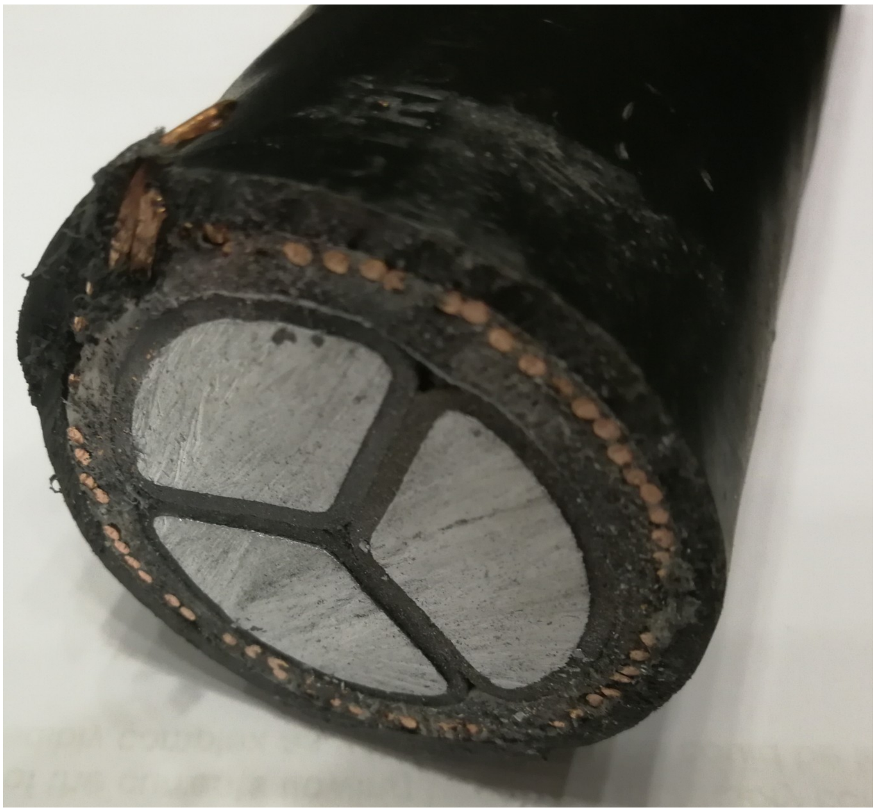
Diverted Neutrals

Discussion of experiences and findings from working on TN-C-S supplies

February 2021



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Contents

Disclaimer

These background notes contain various information and opinions based on events and facts investigated. As with engineering judgement, 'opinions' are formulated based upon a review of the available evidence at a certain time and specific location.

The background information is general in nature, indicating tendencies we have observed on various sites. We have taken all reasonable steps and exercised due care and attention while compiling these items. However, errors can happen, and specific equipment and circumstances can change outcomes significantly. Therefore care should be exercised before designing or basing decisions on these items without further expert input.

Illustration 1: Earthing systems don't always get looked after well, even if they've been installed correctly in the first place.

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Thank-you

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Tangle Tamers Electrical Engineers Ltd

Summary

We undertake varied work, much of it on buildings which contain equipment and processes which are sensitive to magnetic fields and particularly to changes in magnetic field. Such buildings include:

Electron microscopy and spectroscopy facilities

Secure data centres

Recording studios

Medical imaging locations

EMI / RFI screened rooms

Over the years, we have developed our knowledge and understanding of the causes of noise and interference issues which can give these installations and equipment problems. We are particularly interested in low frequency noise and interference.

If currents flow in an installation's earthing and bonding network or its metallic structures, they can generate significant magnetic fields. The fields generated by currents flowing in these elements are not cancelled by fields from return conductors sitting right beside them. So their local magnetic fields are strong and this causes problems.

Electricians are familiar with earth leakage, also known as residual currents, caused by high leakage plant and equipment such as rectifiers or inverter drives. A single item may generate anywhere from a few milliamps to many amps to earth. There is however, a lesser known phenomenon called Diverted Neutral Current (DNC) which can also cause current to flow in an installation's earth network.

In an installation, a single TN-C-S supply to a building can give rise to diverted neutral currents that flow from the main earth terminal via bonding to extraneous-conductive-parts to the mass of earth (the "mud"). TN-C-S was also historically known as PME (Protective Multiple Earthing) - a common historic term – for a more detailed discussion of types of supply system earthing see section 312.2 of BS 7671:2018. Diverted neutral currents also can happen where two or more TN-C-S supplies have their CNEs (Combined Neutral Earth conductors) connected in any way.

