Appendix: The touch voltage concept

See also: *Touch Voltages in Electrical Installations,* B.D. Jenkins (Blackwell Science, 1993).

The object of BS 7671 includes the provision of requirements concerning protection against electric shock.

Two forms of protection against electric shock are recognized in BS 7671: the first of these is termed 'basic protection', which is protection against contact of persons or livestock with live parts and the second is 'fault protection', which is protection against contact of persons or livestock with exposed-conductive-parts made live by a fault.

The touch voltage concept is concerned with the latter form of electric shock. It is used to determine the magnitude of the voltage to which the person at risk would be subjected in the event of an earth fault occurring in an installation. By assuming values of body resistance, the touch voltage concept can be extended to give an indication of the severity of the electric shock that could be experienced by that person.

A study of the touch voltage concept, which is a very simple concept, gives the installation designer, and others concerned with electrical installations, a fuller understanding of the requirements given in BS 7671 for fault protection.

One often hears or reads the statement that provided an item of electrical equipment (intended to be earthed) is properly earthed it is not possible for a person to receive an electric shock in the event of a fault. The touch voltage concept shows such a statement to be totally incorrect.

The connection of all exposed- and extraneous-conductive-parts, either directly or indirectly, to a common terminal, i.e. the main earthing terminal of the installation, leads to the creation of touch voltages in the event of an earth fault and hence to the shock risk. In a correctly designed and erected electrical installation such a shock risk is **not** eliminated. Where the protective measure is automatic disconnection of supply then in the event of an earth fault, the speed of disconnection should be such that should the person at risk experience an electric shock it will not be a harmful one.

Figure A.1 is the basic simplified schematic diagram for a TN-S system comprising a source of energy and an installation.

- E_o = induced emf (to earth of the source), V
- Z_i = internal impedance of the source, ohm
- Z_1 = impedance of the circuit phase conductor, ohm
- Z_2 = impedance of the circuit protective conductor, ohm
- Z_3 = impedance of the supply cable protective conductor, ohm
- Z_4 = impedance of the supply cable phase conductor, ohm

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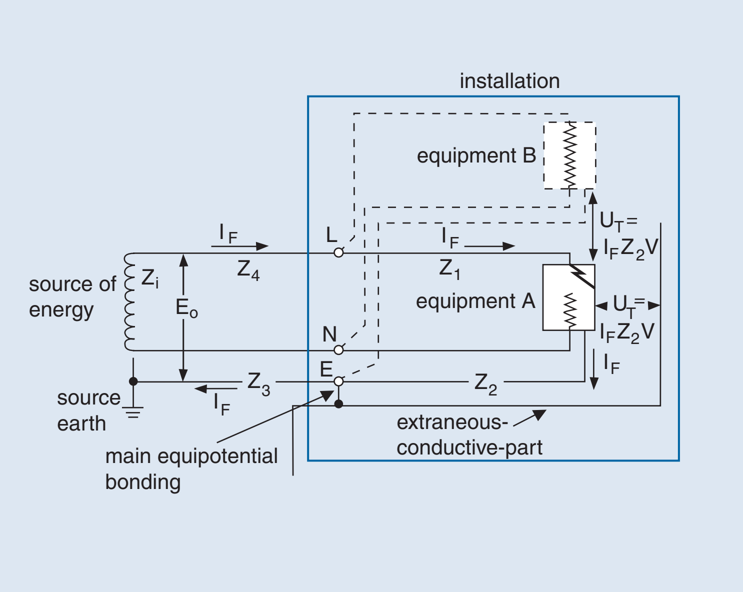

Figure A.1 Basic schematic diagram for a TN-S system showing touch voltages created by an earth fault.

As shown in Figure A.1 an earth fault has occurred in equipment A, the phase conductor coming into contact with the metallic enclosure of the equipment. The assumption is made that the fault itself is of negligible impedance and is accompanied by an open circuit in the equipment so that no part of the equipment impedance is in the earth fault loop.

The earth fault current, I_F, is given by:

$$I_F = \frac{E_o}{Z_i + Z_1 + Z_2 + Z_3 + Z_4} \text{A} = \frac{E_o}{Z_s} \text{A} \qquad (1)$$

Z_s is the earth fault loop impedance.

