Broken Earth Neutral faults in distribution systems with Traffic Signal loads.

Recent issues with PME supply systems could have a maintenance legacy for street equipment such as traffic signals.

As an electrical design engineer I have to work closely with my electricity provider. What they offer in the way of an earthing arrangement will greatly affect my design, and whether or not I will need to use a Residual Current Device (RCD) for earth fault protection. For traffic signals I would rather not use an RCD but what I put on the street must be safe.

If I provided a RCD for every traffic signal site I designed this would amount to a huge maintenance legacy. Could this be avoided? Well, yes, providing the electricity provider, also known as the Distribution Network Operator (DNO) can provide a good earth system such as a Protective Multiple Earth (PME) system sometimes referred to as TN-C-S. However, lately there has been a shift away from offering PME systems to street equipment particularly with a connected load of 2kW or more. This is due to a specific fault that might occur with a damaged DNO supply cable. For traffic signal installations could intelligent traffic signal controllers be the answer?

Introduction

We take electricity for granted. Most of us know there are three pins to be found on a typical BS1363 plug used for an electrical appliance and most people are aware of the terms live, neutral and earth, the earth connection being important for safety. The earth connection ensures the metalwork of an electrical system cannot become live giving rise to danger and thus an electric shock.

Just how does the electrical supply industry provide us, the consumer, with an earth connection? To answer this we need to look back at the history of electricity and then understand how it evolved into the system we now use.

The Background

The idea of a standardised electrical system was first put forward by Charles Merz in 1916, and this eventually lead to the 1926 Electricity Act and the setting up of a national grid for distribution throughout the UK. However, at consumer level the voltages and systems still varied, with both alternating current and direct current systems in common use and the voltage typically around 250v. It would take several more years before we eventually arrived at the standardised system of 230/400volt alternating current using 2/3/4wires for connection. For traffic signals we need only consider the use of a 230volt a.c. 2 wire system see **fig 1**. That is to say 230volt alternating current being supplied using 2 wires, the Live or line as it is now known and a neutral, plus a suitable earthing system.

Local distribution in our towns and countryside normally uses an 11,000volts system which is fed into a substation (**See fig 1**) here, it is then converted or transformed down to a useable voltage. This is our standardised 230volt single phase service or 400volt three phase system which is more commonly associated with industrial and large commercial premises. It is at the substation that the opportunity is taken to reference (connect electrically) one leg of the supply to Earth. Staying relative to traffic signals which only require a single phase, 230volt supply, this is derived from the transformer output by connection to two of the supply wires. One of these two connections from the sub station transformer is connected to Earth and is now referred to as a neutral conductor while the other is referred to as the live or line conductor. Naturally the live conductor is now at 230volt potential difference to both the earth and the neutral.