For example, think about a steel frame building. That building is split into two halves each with its own theoretically-separate installation, each with its own TN-C-S supply.

However, BS 7671 (regulation 411.3.1.2 in the 18th edition 2018) requires that "*in each installation main bonding protective conductors complying with Chapter 54 shall connect to the main earthing terminal extraneous-conductive-parts including (i) Water installation pipes (ii) Gas installation pipes (iii) other installation pipework and ducting (iv) Central heating and air conditioning systems (v) exposed metallic structural parts of the building*".

Therefore to comply with BS 7671 each installation must have the steel frame, services and lightning protection bonded to its own main earth terminal. This creates a common connection between the two TN-C-S supplies, where neutral current from the supply head in one installation can flow (for example) through the building frame or shared service connections, to the second TN-C-S supply head and vice versa. A simplified similar situation is described with a drawing on page 10 in this document, titled Scenario 2 - two interconnected TN-C-S supplies with a local load.

TN-C-S supplies can cause diverted neutral currents to flow in installation earthing and bonding networks. From there, the structures and services can then end up carrying diverted neutral currents when the supplies are not individually separated in stand-alone buildings. Also, some limited diverted neutral currents flow through the mass of earth (soil can be quite resistive).

It is not sufficient just to make the final cable drops to installations using separate CPCs. Similarly, it is not enough to just make a single supply truly TN-S (even properly, all the way back to the substation), when there are also TN-C-S supplies in the area or in that shared building. Diverted neutral currents can flow in something other than the neutral conductors. These currents can cause problems, hazards and danger, particularly when a DNO CNE connection is lost or broken.

REC/DNO/DSO regulations and practice

The regional electricity companies and distribution network operators commonly have rules or guidance which try to stop TN-C-S supply heads being connected together by low resistance earthing systems – e.g. avoiding multiple TN-C-S supplies being run into a common steel framed building, where each one would be correctly connected, earthed and bonded to the requirements of BS7671. For example, Western Power Distribution's document SD5C/2 (2017) states:

4.5.3 New (and replacement) incoming cables to multi-occupancy buildings shall be Separate Neutral and Earth (SNE) type.

However, it is very common in older buildings to see multiple CNE (Combined Neutral-Earth) supply cables right into the building. Furthermore, the REC/DNO/DSOs do not always abide by their own rules. Illustration 2 shows just one recent example we have found of multiple TN-C-S supplies installed in the same building.