Now $Z_i + Z_3 + Z_4 = Z_E$, i.e. that part of Z_s which is external to the installation, so that:

$$I_F = \frac{E_o}{Z_E + Z_1 + Z_2} \text{A} \qquad (2)$$

When the circuit conductors have a cross-sectional area of less than 35 mm^2, their resistance may be used instead of their impedance and a sufficient degree of practical accuracy is obtained if U_o, the nominal voltage to earth of the supply, is used instead of E_o. Thus:

$$I_F = \frac{U_o}{Z_E + R_1 + R_2} \text{A} \qquad (3)$$

If consideration is limited to the case where the person at risk is inside the shock protection zone (i.e. the so-called equipotential zone created by the main equipotential bonding) and therefore is not directly in contact with the general mass of earth, then in the event of an earth fault as shown in Figure A.1, if the person simultaneously touches the extraneous-conductive-part and the exposed-conductive-part of the faulty equipment while the fault current is allowed to persist, he or she will be subjected to the voltage U_T. U_T is the touch voltage:

$$U_T = I_F R_2 \text{ V} = U_o \left(\frac{R_2}{Z_E + R_1 + R_2} \right) \text{V} \qquad (4)$$

'Touch voltage' is a term which does not appear in BS 7671, but the term 'Prospective Touch Voltage' is defined in the International Electrotechnical Vocabulary as 'Voltage between conductive parts when those parts are not being touched by a person or an animal'. The term is also used in BS EN 61140, 'Protection against electric shock. Common aspects for installation and equipment', in relation to protection by automatic disconnection of supply. In this Appendix the term is taken to be 'the voltage between simultaneously accessible exposed- and extraneous-conductive-parts' that may exist in the event of an earth fault.

Again for conductors of cross-sectional area not exceeding 35 mm^2, if the phase and protective conductors of a circuit are of the same material and are run over the same route:

$$\frac{R_2}{R_1} = \frac{A_1}{A_2} = m$$

where A_1 = cross-sectional area of the phase conductor, in mm^2
A_2 = cross-sectional area of the protective conductor, in mm^2
Equation 4 then becomes:

$$U_T = U_o \frac{m}{(Z_E / R_1) + 1 + m} \text{V} \qquad (5)$$

Equation 5 is, therefore, the basic touch voltage equation.

From it a number of important points emerge.

For a particular value of Z_E and of 'm', as R_1 increases, the denominator decreases so that U_T increases. In other words, for a particular circuit, the maximum touch voltage occurs when the earth fault is at the remote end (for a ring circuit, when the earth fault is at the midpoint).

For a particular value of R_1 and of 'm', as Z_E decreases, the denominator decreases so that U_T increases. In other words, for a particular circuit the touch voltage can approach but never quite reach the value obtained by putting $Z_E = 0$ in equation 5 (the basic touch voltage equation).

This gives the asymptotic value denoted here by U_A. Thus:

$$U_A = U_o \left(\frac{m}{m+1} \right) \text{V}$$

Table A.1 is based on the flat twin-core and three-core with cpc 70°C thermoplastic insulated and sheathed cables, but it is equally applicable to single-core cables.

Table A.I Values of m and U_A/U_o for flat twin cable.

Phase conductor cross-sectional area, mm²	Protective conductor cross-sectional area, mm²	m	U_A/U_o	U_A when Uo = 230 V, volts
1	1	1	0.5	115
1.5	1	1.5	0.6	138
2.5	1.5	1.67	0.625	144
4	1.5	2.67	0.728	167
6	2.5	2.4	0.706	162
10	4	2.5	0.714	164
16	6	2.67	0.728	167

Figure A.2 shows a family of curves, each curve for a particular value of m, of U_T plotted against R_1 when $U_o = 230$ V and $Z_E = 0.8$ ohm. Figure A.3 shows a family of curves, each curve for a particular value of Z_E when $U_o = 230$ V and m = 2.5 and superimposed on this family are vertical lines giving values of R_1 for different values of I_b to give a 5% voltage drop in a 230 V single-phase circuit.

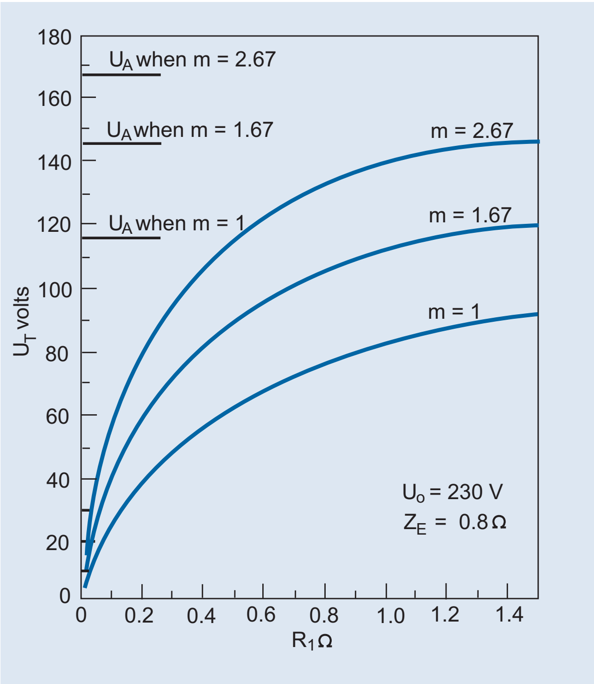

Figure A.2 Touch voltage against resistance of phase conductor (R_1) for various m values when U_o = 230 V and Z_E = 0.80 ohm.