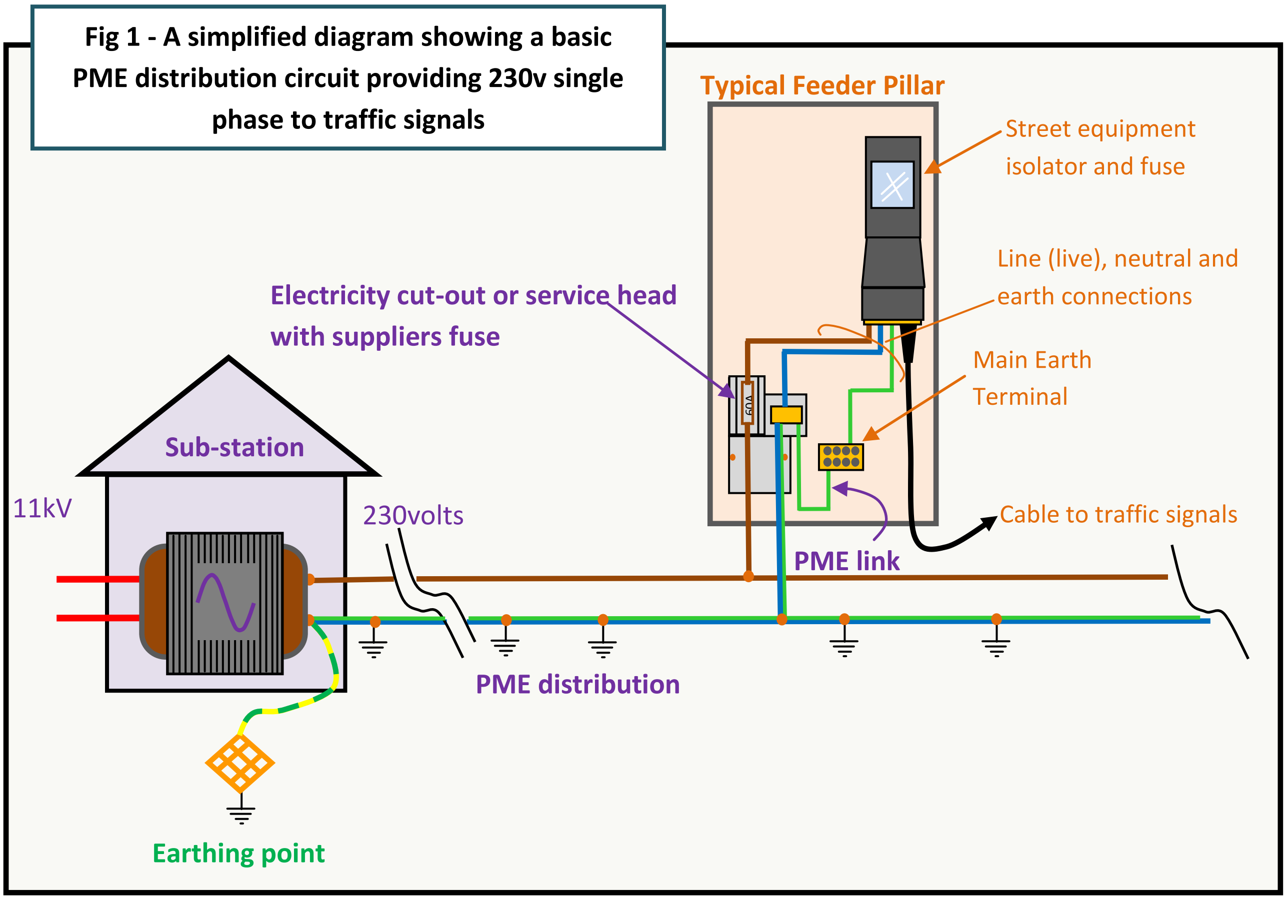


Fig 1 - A simplified diagram showing a basic PME distribution circuit providing 230v single phase to traffic signals

This simply means that connecting one of the transformers output wires to Earth not only gives us a protective system which we commonly call earth but also provides the other connection as a line or live connection. This makes things simple as any fuse or protective device is only required to be placed in the Line or Live wire of the circuit. Another advantage is as long as any protective devices such as circuit breakers, fuses and switches are placed in the line (live) conductor then the circuit will be deemed safe whenever the line (live) conductor is switched (disconnected). Also, in the event of a fault, that is a short circuit to earth and/or neutral, the protective device will automatically operate rendering the circuit safe simply by having disconnected the line (live) conductor. This is one of the basic methods of protection given in the IET regs BS7671:2008 – everything earthed and correct use of automatic protective devices.

So, one element of a good design is fulfilled by ensuring all metalwork associated with the installation is properly connected together and bonded to earth. The earthing system needs to be capable of passing the short circuit current safely without causing damage or causing harm to persons or livestock. This not only means being able to withstand the high currents that may flow during these faults but also ensuring any voltage that may exist in earthed metalwork etc remains low enough not to be harmful. A good system means all metal work being securely connected together and a good connection to Earth, such as offered by the PME system.

However, it would seem changes are ahead of us. The PME earth system is now seen as risky in which case the DNO will force the customer to use Terra Terra (TT) system and thus use an RCD. The use of RCD’s could result in less reliable electrical systems. This might not matter for illuminated advertising or bus stops etc but for traffic signals this might be considered risky. As with most engineering there is a balance to be had and in this case it is the very unlikely occurrence of a person receiving a shock verses possible accidents due to the traffic signals being out. Consideration must be given to which of these two incidents is most likely to occur.

The designer needs to take all this in to consideration. Where traffic signals are in abundance RCD’s could, not only be very expensive maintenance wise, but also be a significant hazard for, when traffic signals are out problems soon start to occur for traffic trying to use busy intersections and/or not to mention the pedestrians trying to cross the road. People soon become impatient and so the less time traffic signals are out the better for all users. RCD’s are brilliant devices but can trip all too easily leaving a critical junction to fend for itsself. Additionally, the RCD will need to be tested regularly, say once a year. While the test doesn’t take too long, the load, namely the traffic signals, will have to be isolated while the testing takes place resulting in more down time.

The PME Issue

The distribution of electricity in towns and cities is complex; however, the service generally comes with a reliable earth connection unlike those in more rural districts where the customers are often required to provide their own connection to the ground in order to get an earth connection. This earth system is referred to as TT. Meaning there is an earth electrode connection at the substation and another at the customer's premises but no direct connection via a cable. Consequently, the TT system tends not to perform as well as a system where the earth connection is derived via the DNO's cables. In this case the designer will use a RCD for protection against faults to earth whereas a fuse or Miniature Circuit Breaker (MCB) may have been acceptable in the PME (TN-C-S) system.

