INTRODUCTION TO ELECTRIC SHOCK PROTECTION

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ABSTRACT

This paper presents a general overview of the principles of electric shock and the systems of protection used to prevent it in electrical installations. Although mainly built around the United Kingdom Regulations, its principles can be applied to any country.

The paper first discusses electric shock and the effects of electric current on the human body. It then outlines the types of earthing systems used. This then leads to the concept of an electric fault, how it develops and how it presents a dangerous condition to people. Protective devices are used to disconnect the supply in case of an electric fault, and these are discussed next. The most used system is the "Equipotential Bonding and Automatic Disconnection of Supply" system, which is further analysed.

The paper then finishes by discussing the role of Residual Current Devices (RCD) in further electric shock protection.

1. INTRODUCTION

"Electric shock happens when the body becomes part of an energised electrical path and energy is transferred between parts of the body, or through the body to ground or the earth. In order for shock to occur, a potential difference or stored electrical charge must be present to cause the current to flow. Current flowing through the highly sensitive central nervous system can, under certain conditions, cause serious injury or death" (Casemore Electric). It is thus important to ensure that, in the event of a fault within an electrical system, adequate protection is provided for the users. We first look at the effects the electric current can have on the human body.

2. ELECTRIC CURRENT EFFECTS ON THE HUMAN BODY

In the context of discussing the protection against electric shock, it is worth highlighting the effect of the electric current on the human body. Five factors are important in understanding the risk of electrical shock:

1. The magnitude of the current.
2. The duration of the current.
3. The path it takes in the human body.
4. The resistance of the body.
5. The frequency of the electrical supply.

Table 1 shows a summary of the effects of the different magnitude of current at different frequencies and against gender.

Table 1: Effect of electric current on the human body at various levels (Dalziel, 1961).

	Current (mA)					
Effects	DC		AC 60 Hz		AC 10 kHz	
Gender	M	F	M	F	M	F
Slight sensation on hand	1	0.6	0.4	0.3	7	5
Perception threshold (median)	6.2	3.5	1.1	0.7	12	8
Shock not painful and no loss of muscular control	9	6	1.8	1.2	17	11
Painful shock and muscular control lost by ½%	62	41	9	6	55	37
Painful shock- let go threshold median	76	51	16	10.5	75	50
Painful and severe shock - breathing difficulty, muscular control lost by 99.5%	90	60	23	15	94	63

In view of the fact that the duration of the current is an important factor in the effect on the human body as much as the magnitude of the current, a better way of showing the areas of risk is to plot the zones against both magnitude and duration of current. This is shown in Figure 1, which is extracted from IEC Publication 479, 1974, Zone of effects of A.C. Currents (50 or 60 Hz) on Adult Persons.