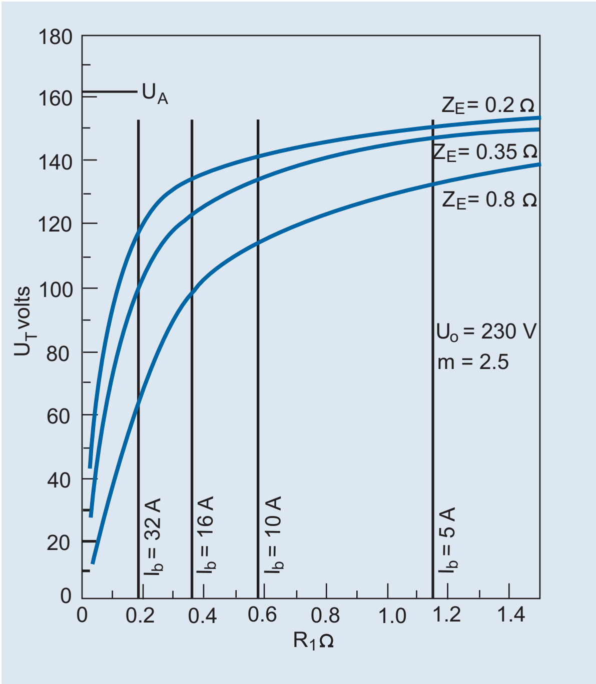

Figure A.3 Touch voltage against resistance of phase conductor (R_1) for various Z_E values when U_o = 230 V and m = 2.5. The vertical lines for various values of I_b correspond to a permitted voltage drop of 5%.

Returning for the moment to Figure A.1 it will be seen that the touch voltage, $U_T = I_F Z_2$ V also exists between the exposed conductive parts of the faulty equipment and those of the healthy equipment fed by another circuit because of the common connection of the protective conductors of both circuits to the main earthing terminal (E) of the installation.

Figure A.4 shows the schematic diagram for a multi-outlet radial circuit and the earth fault is at the remote outlet. x_1, x_2 and x_3 are the fractional distances of the protective conductor ($x_1 + x_2 + x_3 = 1$). It will be seen that touch voltages of different magnitudes exist, even between exposed conductive parts of two healthy equipments, but the maximum value occurs between the exposed-conductive-part of the faulty equipment and extraneous-conductive-parts.

Thus, in the event of an earth fault, the zone created by the main equipotential bonding is far from ‘equipotential’, hence the preference for calling the zone the ‘protected’ zone. The zone is truly equipotential only when the earth fault occurs outside the zone. When this happens the main earthing terminal will take up some potential with respect to true earth and all the exposed- and extraneous-conductive-parts will take up that potential.

Having considered the magnitude of the touch voltages occurring in an installation, at least those related to a circuit connected directly at the origin of the installation and not via, for example, a sub-distribution board, there remains the aspect of what is considered to be the time for which those touch voltages can persist without causing danger.

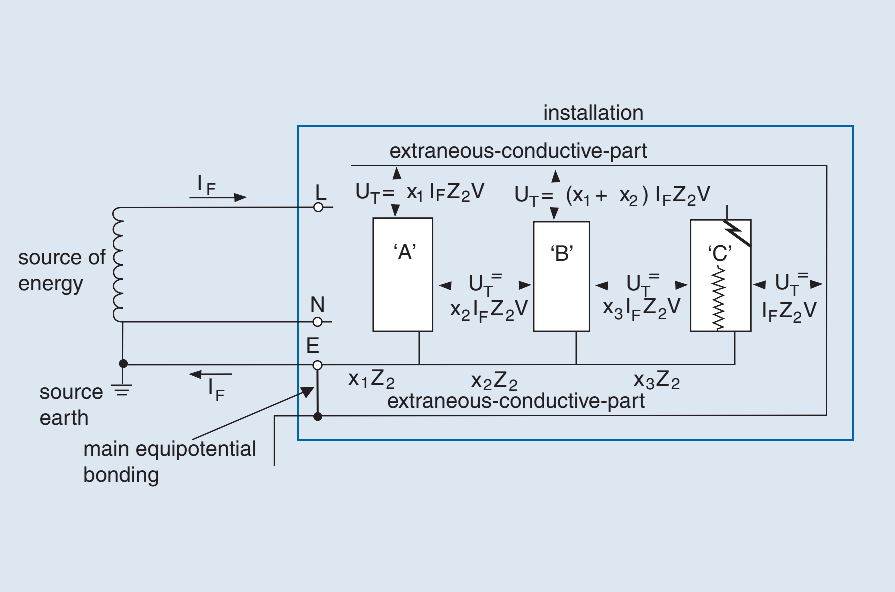

Figure A.4 Basic schematic diagram for a multi-outlet circuit in a TN–S system showing touch voltages created by an earth fault.