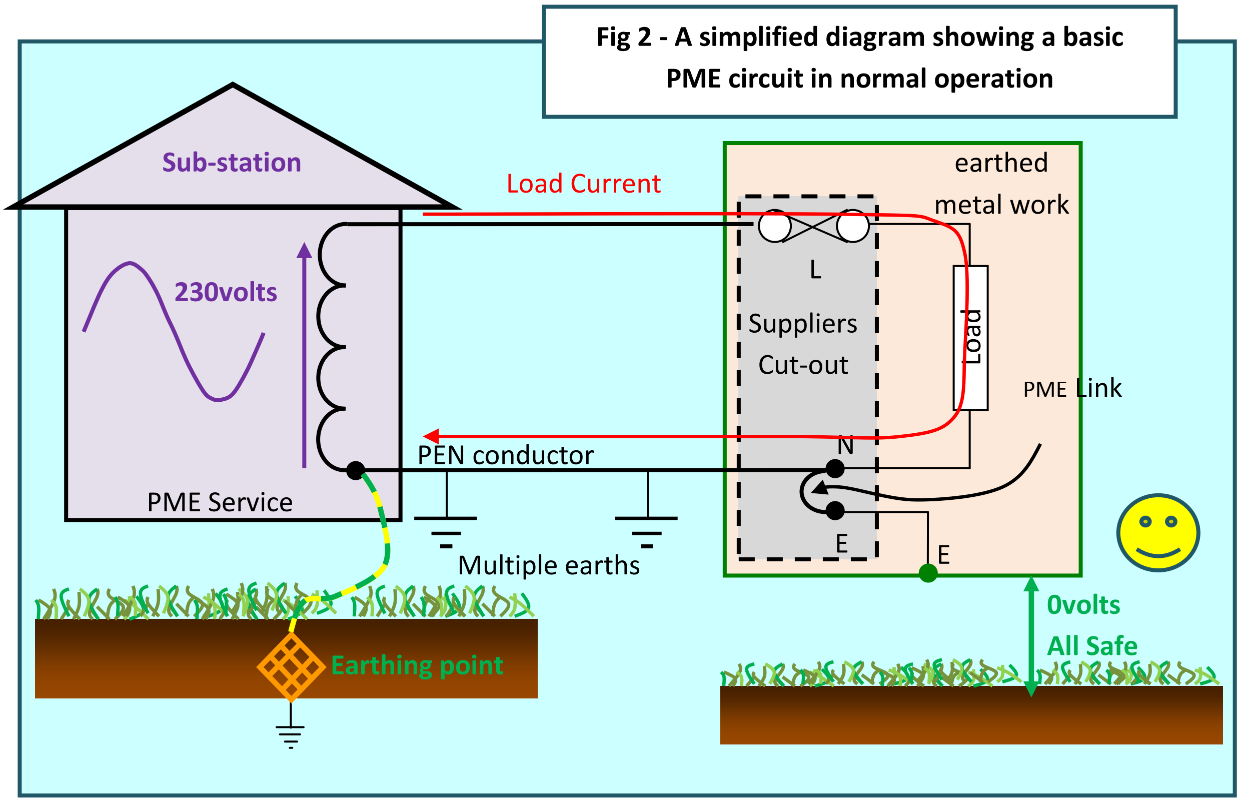


Fig 2 - A simplified diagram showing a basic PME circuit in normal operation

RCD's are very good at detecting leakage currents to earth but are, unfortunately, unforgiving with stray currents caused by say, electronic equipment incorporating filters, or even those caused by maintenance personnel connecting test equipment. Naturally this depends on the type of RCD device selected, for example, a 30mA device will trip more easily than say a 300mA and again careful good design must prevail.

As mentioned, earthing in towns and cities is normally provided by using the PME system. The distribution cable being of a special design and consists of three line conductors, (one for each of the three phases) surrounded by the protective earth neutral on the outside. This is referred to as a Protective Earth Neutral (PEN) conductor. It has been common practice for a number of years to use this combined neutral and earth system along with its multiple earthing points as a means of supplying electricity to customers. It was deemed to be not only cost effective, but better and safer than having a cable with separate earth and neutral conductors. This gave rise to the popularity of the PME system. This is also referred to as TN-C-S, meaning Terra (earth) and neutral connected at the sub-station (TN) and then combined (C) together in the supply cable (this is the PEN conductor) to the customer where the earth and neutral are then separated (S). Multiple earth because the PEN conductor is connected to Earth at regular points along the length of the cable **Fig 2**. Thus the PME system became widely adopted by the UK. However, now, the PME system is being viewed as risky and particularly where the customer is using electricity on the street, for surrounding the installation is a large conductive area, open to the elements and often wet with rainfall, a very risky environment.

The PME risk increases with large loads exceeding 2000 watts (2kW). These loads are not seen as safe for connection to a PME system in the street environment. The reason being is that it is a risk within the supply network itself. There is now a danger that all earthed metalwork associated with a PME services could become “live” if there is a damaged or disconnected PEN conductor in the supply cable.

Normal operation

In normal operation, the current drawn by the load returns back to the source transformer via the installation neutral conductors and then via the PEN conductor in the distribution network’s PME cable. See load current in **Fig 2**.