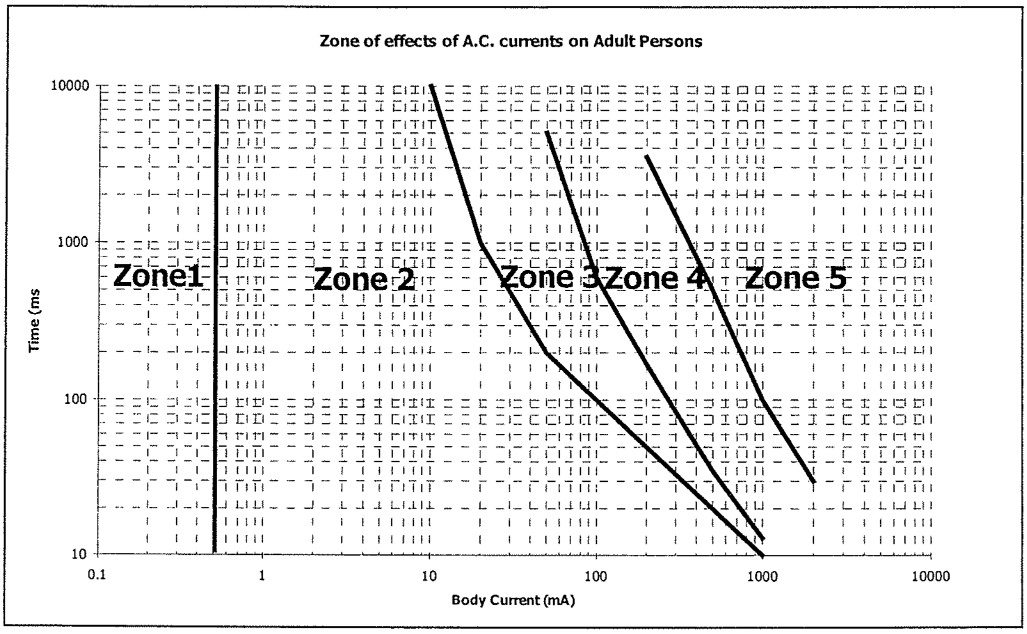

Figure 1: The various zones in relation to magnitude and duration of current (IEC 479, 1974).

The area is broken down into five zones. These zones are defined as follows:

- Zone 1: Usually no reaction effect
- Zone 2: Usually no pathophysiologically dangerous effect.
- Zone 3: Usually no danger of fibrillation.
- Zone 4: Fibrillation possible (up to 50% probability).
- Zone 5: Fibrillation danger (more than 50% probability).

This emphasises the importance of not only considering the magnitude of current during an electric shock, but also its duration. This can be clearly seen when examining the wiring regulations, as they specify disconnection time of the supply in the case of fault. The rest of this paper concentrates on the main method of preventing electric shock: Earthed equipotential bonding and automatic disconnection of the supply.

3. TYPES OF EARTHING SYSTEMS

At the heart of any system for electric shock protection is an earthing system. To provide earthing for an installation, an earthing terminal is needed. This is achieved using one of five different methods:

TN-C System: In which the neutral and the earth terminals are combined.

TN-S System: In which the neutral and earth terminals are completely separated.

TN-C-S System: In which the neutral and earth terminals and combined, but the separated just outside the consumer's installation.

TT System: In which no earth terminal is provided, but the star point of the supply is connected to the mass of the earth, and the consumer's installation is also connected to the mass of the earth. The earth at the consumer's installation is usually provided by installing local earthing systems (e.g., rods or mats).

IT System: This is similar to the TT system, with the difference that a resistor is inserted between the star point of the supply and the earth.

Examples of the TN-S, TN-C-S and TT systems are shown in Figure 2, Figure 3 and Figure 4 respectively.

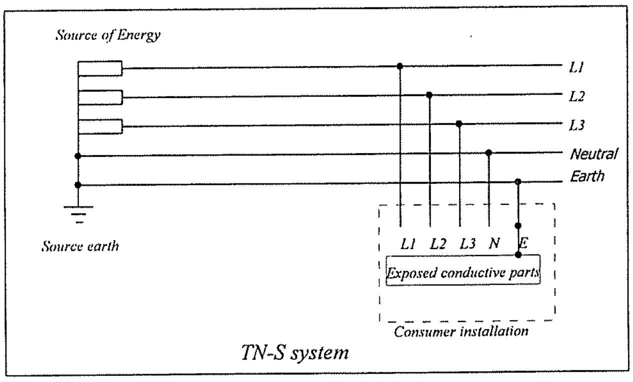

Figure 2: TN -S system of earthing.

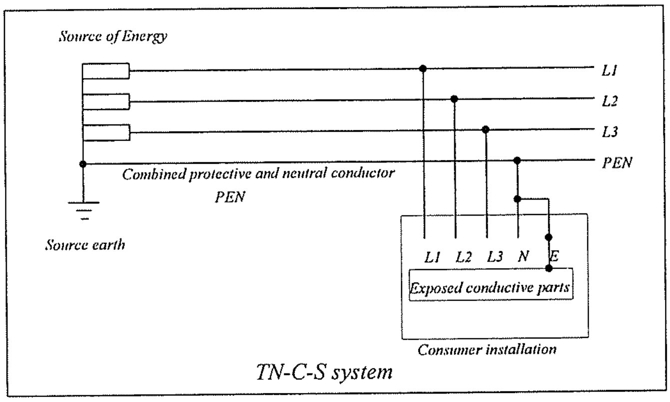

Figure 3: TN-C-S system of earthing.