Based on the data given in the IEC Technical Specification 60479-1:2005 *Effects of current on human beings and livestock* – (identical to the BSI Publication DD IEC/TS 60479–1) and using certain values for the resistance of the human body, the current/time zones of that publication were translated into the two touch voltage duration curves as shown in Figure A.5 for 50 Hz a.c.

The curve L1 relates to Condition 1, defined as normally dry situations, where the surface on which the person at risk is standing presents some resistance (to the general mass of earth) and that person is assumed to have dry or moist skin.

The curve L2 relates to Condition 2, defined as wet locations, where that surface does not present any resistance and the person is assumed to have wet skin.

The international committee IEC TC 64 decided not to adopt these touch voltage duration curves into the international Chapter 41 but adopted the maximum disconnection time used in BS 7671 of 0.4 s for circuits having $U_o = 230\,V$ in TN systems.

Limiting consideration to Condition 1 it will be noted that when the touch voltage is 50 V the disconnection time can be 5 s **or greater**. In other words, if the touch voltage is 50 V or less automatic disconnection of the supply is not required from consideration of electric shock. Disconnection is required, however, from thermal considerations. This value of 50 V is known as the conventional touch voltage limit (U_L).

The earth fault loop impedance, Z_s, at the remote end of a radial circuit (or at the midpoint of a ring circuit) determines the magnitude of the earth fault current, I_F. This in turn determines the time of disconnection of the overcurrent protective device being used to provide protection against indirect contact. The maximum touch voltage which can be tolerated for that disconnection time is

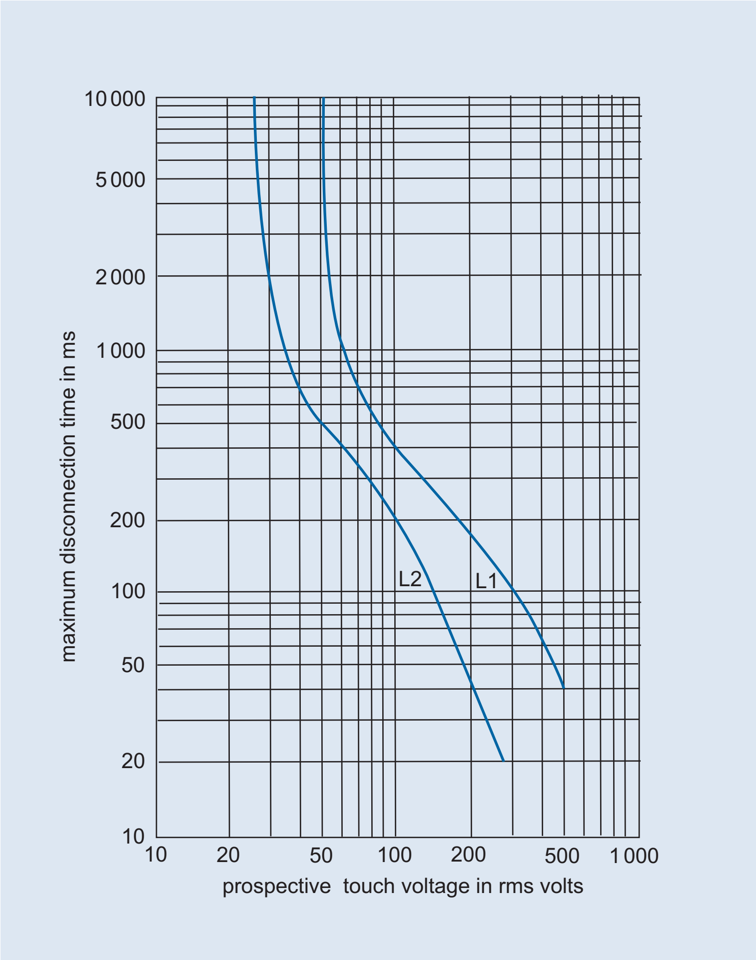

Figure A.5 Touch voltage duration curves derived from IEC Publication.

then obtained from the relevant touch voltage duration curve. It is an easy matter to check whether the resistance of the circuit protective conductor (R_2) is such that the calculated touch voltage is less.

There is, however, a very simple graphical method that can be used, developed by one of the authors of this book some years ago, which requires the production of what are called 'impedance characteristics' for fuses and miniature circuit breakers (mcbs). These are obtained in the following manner.

Figure A.6 shows the time/current characteristic for an HBC fuse and the touch voltage duration curve, but solely for the purpose of explanation the mirror image of the latter has been used.