An earth fault current will return to the source transformer in a similar way using the customer’s earth conductors, then by way of passing through the PME link to the PEN, conductor. This has the advantage of providing low earth loop impedance, that is to say the resistance in the circuit is low which ensures a high fault current which, in turn is important for operating the fuse or MCB and removing the danger quickly (automatic disconnection).

The Culprit

So, it can be seen that the distribution network’s PEN conductor along with its multiple earth points is paramount to safe operation of equipment and circuits within the customers’ installation. However, it cannot be ignored that if the PEN conductor did become broken somewhere between the customers installation and the last reliable earthing point any earthed metal work could be live. This may sound strange at first but studying the diagram **Fig 3** it can be seen the culprit is the link between neutral and earth, the PME link. Consider that in basic circuit theory if no current flows then no voltage can be dropped or lost across the load and therefore the supply voltage will be found to exist on the neutral side of the load as well as on the live/line side. Now consider, the neutral conductor is also connected to earth via the

PME link and so the supply voltage that is on neutral will now appear on everything that is connected to it including all items that are “earthed”.
It therefore follows that a person in contact with true Earth could experience a shock of some severity. **Fig 3**

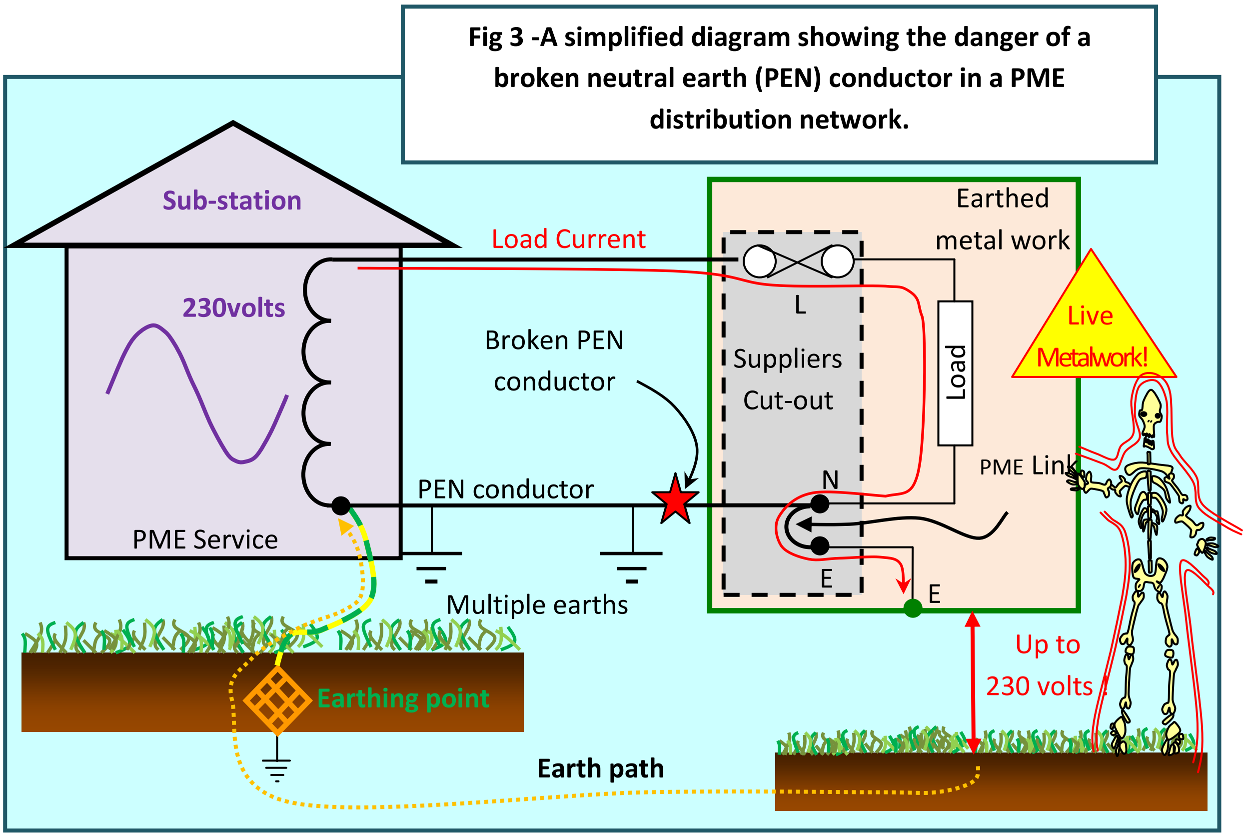


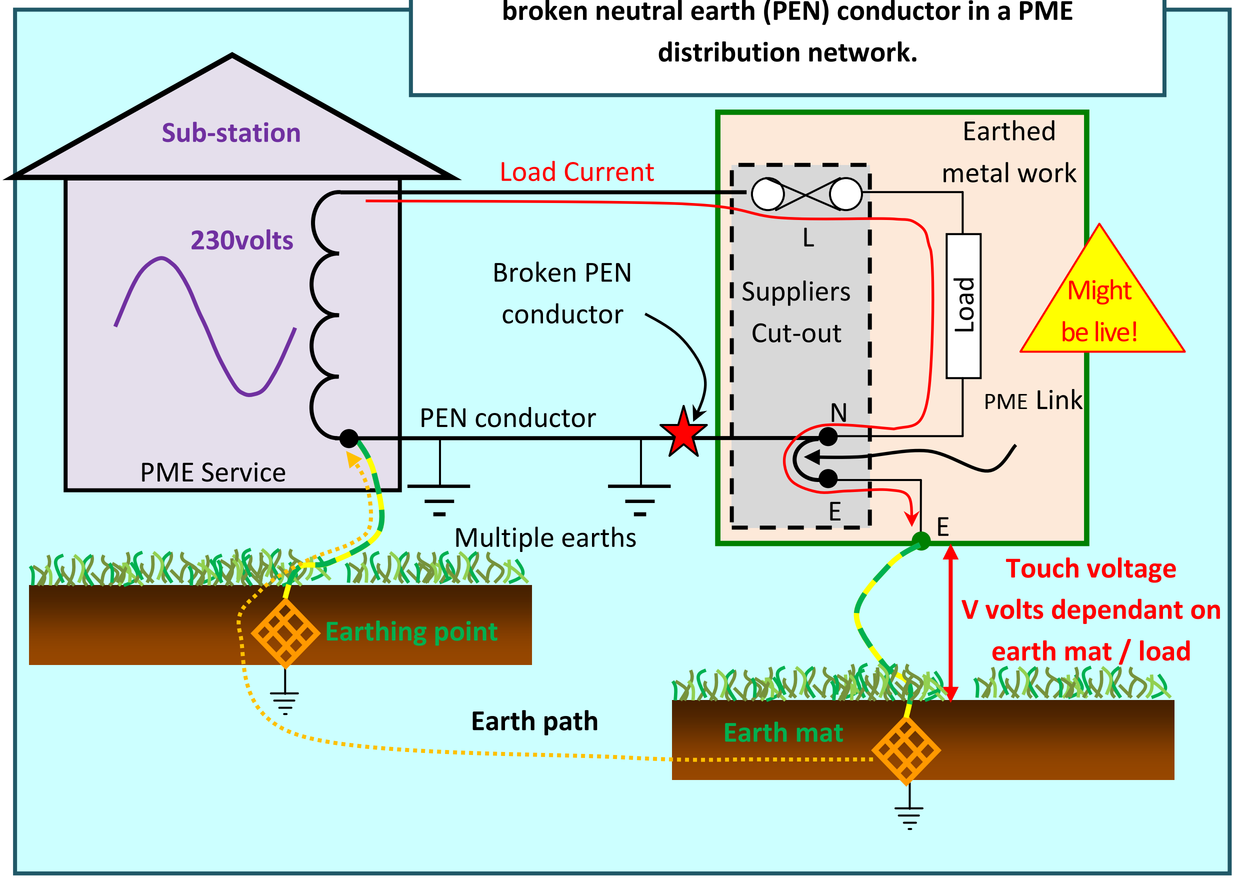
Fig 3 -A simplified diagram showing the danger of a broken neutral earth (PEN) conductor in a PME distribution network.