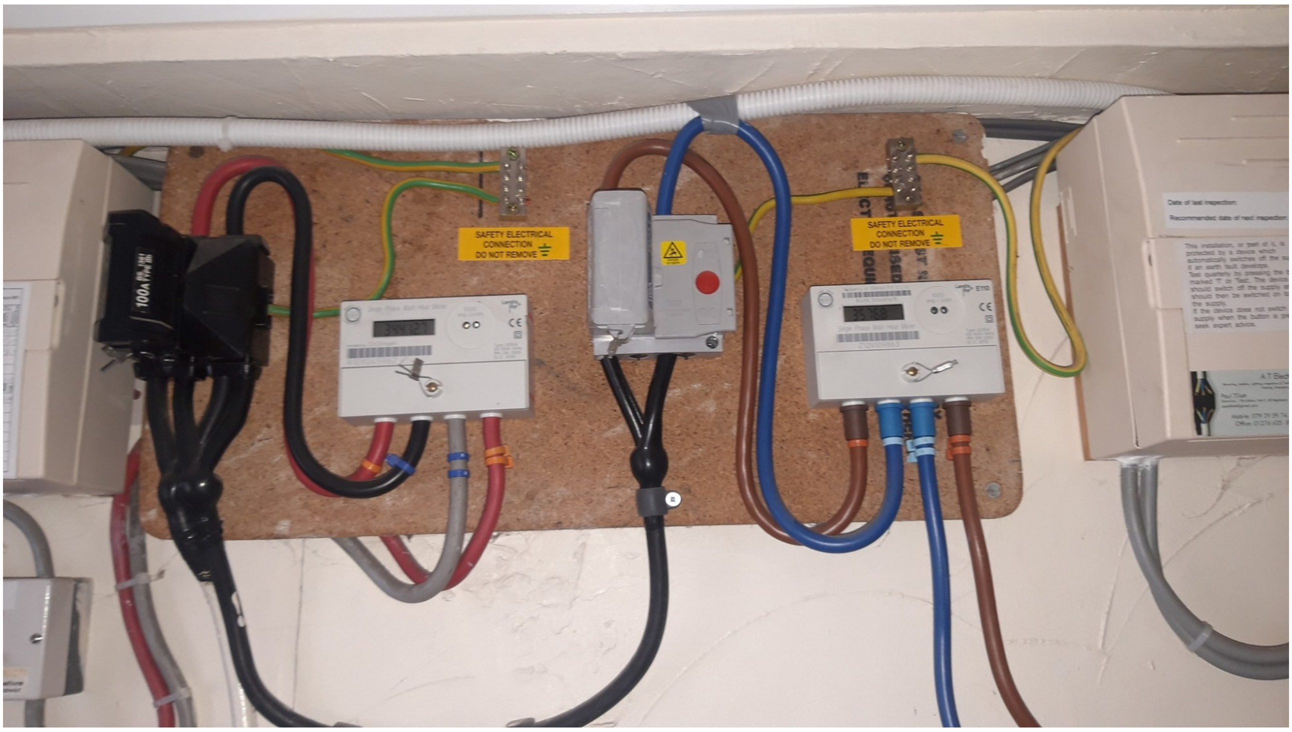

Illustration 2: 2 TN-C-S supplies installed in a common switch-room.   *Thanks to M. Harris*

Earth & protective conductor currents from TN-C-S

TN-C-S supplies have many regulations surrounding them in BS7671. They are associated with an underlying risk of neutral currents flowing in the earthing system of a single installation from the "earth" or (more realistically and using a less confusing word) the "mud" outside an installation.

The wiring regulations aim to ensure that an installation is ideally an intact single equipotential zone and that the earthing and bonding conductors have cross-sectional areas which are sufficient to safely carry their currents under normal operation and fault conditions.

In “good” modern 3-phase systems neutral currents are often still big. Even where phase currents are perfectly balanced, the sum of the triplen harmonic currents appears on the neutral. The Regs acknowledges that neutrals may even need to be bigger than the phase conductors on occasion to accommodate this. However, the Regs allow a default choice of protective conductors that have a much smaller cross section than the phase conductors.

The arrival of section 607 in the 16th edition of BS7671 (“*EARTHING REQUIREMENTS FOR THE INSTALLATION OF EQUIPMENT HAVING HIGH EARTH LEAKAGE CURRENTS*” - and its successors) shows that protective conductors are expected to carry some current in various “normal” operating conditions. However, little is said in the Regs about up-sizing protective conductors for significant standing currents. The implication is that protective conductor currents are expected to be small, at least relative to the protective conductor size and capacity. When diverted neutral currents are added to the mix, this is not always true, and protective conductors should be sized appropriately for their standing currents as well as for any fault currents they may have to carry.

Illustration 3: Measurement on an Earth Conductor of current from a shared water system in a multi-occupancy brick building with multiple TN-C-S supplies

Secondarily, the Regs aim to ensure that the "earth" of a (TN-C-S) equipotential zone cannot readily be taken to outside locations where it might give danger (via the feed to a caravan, for example), without appropriate precautions. Where the earthing arrangements of multiple TN-C-S installations are cross-connected (whether correctly or even inadvertently) the problem becomes difficult: parallel neutral paths are created through the earthing networks and the neutral current splits between the REC/DNO neutral path and the installations' earth paths.

Many locations with multiple TN-C-S supplies interconnect them at least by the arrangement of the services, and by the bonding (even in brick buildings, and as the Regs require).

Illustration 3 shows a current measurement on the earth conductor in a business unit which is a laboratory. The current was low on the day the photograph was taken – historically we have seen over 5 Amps here sometimes. In this unit, the water system is bonded to the TN-C-S head via the main earth conductor and the main earth terminal.

The building's water system is also bonded to other TN-C-S supply heads in a number of other units and in the shared common area of the building. This is a 1920s brick building but, even without a steel frame, we still find very significant currents flowing from supply head to supply head via the services and the bonding. The currents here are high enough that their magnetic fields ruin some types of measurements in this laboratory.