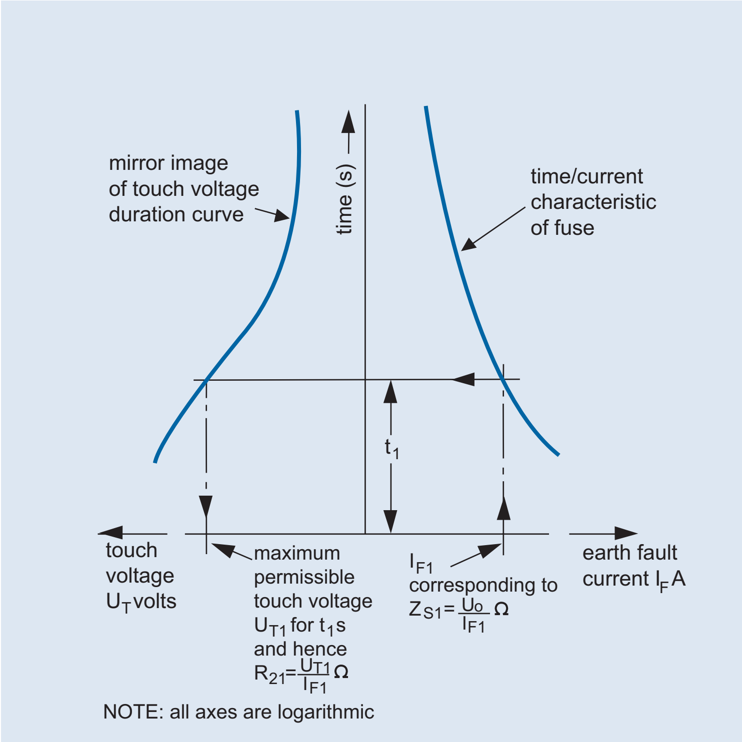

Figure A.6 Derivation of an impedance characteristic.

Take any value of earth fault current such as I_{F1}. This corresponds to an earth fault loop impedance Z_{S1} given by:

$$Z_{S1} = \frac{U_o}{I_{F1}} \text{ ohm}$$

From the time/current characteristic, obtain the corresponding disconnection time t_1. Then from the touch voltage duration curve, obtain the maximum value of the touch voltage U_{T1} which can be allowed to persist for this time t_1.

The maximum permitted value of the circuit protective conductor resistance is then given by:

$$R_{21} = \frac{U_{T1}}{I_{F1}}$$

On plain graph paper plot R_{21} against Z_S.

This procedure is then repeated for other chosen values of earth fault current.

In producing an impedance characteristic there is no point in considering values of the disconnection time t below that value on the touch voltage duration curve corresponding to U_T being equal to U_o.

For values of Z_s greater than that corresponding to a 5 s disconnection time, the maximum permissible value of R_2 is no longer dependent on the time/current characteristic of the protective device concerned but varies linearly with Z_s and is given by:

$$R_2 = \frac{U_L}{U_o} \times Z_s \text{ ohm}$$

For Condition 1, $U_L = 50\,V$ and if $U_o = 230\,V$, $R_2 = 0.217\,Z_s$.

Using the above procedure the following impedance characteristics have been developed, all for $U_o = 230\,V$ and Condition 1.

- Figure A.7 25 A BS 88 fuse
- Figure A.8 30 A BS 3036 fuse
- Figure A.9 20 A BS EN 60898 Type B mcb

When the resistance of the cpc is limited to the nadir value, R_{2N}, the 0.4 s maximum disconnection time for socket outlet circuits can be increased to 5 s. But it also means that, even if the earth fault itself has some impedance or if part of the load impedance is on the earth fault path, the circuit will still comply with the touch voltage curve.

Examination of the time/current characteristics for mcbs given in Appendix 3 of BS 7671 shows that, for a particular type and rating of mcb, the prospective currents for 0.1 s, 0.4 s and 5 s disconnection times are of one value. Thus there is no practical use of the nadir value for mcbs because the maximum permitted earth fault loop impedances for these times are of one value. In any event, the 0.1 s disconnection time is below the 0.16 s maximum allowed in the touch voltage duration curve for a touch voltage of 230 V and within the so-called equipotential zone of an installation having $U_o = 230\,V$ the touch voltage cannot, in fact, attain that value.

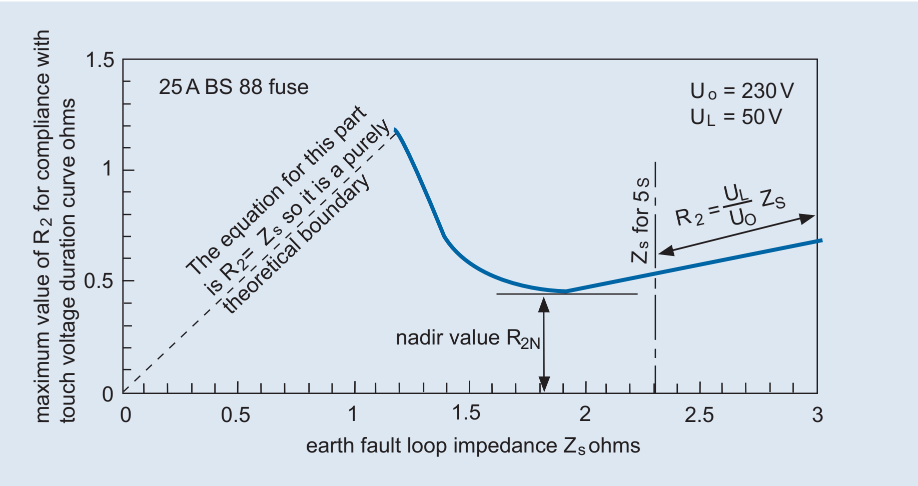

Figure A.7 Impedance characteristic for a BS 88 'gG' fuse.