In order to try and control this risk Earth mats can be fitted at the feeder pillar location and act as a supplementary connection with the ground, or true Earth as it was referred to above. The Earth mat is an earth electrode consisting of a lattice of copper conductors planted in the soil. All Earth electrodes will exhibit some resistance in their contact with the ground. This is dependant on many factors such as the soil resistivity, dampness of the soil the size of the electrode to name a few. The ideal resistance should be just a few ohms. **Fig 4.**

A brief evaluation was to show earth mat resistances varied enormously through out London and there was no way of predicting the likely result. This is partly due to the type of soil encountered and partly due to depth. Don’t forget, as with most urban centres, London is mostly paved over and so the soil is extremely dry. Depth will improve performance but it is difficult to excavate a deep hole economically in a city particularly with so many other utilities etc present. Driving in earth rods can be dismissed, being considered too risky, hence a lattice copper earth mat is used measuring 500mm x 500mm. This is bedded in with the surrounding ground using a conductive backfill which gives around a 30% better reading than would have otherwise been achieved. Generally sites varied from a few ohms to 50ohms or more. Additionally, there is the earthing via the poles and roots of cabinets which is not a recognised method but they do perform rather well. Adding this into the equation would practically halve a typical earthing for a site bringing it close in line with 20ohms and normally well below 100ohms which is considered acceptable (based on G12/3 table 6.2.15). In any case this was better than doing nothing and given this was to act as damage limitation, in the event the DNO did have this type of fault occur which seems to be quite rare, seemed a reasonable way forward.