As another example, we worked on a building that contained a large number of small recording studios, which had 3 separate TN-C-S supply heads within the building. The protective conductor system was carrying over 25 Amps diverted neutral current flowing from supply head to supply head when we measured it, due to this supply configuration. Because the earth currents generated strong magnetic fields, electric guitars could not be used in some of the studios.

This shows that the interpretations of the definitions of multi occupancy are not being followed properly (or even listened to, sometimes – in the last example, one of the supply heads fed a bunch of new flats above the studio complex...).

Note that a separate earth entering the premises is not sufficient on its own. The local REC/DNO network, behind the final drop cables to the premises, may still be TN-C. The RECs often claim that an SNE (separate neutral and earth) cable entering the premises gives the premises TN-S.

This is not so. Consider if that premises has an SNE cable which connects to a CNE (common neutral and earth) cable in the street. Say the next-door unit in the same building also has an SNE cable to the CNE cable, connected to a different point on the CNE cable. Neutral current flowing through the CNE outer layer of the cable faces a parallel path through the 2 installations, if the systems, services, frame, lightning protection systems or other extraneous-conductive-parts of the 2 units interconnect to each other in any way.

This sharing of currents via parallel paths continues while the various supply heads are connected correctly. However, if the CNE conductor of one or more supplies breaks, the sharing path becomes the path for all the neutral current which would otherwise have gone along the failed conductor. Thus the sharing path can also become the path for load and fault currents, when it has already been carrying an excessive standing current.

SNE, TN-S, CNE, TN-C-S....

Using an SNE cable to a premises connects the customer's installation earth and neutral with separate conductors *at the customer's installation*. It does not guarantee to connect the other end to separate cable cores back to the substation star point and earth. It also gives no guarantee about the other installations in a multi-occupancy building.

Illustration 4: REC 3-phase cables – CNE & SNE thanks to P. Meenan

The utilities routinely install CNE-cabled TN-C networks, almost by default. However, using combined neutral earth conductor cable within the wiring of the installation itself is regarded as a major defect and a very significant issue. Mud and concrete are resistive, they are not good insulators.

It has however become quite common practice for REC/DNOs to give an SNE final connection that goes back into the road: this then often joins on to a CNE (3-phase, 3 core + CNE armour) cable and carries on that way back to the substation.

In our opinion, this is not TN-S. TN-S is a separated Neutral and Earth all the way back to the substation. Take a look at the drawing - Fig 3.8 "*TN-S system"* in the Regs, in 312.2.1.1 *"Single source systems".* The separation of the cpc and neutral goes all the way back to the transformer, not just to an arbitrary point a few metres outside an installation.

If the separation is not maintained all the way back to the source of supply for all the installations, then when those installations' Earthing networks or bonded metalwork connect, you have a possible neutral path via the earths. That path is in parallel with a length of the outer sheath / armour / CNE conductor of the DNO's cabling. The current flowing in each path is then determined primarily by the load *on the distribution network* and the relative impedances of the two paths.

Finally, for now, it may be interesting for the reader to contemplate TN-C-S supplies in multiple earth-coupled installations, and to then consider what happens when the DNO CNE conductor breaks outside the installation(s).

The following appendix pages go into a deeper explanation of diverted neutral currents.

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TN-C-S Diverted Neutral Currents

Scenario 1 – Ideal conditions

Illustration 5 shows a TN-C distribution network in ideal conditions. TN or 'Terre Neutre' references the earthed neutral on the secondary 230V/400V output of the DNO's / distribution network operator's 11kV transformer. The ***'C'*** in TN-***'C'*** represents a single **Combined neutral and earth** return and protective conductor, also known as a **CNE** or PEN conductor, coming from there.

For simplicity below, one single phase TN-C supply is shown connected to all the properties. Where the supply enters a property the combined neutral-earth conductor is ***'Separated'*** at the supply head and the supply becomes TN-C-'***S'***. Property B has a load connected. The red arrows show where current flows in this TN-C-S system under ideal conditions for one installation's load.