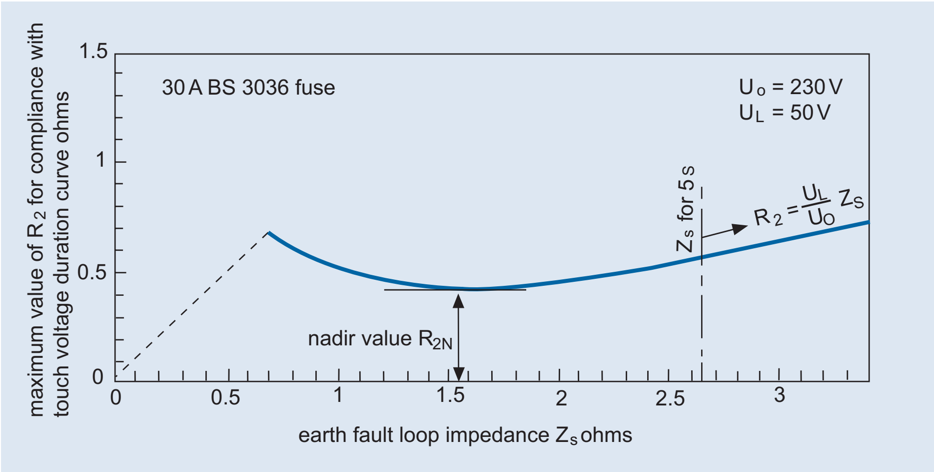

Figure A.8 Impedance characteristic for a BS 3036 semi-enclosed fuse.

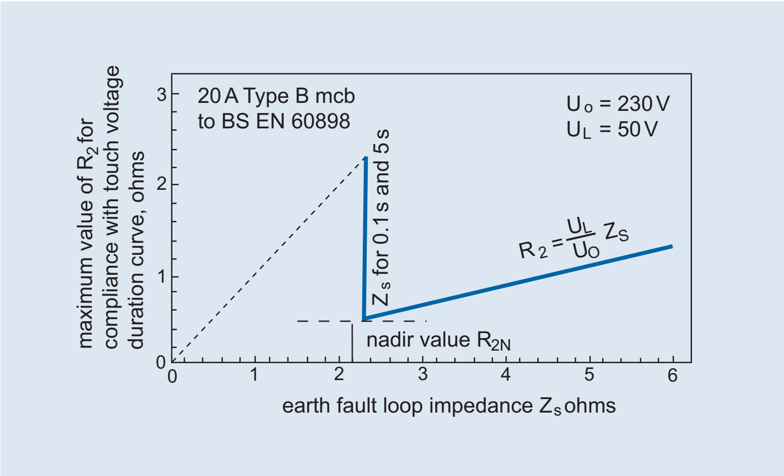

Figure A.9 Impedance characteristics for a Type B mcb.

Figures A.10 and A.11 show the two basic ways in which the impedance characteristic may be used for design purposes. Figure A.10 is used for cases where the 'm' value is known, e.g. in flat two-core and three-core thermoplastic insulated and sheathed cables. The line AB is the locus of operation and where it meets the impedance characteristic this gives the maximum value of (R_1 + R_2) that can be tolerated and this can then be translated into maximum circuit length. Figure A.11 is used for cases where Z_E and R_1 are known and one wishes to determine the maximum value of 'm' which can be tolerated, i.e. the minimum cross-sectional area for the circuit protective conductor. The line BC is the locus of operation and its point of intersection with the impedance characteristic gives the maximum tolerable value of 'm'.

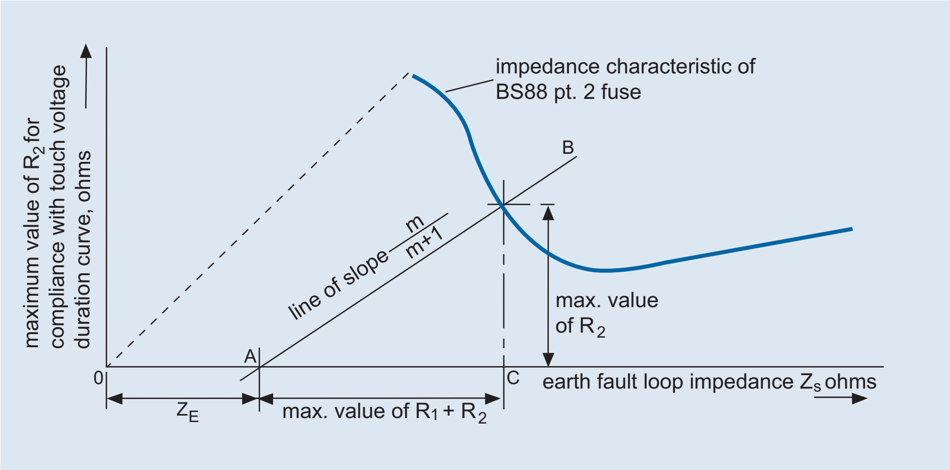

Figure A.10 Using impedance characteristic to determine maximum tolerable value of (R_1 + R_2) and R_2.