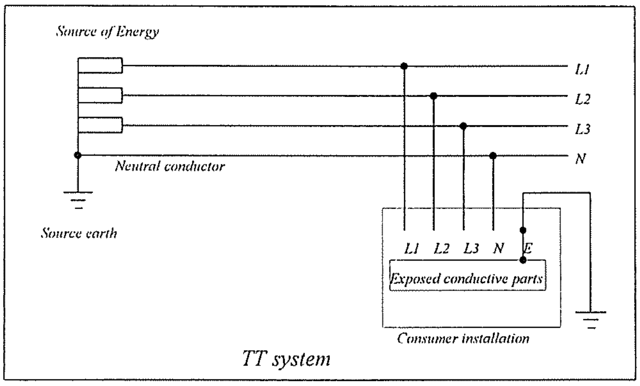

Figure 4: TT earthing system.

In a TN-C-S system, the electricity supplier will provide a combined protective and neutral conductor (PEN), which is split into a protective conductor (i.e., earth) and a neutral at the input of the installation, as shown in Figure 3.

In general we can see that the main two types of systems are the TN type systems, in which there is clear electrical path back to the star point of the energy source via the electrical cable, and the TT system, in which the mass of earth completes the path back to the star point of the electrical installation. The main difference between the two systems is in the value of the earth loop impedance (i.e., the impedance of the return path), which is higher on the TT system, compared to TN system. This affects the method of protection against electrical shock.

4. EARTHING & BONDING

Before discussing how a fault takes place and how the protection system operates, it is important to introduce the concept of earthing and bonding. An "exposed conductive part is a conductive part of equipment which can be touched and which is not a live part but which may become live under fault conditions." (P 11, 16th edition, Wiring Regulations). We say that a fault has taken place in a system if an exposed conductive part becomes live. For this reason, any exposed conductive part of the installation should be connected to earth. This ensures that a path exists for the fault current to flow, and to trip the automatic disconnection devices. However, on its own this is not enough, as another risk also exists during a fault.

An extraneous conductive part is a conductive part liable to introduce a potential, generally earth potential, and not forming part of the electrical installation. During the fault, a person touching an exposed conductive part at the same time as he/she is touching an extraneous conductive part would be exposed to a dangerous potential difference. For this reason, any metallic work which can introduce the earth potential (extraneous conductive parts, e.g., a piece of metallic pipework) should also be bonded to the incoming earth terminal. This ensures that during an electrical fault, and until automatic disconnection of the supply takes place, no dangerous difference of potential exists between the metallic piece which is connected to earth and the casing of the electrical equipment.

The conductor connecting all the exposed conductive parts to earth is called the cpc (circuit protective conductor). The conductor connecting the extraneous conductive parts to earth is called the main equipotential bonding conductor. The conductor connecting the exposed conductive parts to the extraneous conductive parts is called the supplementary bonding conductor.