The object of achieving 20 Ohm resistance at the electrode seems to be based on an old guidance of having a maximum 2kW load with a 20ohm earth electrode. This would limit the touch voltage in the event of a broken PEN conductor to about 100volts between true earth and the metalwork in the affected earth system see **fig 4**. This is commonly referred to as touch voltage; the voltage a person might feel if they simply touched any earthed metalwork associated with a defective PEN conductor. This principle now appears in to ENA G12/3

Fig 4 -A simplified diagram showing the danger of a broken neutral earth (PEN) conductor in a PME distribution network.



The Touch voltage

To explain how this works we need to consider how the current flows through the load and passes back to the substation via Earth. In a simplified circuit, we are now looking at the load resistance (traffic signals in this case) being in series with the Earth electrode resistance. In any series circuit the supply voltage will be partly lost across each of the resistances, which in this case the load is one and the other is the earth electrode. **Fig 5**.

A simplified way of looking at this would be to consider the arrow diagram where the length of the arrow represents the magnitude of the voltages across each resistor. If a 130volts is lost across the 2kw load that would leave 100volts remaining across the resistance of the earth mat hence this is the touch voltage. **Fig 5**.

This can be shown using simple Ohms law thus...

Ohms Law... $V = I \times R$

If the resistance of a typical 2kw load is taken as say 26 ohms

And the resistance of the earth is taken as 20 ohms

The combined resistance of the circuit equals 46 ohms

The current that will flow is thus...

$$I = \frac{V}{R} \qquad I = \frac{230}{46}$$

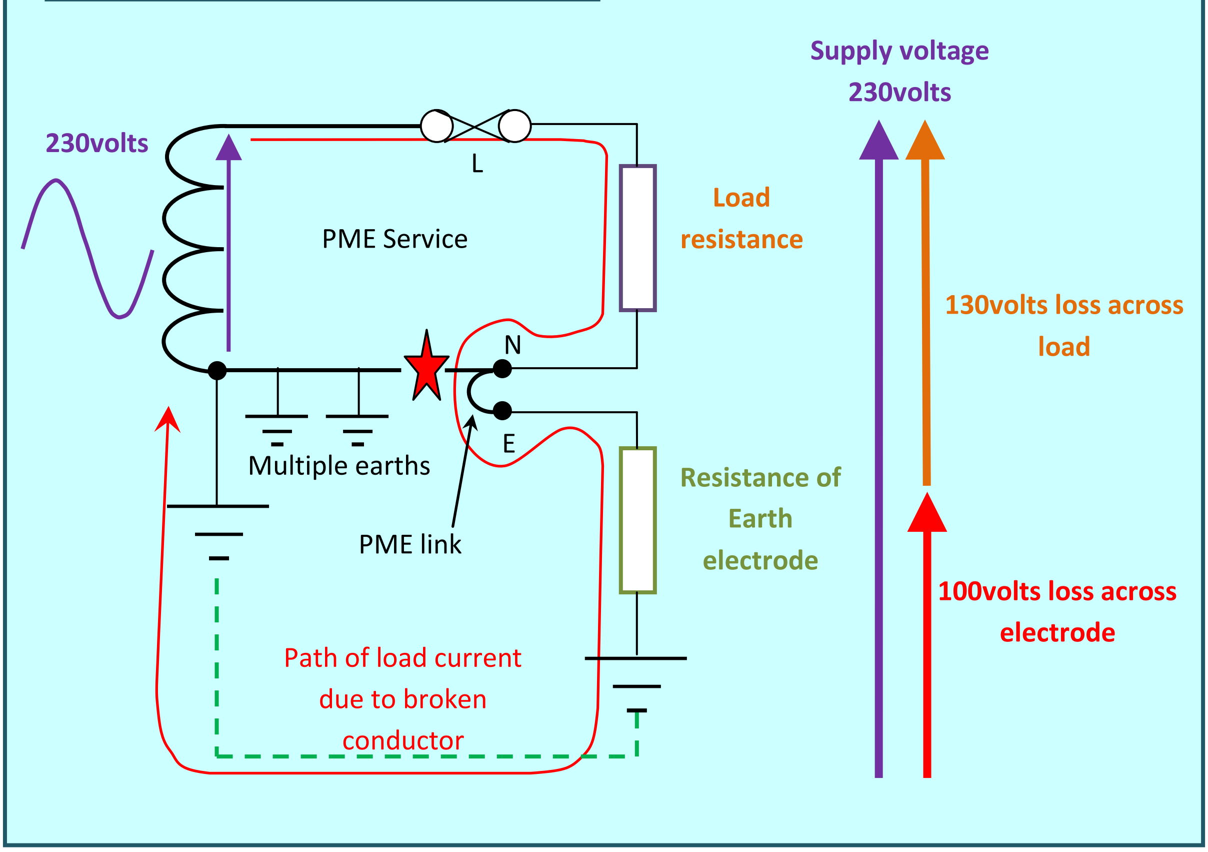
$$I = 5\text{amps}$$

The touch voltage will be the voltage that appears across the Earth electrode and on all bonded metalwork is therefore..

$$V = I \times R \qquad V = 5 \times 20$$

$$V = \underline{100\text{volts}}$$

Fig 5 - Diagram showing the path of the load current and the corresponding voltage on earthed metalwork.