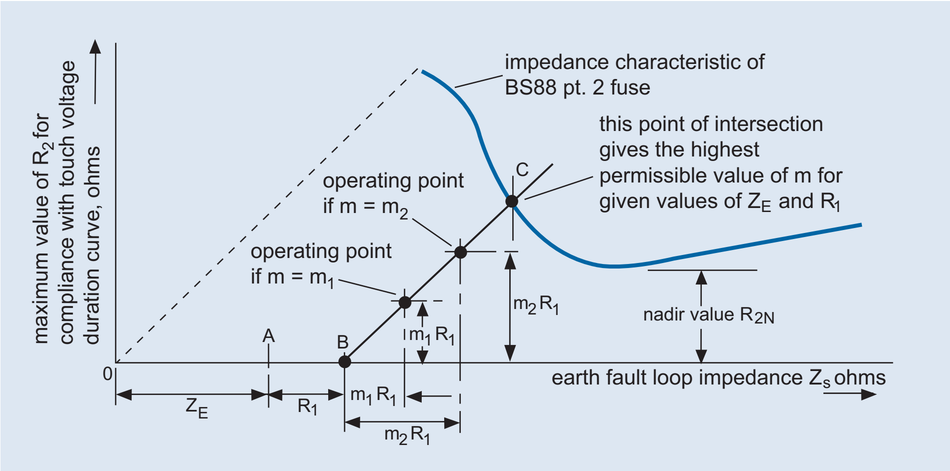

Figure A.11 Using impedance characteristic to determine maximum tolerable value of m.

It is necessary in both cases to check that the circuit meets the thermal requirements of Chapter 54 of BS 7671.

The particular advantage of using impedance characteristics is that there is no need to calculate the touch voltage as such, but various values of touch voltage can be constructed on the impedance characteristic as indicated in Figure A.12.

For a touch voltage of U_T the slope of the corresponding line is given by U_T/U_o. It would therefore seem that the impedance characteristic (and the touch voltage concept itself) could be used as a design approach and it would be practicable to check compliance by measuring Z_E and (R_1 + R_2).

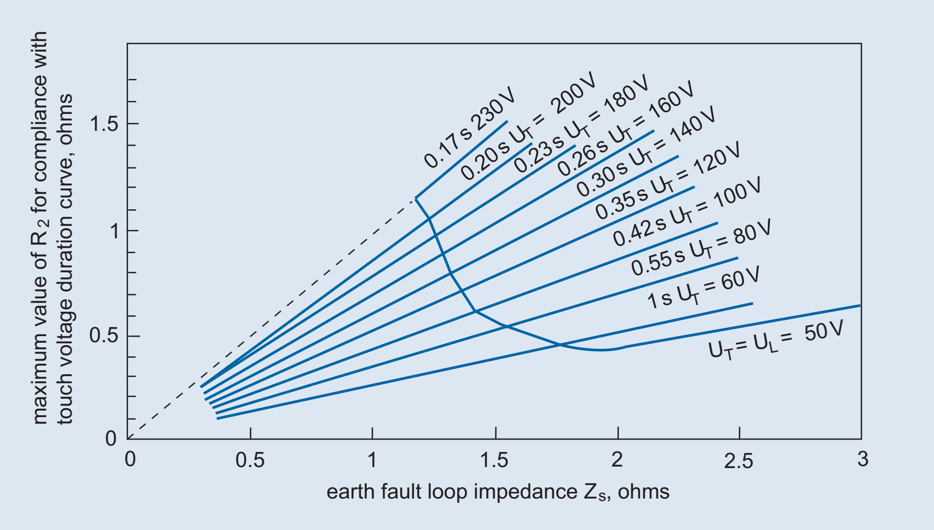

Figure A.12 Impedance characteristic and superimposed touch voltage lines.

Certainly for single-phase circuits meeting a 5% limitation in voltage drop, there is no difficulty in meeting the touch voltage duration curve and often meeting the R_{2N} limit presents no problem. For three-phase circuits compliance with the touch voltage duration curve is a little more difficult but not impossible.

In practice the problem arises because either deliberate supplementary bonding is used or there is a fortuitous contact between exposed-conductive-parts and extraneous-conductive-parts. For example, returning to Figure A.1, the exposed-conductive-parts of equipment A could be locally bonded to the extraneous-conductive-part, because the metallic enclosure of the equipment could be bolted to a stanchion or other metallic part of the building structure.