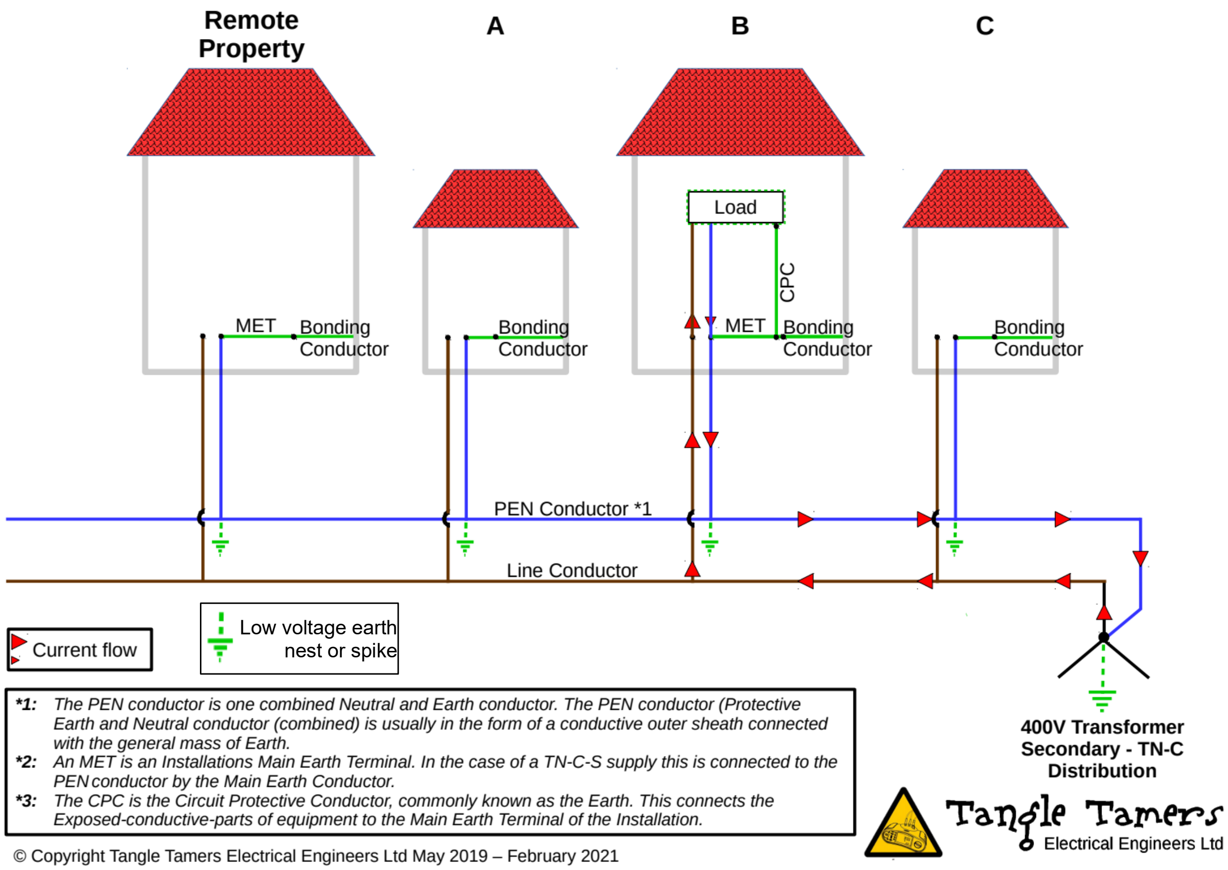

Illustration 5: Single phase TN-C-S supply to a domestic property.

Scenario 2 – Two interconnected TN-C-S supplies with a local load

Illustration 6 shows an installation (property B) with a load connected. In this scenario the earthing system for property B is connected by something to property A's earthing system. The connection between the earthing systems provides a parallel path for neutral current to flow back to the substation via both supply heads from a single load. In this example neutral current splits or divides where the neutral and main earth conductor join the supply head and CNE conductor at the origin of the supply in B.

The proportion of the neutral current that flows into the earthing system depends on the resistance of each of the parallel paths. The size of the total current is governed firstly by the load on the supply.

Equally or similarly, any load applied to building A will also see the earth system interconnection as a parallel path for neutral current to flow through building B's earthing system to B's supply head and on.

The current for the most part will follow the path of least resistance within the buildings' earthing, metallic structures and services. There will be some branching and distribution of the current because of the interconnection of any services. As a result, it is likely that currents will flow not just in in the supplementary or main bonding conductors, but also in some CPC's and metallic building structures.