This explains the reasoning behind having a 2kW load operating with a 20 ohm (max) Earth electrode. However, what happens if either the load or the Earth electrode resistances are varied?

Starting with the Earth electrode; consider the load remaining at 26 ohms (roughly the resistance of a 2kW load) and as the resistance of the Earth electrode approaches 0 ohms so the voltage dropped across it approaches 0 volts. This means the touch voltage is becoming less dangerous **Fig 6.**

Conversely, if the Earth mat resistance increases above 100ohms then the touch voltage increases towards the supply voltage 230volts. **Fig 7.**

Now, let's consider variations in the load resistance. Consider the Earth electrode remaining at 100 ohms and the resistance of the load decreasing due to having a larger connected load, an increase in kW. As this resistance approaches 0 ohms so the voltage dropped across the connected load decreases and this means the remaining voltage, the touch voltage, is becoming dangerously high. **Fig 7.** That is to say it increases towards becoming the same magnitude as that of the supply voltage, 230volts.

Alternatively if the connected load is reduced which corresponds to increasing the resistance of the load then the touch voltage will become less dangerous. This is because the bulk of the 230volt supply voltage is dropped across the load and the remaining voltage is the touch voltage to be found on the earth metal parts. **Fig 6.**

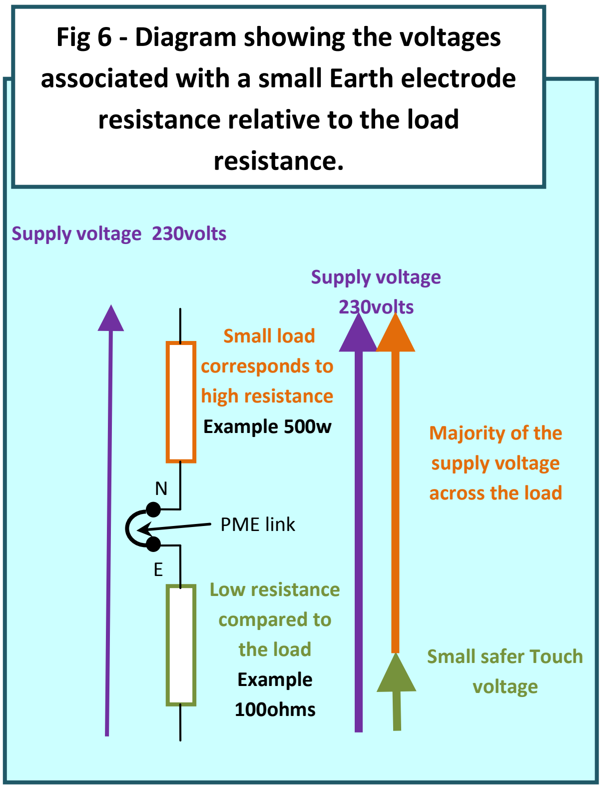


Fig 6 - Diagram showing the voltages associated with a small Earth electrode resistance relative to the load resistance.

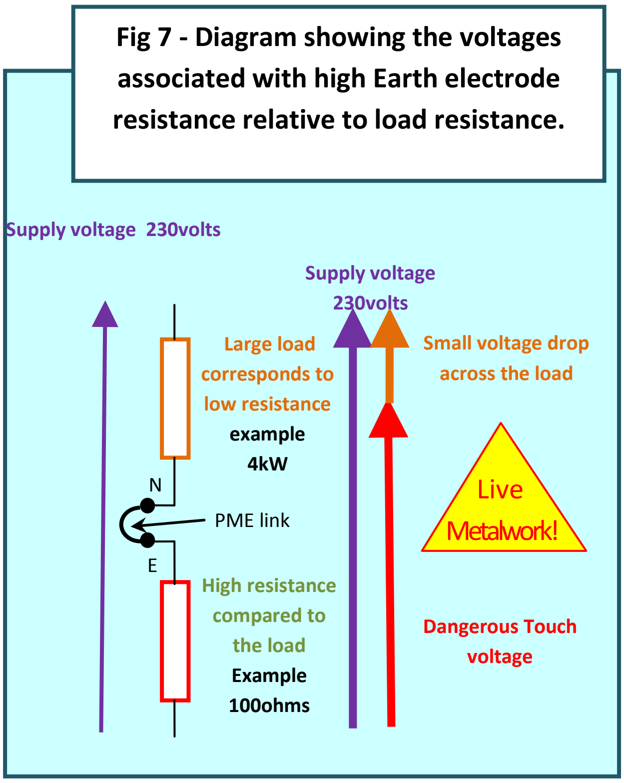


Fig 7 - Diagram showing the voltages associated with high Earth electrode resistance relative to load resistance.