In either case the touch voltage between the exposed-conductive-parts of the faulty equipment and such parts of other circuits or extraneous-conductive-parts not associated with the local bonding is far less than the design value. As indicated in Figure A.13, the locus of operation will no longer be a straight line. As shown in Figure A.13 the design value is outside the impedance characteristic but, either because of supplementary bonding or a fortuitous earth current path, the circuit actually complies with the touch voltage duration curve. The touch voltage between the exposed-conductive-parts of the faulty equipment and the extraneous-conductive-part to which the bonding has been made will be usually very low.

All the previous comments have related to the shock risk hand-to-hand. Referring back to Figure A.1, the exposed-conductive-parts of the faulty equipment will attain a potential above that of the reference Earth. The floor on which the person is standing is considered to be an extraneous-conductive-part and that person is subjected to the shock risk hand-to-feet when he touches the exposed-conductive-parts of the faulty equipment.

The potential of those exposed-conductive-parts above the reference Earth can be taken to be $I_F(Z_2 + Z_3)$ V, but the current through the person's body hand-to-feet will now be determined by the resistance of the body, that of the floor on which the person is standing, and that of the person's footwear.

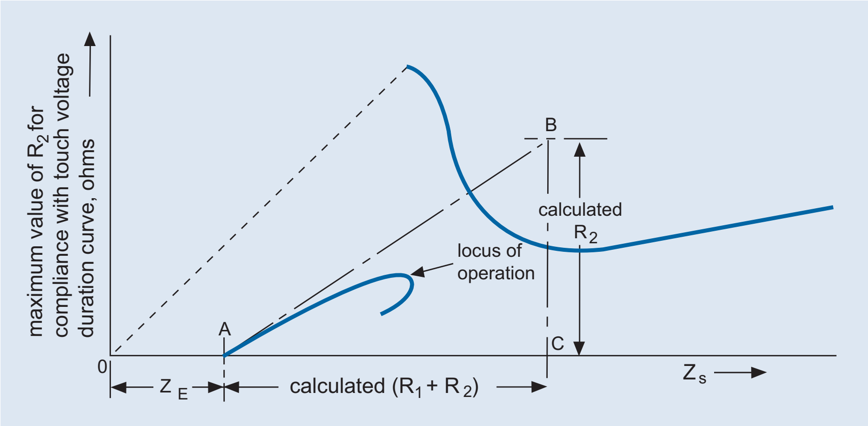

Figure A.13 Showing effect of supplementary bonding.

Finally, consider the case of final circuits fed from a sub-distribution board, as shown in Figure A.14, where R_{21} is the resistance of the protective conductor of one of the final circuits and R_{22} is the resistance of the protective conductor to the sub-distribution board.

When there is no local equipotential bonding (or fortuitous path to earth) at the board and the fault has occurred in a final circuit rated at more than 32 A, which normally has no limitation for touch voltage but should disconnect within 5 s, the touch voltage from exposed-conductive-parts of a **healthy** circuit feeding socket-outlets to the extraneous-conductive-part could be higher than the acceptable value.

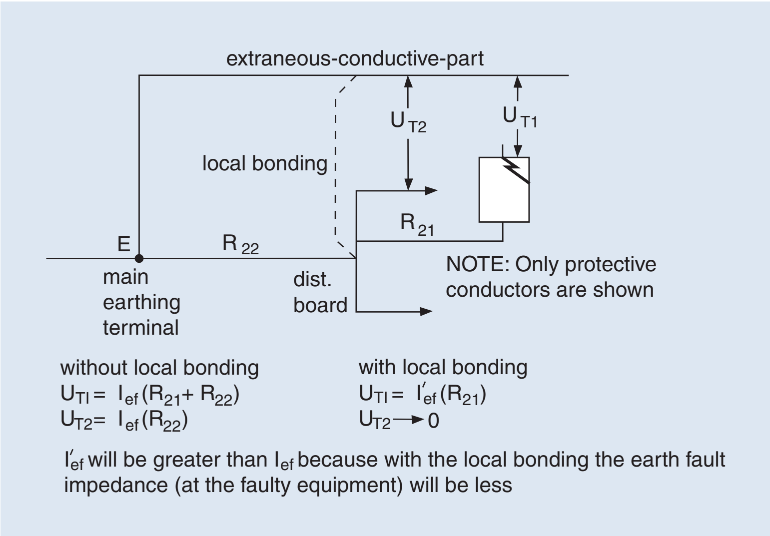

Figure A.14 Touch voltages with and without local equipotential bonding.

The treatment of touch voltage in TT systems is different to that explained for TN systems, but it is sufficient here to indicate that the touch voltage hand-to-hand in the equipotential zone created by the main bonding will be less in the former. But an installation in a TT system may be protected by only one RCD at the origin, so account has to be taken of the case where the person protected may be outside the equipotential zone.