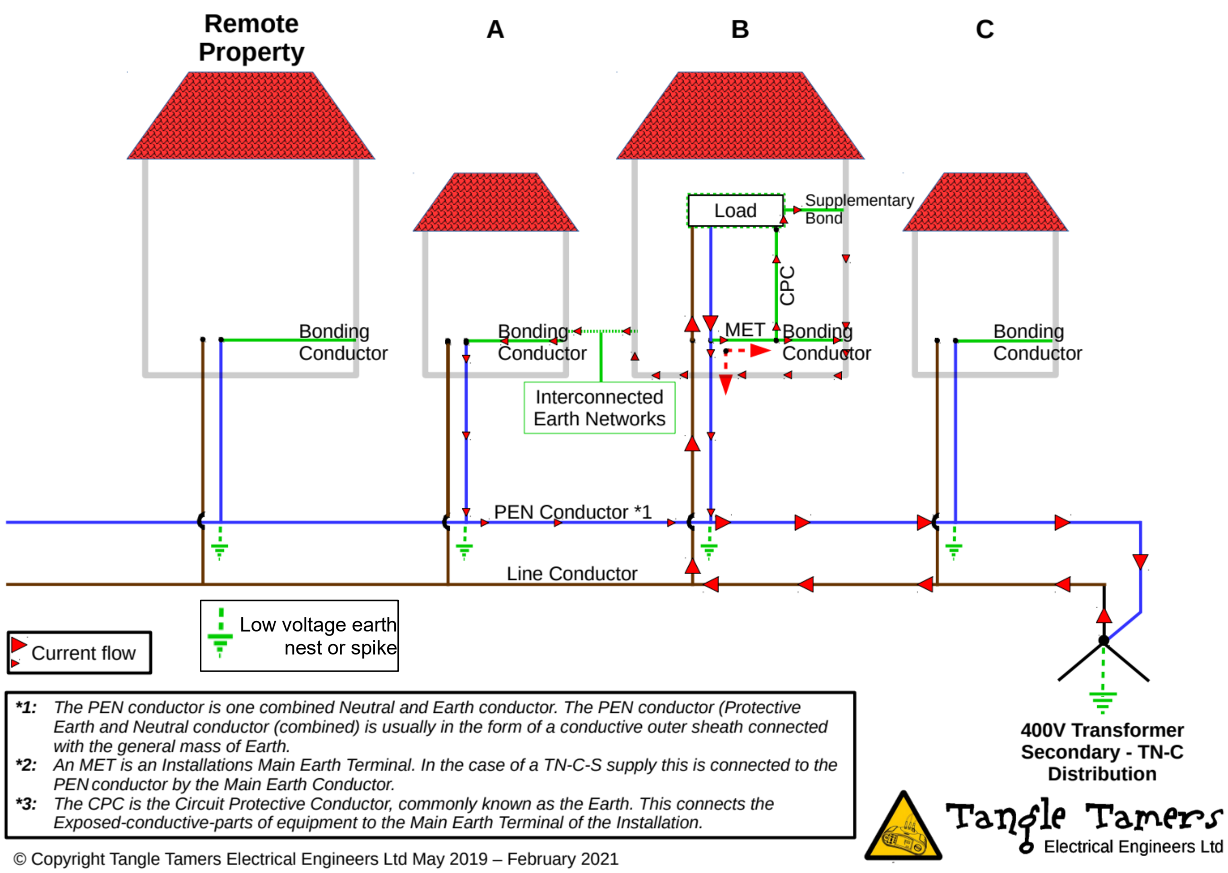

Illustration 6: TN-C-S supply where two earth systems have been interconnected.

Scenario 3 – Two interconnected TN-C-S supplies with a remote load

Illustration 7 demonstrates how current from a remote load elsewhere on the same network can flow through the Earthing systems of property A and B where both earthing systems are interconnected. In this instance, the electricity network sees the earth system of these two buildings as a parallel path for neutral current to flow through. This is due to the combined neutral and protective earth conductor or ‘CNE’ conductor of the main DNO network cable.

The part of current that flows through the earthing system depends on the ratio of the resistance of the CNE conductor going past properties A and B, and the combined resistance of both properties’ earthing networks. For example, if the combined earth network resistance of property A and B is lower than the CNE conductor then a majority of the neutral current will flow in their earth systems. The total current that flows through the earth systems will vary with the load.