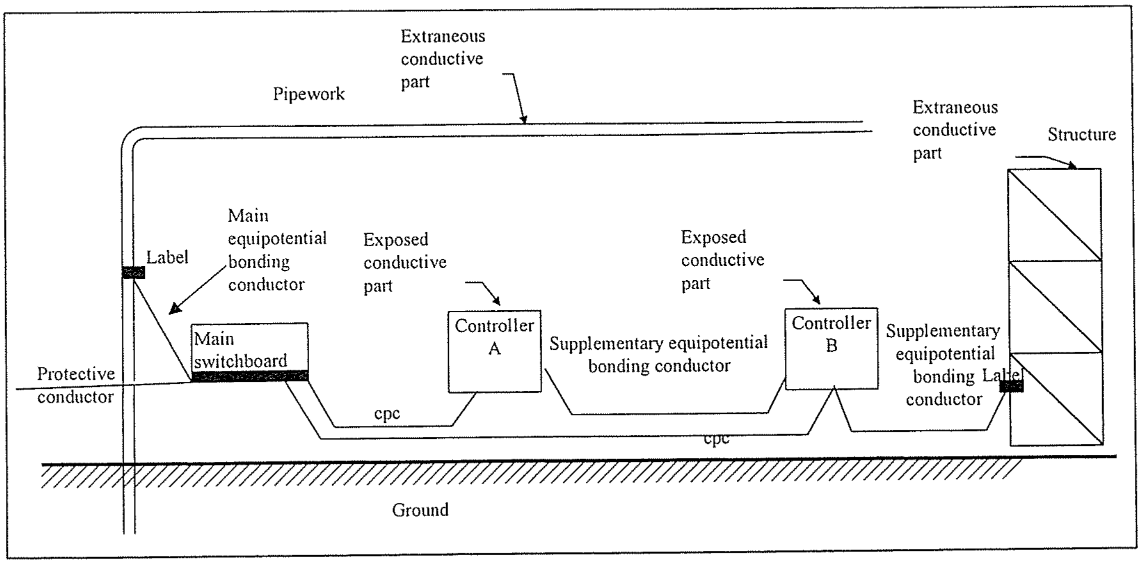

Figure 5: Diagram illustrating the concepts of equipotential bonding.

Figure 5 shows an example installation where there are two electrical controllers (e.g., controlling escalators) and a pipe and a piece of trusswork (representing extraneous conductive parts). The use of the supplementary equipotential bonding is required when the exposed conductive part and the extraneous conductive part are accessible simultaneously.

5. FAULTS CONDITIONS

As discussed in the last section, electric shock can take place if a fault develops within the electrical installation, and a person is touching the exposed metalwork of an electric appliance for example. When an earth fault takes place (i.e., a short circuit between a live conductor and the earth or the exposed conductive parts), the fault current will flow from the live conductor in the earth terminal and back to the source earth.

In a TN-C-S (Figure 6) the fault current will flow into the PEN conductor back to the source of energy. On the other hand, in a TT system (Figure 7), the fault current will flow back through the general earth path back to the source earth. This impedance is higher in value than the PEN conductor impedance.

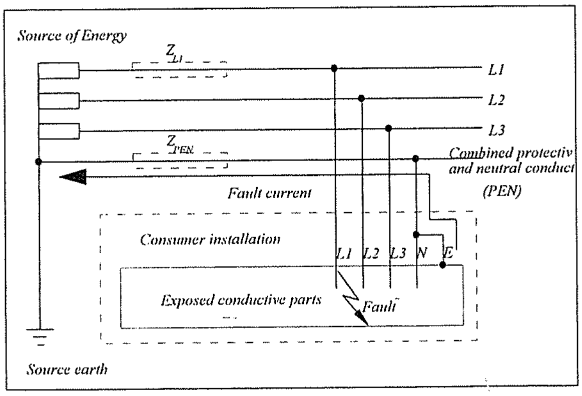

Figure 6: Fault current path in a TN-C-S system during an earth fault.

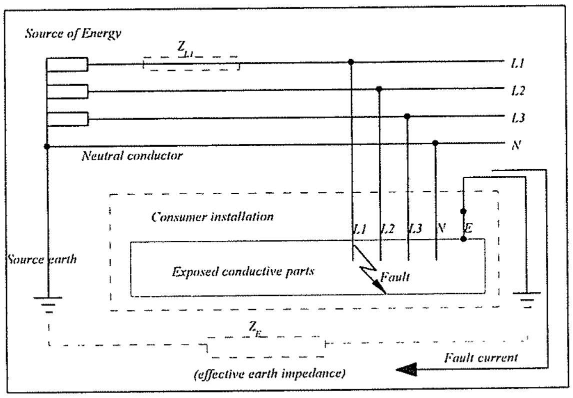

Figure 7: Fault current path in a TT system during an earth fault.