The Intelligent / active Load

Having got to the concept in this fault condition the supply voltage is being divided between the earth electrode and the connected load we can then consider a proposal. What if the connected load, whatever size it might be, was able to react such that it is reduced thus ensuring the dangerous touch voltage did NOT occur?

Some traffic signal controllers are capable of monitoring the voltage which is used by the traffic signals and if this is too low will automatically turn off the traffic signals. This is a performance feature to ensure correct illumination of the signals (lights) and is the same feature we are looking for. Some basic concept testing has shown this action can occur in 4 cycles of the 50Hz mains frequency, that is 0.08sec which is well within 0.4sec given by the IET regs (BS7671:2008 table 41.1) for disconnecting 230volts and minimising the risk of electric shock.

The traffic signals (lights) constitute the bulk of the connected load for a traffic signal installation. In **Fig 7** the example given shows a 4kW load working in conjunction with 100ohms earth via the earth mat. If the PME supply had a broken PEN conductor a dangerous touch volt would be present on all earth metalwork.

However, with an intelligent load such as a traffic signal controller the reduced voltage appearing across the load would cause the traffic signal controller to turn off the traffic signals (lights) and this results in a much reduced load typically below 500watts. The touch voltage now becomes safe with typically under 100volts as per the original requirement of G12/3.

After a while the Traffic signal controller may try to switch on the traffic lights and so it could be programmed to try three times and then remain off. Traffic signals that are out are sure to be reported and attended to. Thus it will not be long before the real reason for the situation is discovered, thus resulting in the supply earth neutral fault being quickly repaired.

The proposal to allow intelligent / active loads to be used with a PME system is to be put to the DNO for their consideration. The DNO may take a view that there is still a risk that the intelligent load could fail to conform to the principles outlined above. In order to guard against dangerous voltages occurring at the feeder pillar, particularly for loads over 2kW, the DNO may, therefore, require the feeder pillar to be class 2 insulated, or if metal insist on other precautions being taken.

The Designers Responsibility

At first there seems no real benefit in the DNO insisting on a class 2 insulated feeder pillar as anything external to the feeder pillar will be bonded to the same earth, and therefore would be a subjected to the same touch voltage. However, it shifts the onus to the designer to ensure that a safe installation is connected to that supply and that includes anything being taken beyond the feeder pillar. This makes the designer responsible for ensuring that any metalwork beyond the feeder pillar will not present a dangerous touch voltage in the event of a PME fault. This is not readily worded in the IET Regs but would most likely come under ENA document G12/ which the DNO will use as a guide to what type of earthing arrangement they will provide to the customer. In most cases this may mean a TT earthing arrangement along with a RCD's for protection.

If a customer has a particular need for a PME earthing arrangement they may well have to meet key criteria and this could be the use of intelligent or active loads as in the case of traffic signals.

Summary

Perhaps an intelligent / active load could be deemed acceptable for connection to a PME service and thus avoiding the need to use an RCD.

The only other alternative is a complete shift to using Class 2 insulated equipment throughout and having no requirement to use earthing at all. But that is not realistic not just yet.

This means that the DNO could offer a PME earth quite safely for equipment such as traffic signals or any equipment providing the following criteria are met:-

- The equipment has the capability to monitor its own operating voltage and rapidly reduce the connected load below 500watts. This is based on G12/3 table 6.2.15 - 500watts with earth mat 100ohms,

- Reducing the load to below 500watts must occur within 0.4s. This is based on IET regs BS7671:2008 table 41.1,

- A Class 2 type insulated feeder pillar is used where the customer will be connecting loads over 2kW,

- The supply pillar will have a supplementary earth electrode achieving at least 100 ohms to work in conjunction with the 500watts. This is based on G12/3 table 6.2.15

- The customer has a good responsible design process and is able to demonstrate this process to the DNO.

- The customer can control any modification made to the installation during the installation's life time so the principle is not changed in any way. This could be achieved with clear labelling in the feeder pillar and the use of a site by site database/ logbook system.

- Satisfying the DNO there is a maintenance regime in place to quickly deal with faults that may occur to the equipment.

Glossary of terms

RCD	Residual Current Device used for detecting leakage current to earth and rapidly switching off the circuit.
DNO	Distribution Network Operator
PME	Protective Multiple Earth
a.c.	Alternating Current. 50 cycles per second.
TT	Terra Terra. An earthing system where the customer provides the earth
TN-C-S	Terra Neutral – Combined – Separate.
PEN	Protective Earth Neutral – a conductor used for both functions in a supply cable.
Protective Device	A fuse, MCB or RCD which automatically disconnects the circuit due to a fault.
ENA	Energy Networks Association.

References:

Energy Networks Association document G12/3

Wiring Matters No 45 – PME supplies

IET Wiring Regulations BS 7671:2008

UK Power Networks Earthing design manual 06

UK Power Networks Customer installation earthing design 07