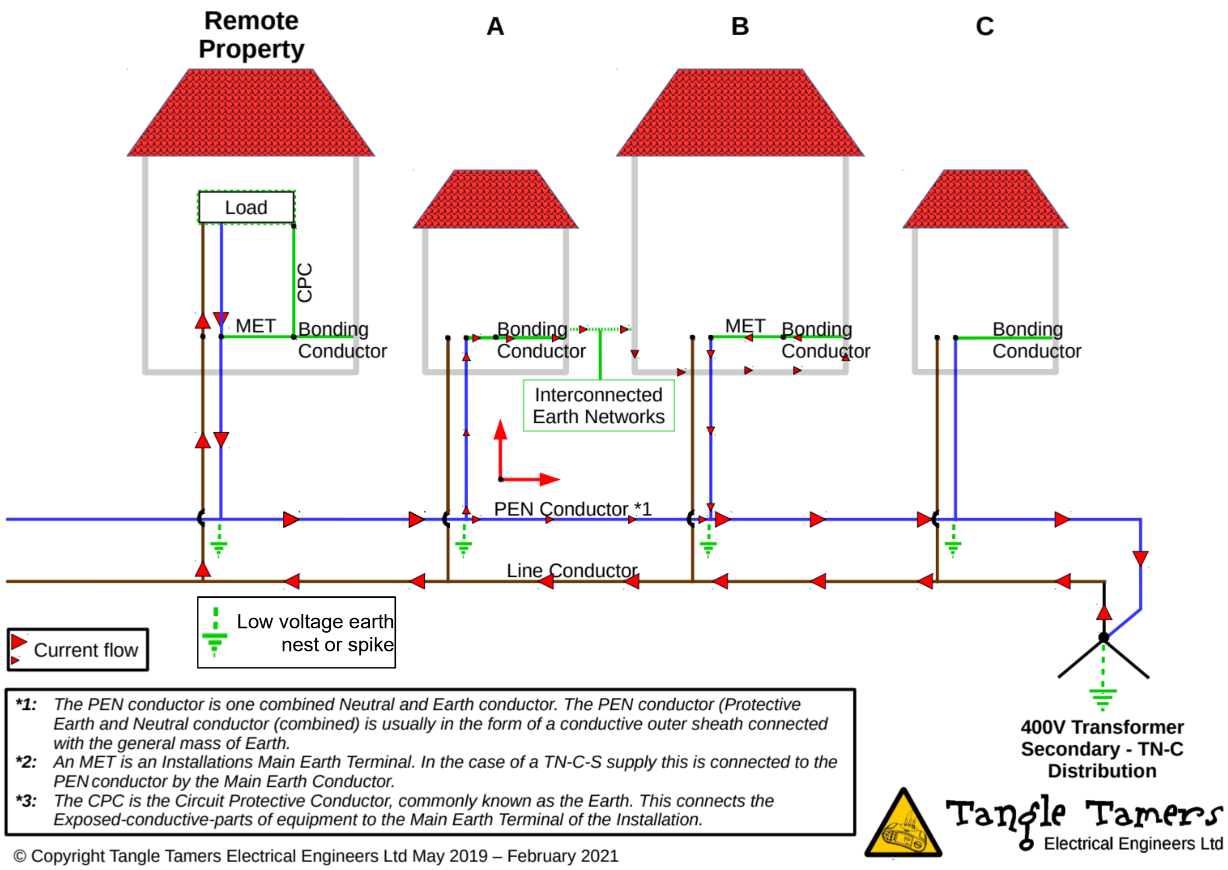

Illustration 7: Single phase TN-C-S supply where two earth systems have been interconnected with a remote load.

Scenario 4 – Three interconnected TN-C-S supplies with a remote load

Illustration 8 shows what would happen if 3 installations' earth networks are interconnected. However this time the DNO feed cable to property B is fully disconnected from the electricity distribution network. Despite that isolation, because there is a conductive path through property B between property A and C, current still flows through property B's earth system. This current does not depend on B's external DNO earthing connection. B's supply cable is fully disconnected, but current can still flow from A to C.

The path from A to C through property B could be any conductive structure or services installed in or entering the buildings. For example, rebar, structural beams, or water and gas service pipes. Old water pipes left in the ground or even a metal stud or a fixing shorted to the rebar of a neighbouring building can also form part of a route for current to flow. The path can be anything that electrically couples two or more buildings' earthing systems together.

