left hand to both feet condition and consequently the additional resistance is calculated taking into account the effect of two shoe and standing surfaces in parallel. In other words:

$$R_{additional-feet} = \frac{R_{shoe} + R_{standing\ surface}}{2}$$

Step potentials are assessed using the left foot to right foot condition and consequently the additional resistance is calculated taking into account the effect of two shoe and standing surfaces in series. In other words:

$$R_{additional-feet} = 2\ x\ \left(R_{shoe} + R_{standing\ surface}\right)$$

	$R_{additional-feet}$ (Ω)	
	Touch	**Step**
Barefoot on Soil	150	600
Old & Wet Shoes (2kΩ) on Soil	1,150	4,600
Normal Shoes (4kΩ) on Soil	2,150	8,600
Normal Shoes (4kΩ) on 75mm Chippings	2,500	10,000
Normal Shoes (4kΩ) on 150mm Chippings	3,000	12,000
Normal Shoes (4kΩ) on Tarmac / Bitmac / Asphalt	17,000	68,000

5.3.2 Additional Resistance - Hands

Touch potentials are normally assessed using the left hand to both feet condition and consequently the additional resistance is calculated taking into account the effect of a single glove. In other words:

$$R_{additional-hands} = R_{glove}$$

Hand to hand potentials are assessed taking into account the effect of two gloves in series, in other words:

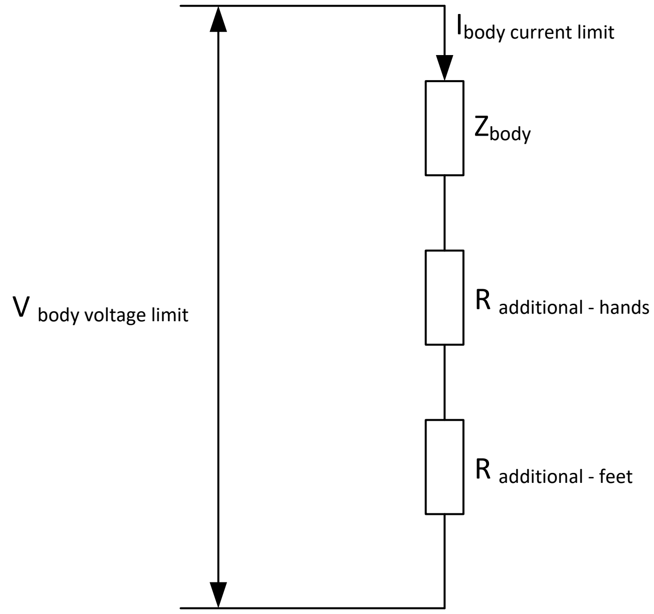
$$R_{additional-hands} = 2\ x\ R_{glove}$$

Within a WPD substation it should be assumed that gloves will not be worn.

	$R_{additional-hands}$ (Ω)
Hand to feet	0
Hand to hand	0

5.4 Calculation Of Body Voltage Limits

Consider the following diagram:



From 5.1.5 and 5.1.6

$$I_{body\ current\ limit} = \frac{Body\ Current\ Limit_{\ left\ hand\ to\ feet}}{Heart\ Current\ Factor}$$

From 5.2.3 and 5.2.4

$$Z_{body} = Body\ Impedance_{hand\ to\ hand} \times Body\ Factor$$

Therefore

$$V_{body\ voltage\ limit} = I_{body\ current\ limit} x\ [Z_{body} +\ R_{additional-hands} +\ R_{additional-feet}]$$

5.4.1 Worked Example

Consider an assessment of the permissible left hand to both feet touch voltages in a location where there is bare soil. Personnel should be assumed to be wearing good quality footwear, but no gloves.

It is apparent that:

- The Heart Factor is 1.0 (from Section 5.1.6)
- The Body Factor is 0.75 (from Section 5.2.4)
- The Additional Resistance (feet) is 2,150Ω (from Section 5.3.1)
- The Additional Resistance (hands) is 0Ω (from Section 5.3.2)

The table overleaf was constructed using the above information in conjunction with the body impedance data in Section 5.2.3

If the fault clearance time was 1,000ms then, from Sections 5.1.5 and 5.1.6, the Body Current Limit is 80mA ÷ Heart Factor = 80mA. From the table overleaf it is apparent that a body voltage of 225V equates to a current of 82.4mA. In other works, the body voltage limit (i.e. touch voltage limit) is a little under 225V.

If the fault clearance time was 500ms then, from Sections 5.1.5 and 5.1.6, the Body Current Limit is 200mA ÷ Heart Factor = 200mA. From the table overleaf it is apparent that a body voltage over 500V equates to a current of 190.9mA. In other works, the body voltage limit (i.e. touch voltage limit) is a little over 500V.

Body Voltage [A]	Body Impedance	Body Factor x Body Impedance [B]	Additional Resistance [C]	Total Resistance [D] = [B]+[C]	Body Current [A] / [D]
25 V	1750 Ω	1313 Ω	2150 Ω	3463 Ω	7.2 mA
50 V	1375 Ω	1031 Ω	2150 Ω	3181 Ω	15.7 mA
75 V	1125 Ω	844 Ω	2150 Ω	2994 Ω	25.1 mA
100 V	990 Ω	743 Ω	2150 Ω	2893 Ω	34.6 mA
125 V	900 Ω	675 Ω	2150 Ω	2825 Ω	44.2 mA
150 V	850 Ω	638 Ω	2150 Ω	2788 Ω	53.8 mA
175 V	825 Ω	619 Ω	2150 Ω	2769 Ω	63.2 mA
200 V	800 Ω	600 Ω	2150 Ω	2750 Ω	72.7 mA
225 V	775 Ω	581 Ω	2150 Ω	2731 Ω	82.4 mA
400 V	700 Ω	525 Ω	2150 Ω	2675 Ω	149.5 mA
500 V	625 Ω	469 Ω	2150 Ω	2619 Ω	190.9 mA
700 V	575 Ω	431 Ω	2150 Ω	2581 Ω	271.2 mA
1000 V	575 Ω	431 Ω	2150 Ω	2581 Ω	387.4 mA

APPENDIX A

SUPERSEDED DOCUMENTATION

This document supersedes ST: TP21A/2 (Safety Limits for Touch and Step Voltages - Earthing System Design/Assessment) dated August 2009, which has now been withdrawn.

APPENDIX B

RECORD OF COMMENT DURING CONSULTATION

No comments received.

APPENDIX C

ANCILLARY DOCUMENTATION

POL: TP21 - Fixed Earthing Systems

APPENDIX D

KEY WORDS

Earthing; Electrode; Shock; Step; Touch; Voltage