When a phase to earth fault takes place in an TN-C-S system, the value of the fault current is usually very large. This is because of the low earth loop impedance achieved through the PEN (combined protective and neutral conductor) return path. The principle of protection relies on the fact that a fault current will flow from a live conductor through the earth path, and will be of such a magnitude to trip the protection (a fuse or a circuit breaker). This removes the source of danger for the person touching the exposed conductive part. It is required that the supply be disconnected in less than 0.4 of a second. As the earth loop impedance is low in the TN system, the value of the fault current is high enough to enable the disconnection of the overcurrent devices (e.g., a fuse or a circuit breaker), which makes 0.4 second disconnection time feasible. If this disconnection time is not possible, then an upper limit of 5 seconds is allowed, provided that the touch voltage during the fault does not exceed 50 V (see next section for explanation of touch voltages).

The fault current path during a fault in a TT system is shown in Figure 7. In this case, the current flows back to the source's earth through the general mass of earth. This has a higher impedance value than that of a TN system. For these reasons the value of the fault current is smaller that the TN system, and the value of the fault current might be too small to trip the overcurrent protective device. In these cases it is recommended that an RCD is used, which can limit the value of the touch voltage to 50 V as well (this is further discussed later in the paper).

6. TOUCH VOLTAGES

During a fault, a touch voltage will develop on the exposed conductive part, which can present a hazard to a person touching the exposed conductive part.

The touch voltage is the voltage which develops during a fault on the exposed conductive part. It is this voltage that presents a hazard to the users of the system. Figure 8 shows how the touch voltage on the exposed conductive parts of equipment can be calculated during a fault for a TN-C-S system.

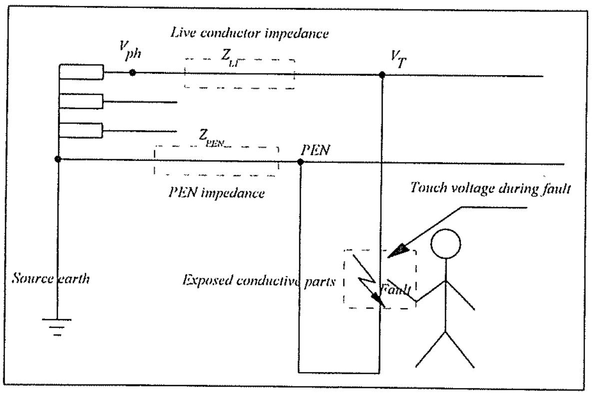

Figure 8: Touch voltage during a fault in a TN-C-S system.

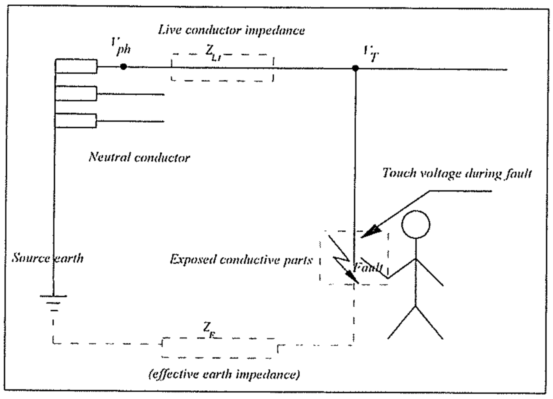

Figure 9: Touch voltage during a fault in a TT system.

The touch voltage is the effective voltage an individual will be exposed to if touching the casing of equipment. It only persists during the fault. The touch voltage during the fault is equal to:

$$V_T = V_{ph} \times \left(\frac{Z_{PEN}}{Z_{PEN} + Z_{L1}} \right)$$

Where:

V_T is the touch voltage.
V_{ph} is the value of the phase voltage (usually 220 - 240 V).
Z_{PEN} is the effective earth impedance.
Z_{L1} is the live conductor impedance to source.

As an example, if we assume that Z_{PEN} is equal to Z_{L1}, the value of V_T will 115 V (assuming a phase voltage of 230 V). If the earth loop impedance is sufficiently low, the value of fault current would be large to allow the automatic disconnection devices (e.g., fuses or circuit breakers) in less than 0.4 of a second. As mentioned in the last section, if the value of the fault current is not sufficient to trip the protection device in 0.4 seconds, then an upper limit of 5 seconds is allowed, provided the touch voltage is limited to 50 V. This in practice means that a larger circuit protective conductor has to be used, to provide a lower earth loop impedance.

Figure 9 shows the touch voltage calculation in a TT system under fault conditions. Again, the touch voltage during the fault is equal to:

$$V_T = V_{ph} \times \left(\frac{Z_E}{Z_E + Z_{L1}} \right)$$

Where:

V_T is the touch voltage.
V_{ph} is the value of the phase voltage (usually 220 - 240 V).
Z_E is the effective earth impedance.
Z_{L1} is the live conductor impedance to source.

As mentioned earlier, it is generally not possible to have a large fault current which can trip the protection devices. For these reasons, a residual current device is usually used to protect a TT installation, as discussed in the next section.

7. USE OF AN RCD IN A TT SYSTEM

Due to the larger value of earth loop impedance in a TT system, the fault current is smaller. This causes the problem that it is not possible to disconnect in less that 0.4 seconds. For this reason, disconnection time of 5 seconds is allowed, provided that the touch voltage during the fault does not exceed 50 V. This protection, can either be achieved by using an overcurrent protective device or a residual current device (the later being the preferred option).

The IEE Wiring Regulations requirement regarding the TT system is regulation number 413-02-20

"The following condition shall be fulfilled for each circuit: $R_A \times I_a \leq 50V$*, where:*
R_A is the sum of the resistances of the earth electrode and the protective conductor(s) connecting it to the exposed-conductive part.
I_a is the current causing the automatic operation of the protective device within 5 s;
When the protective device is a residual current device, Ia is the rated residual operating current $I_{\Delta n}$."

It is important to note, that even if a fault does not exist, modern equipment does draw leakage currents. These current should be limited in value. Otherwise, they can also raise the value of the touch voltage. For these reasons, using an RCD device to protect a TT system, can offer protection in the case of a fault current, as well as when the system is drawing excessive leakage currents.

8. CONCLUSIONS

The electric current can have fatal effects on the human body. The severity of shock depends on a number of factors: Size of electric current flowing in the body; resistance of the body; path taken by the current; duration of the current; and the frequency of the electrical supply.

The main method of protecting from electric shock is the use of the principle of earthed equipotential bonding and automatic disconnection of the supply. There are five types of earthing systems: TN-S, TN-C, TN-C-S, TT and IT.

The main difference between the TN systems and the TT system, is the higher value of the effective earth impedance as compared to the PEN conductor impedance. This has the effect that the value of the fault current becomes smaller (as it is faced by a larger earth loop impedance). This makes it difficult to disconnect the supply within 0.4 of a second using automatic protection devices (e.g., fuses or circuit breakers) and a more realistic time is 5 seconds.

It was shown how touch voltages develop and how they can be calculated. When the disconnection time of 0.4 seconds cannot be achieved, the value of the touch voltage must be limited to 50 V.

AUTOBIOGRAPHICAL NOTES

The author graduated in Electrical Engineering in 1987, and worked for two years as an electrical and electronic lift systems design engineer. He received his M.Sc. in Remote Lift Monitoring in 1990, and his Ph.D. in Artificial Intelligence Applications in 1992 from UMIST (Manchester, U.K.). He was then appointed as Senior Electrical Engineer for Lifts & Escalator at London Underground, and is still working for London Underground, currently as Team Delivery Manager in the Station Systems Area. He is also a Corporate Member of the IEE and a Chartered Electrical Engineer.

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