This can be particularly problematic in multiple occupancy buildings where BS7671 requires each installation to be at least main-bonded. The issue can be made worse where class 1 equipment with high leakage current is installed with its own CPC but in addition is fixed down so that its casing is fortuitously connected to bonding elsewhere (e.g. a pump on a water system).

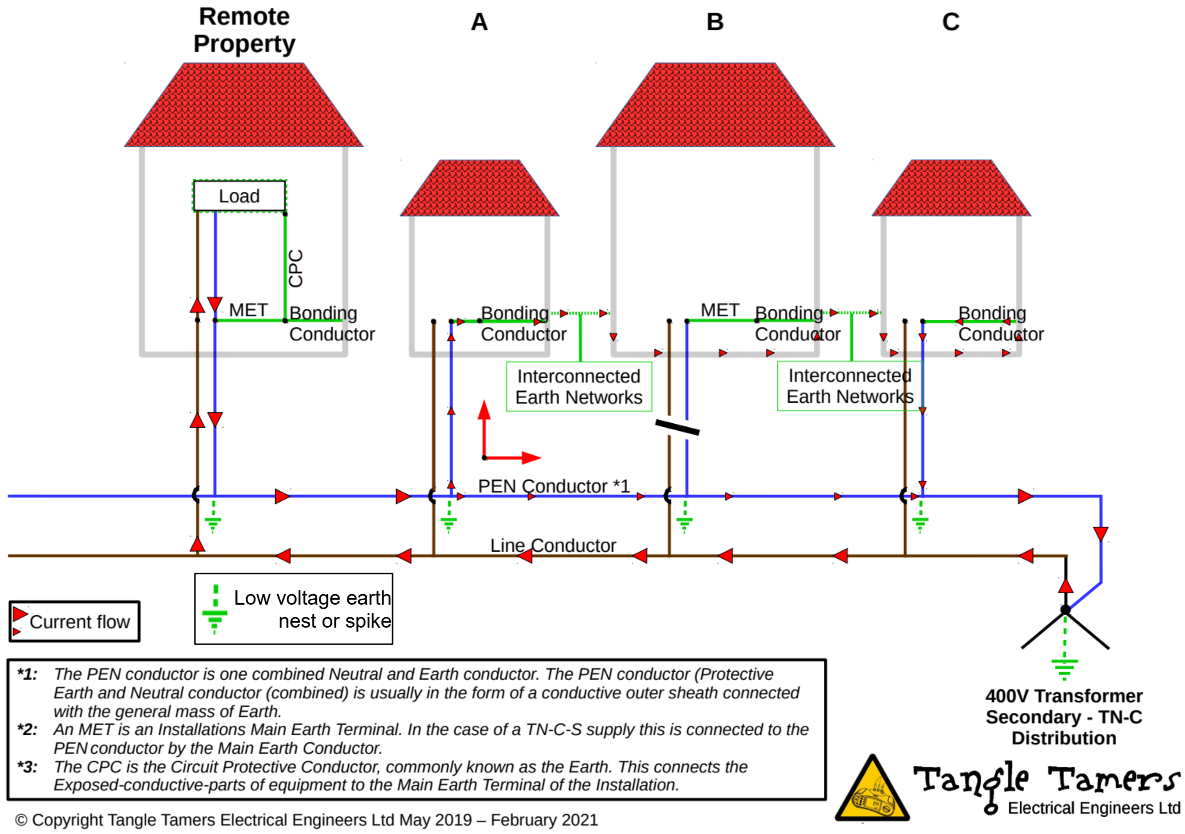

Illustration 8: TN-C-S supply where 3 earth systems have been interconnected, with a remote load. Property B has been isolated from the supply network.

In South Manchester, the local utility invested in "upgrading" a town centre with new PME cabling. A retailer with large chiller loads in a 50 year old building was given a new TN-S supply from an old substation ~15 metres away. This supply suffered diverted neutral current pollution of about 5 Amps from nearby units in the same building. When challenged, the utility had no record of measurements on earth electrodes which should have been installed at the cable joints. The "core balance" or residual current measured at the substation peaked at more than 50 Amps.

Scenario 5 – The combined effects of Scenarios 1 – 4

Illustration 9 demonstrates the resultant mess that occurs when multiple loads and earth bonding interconnections exist on the same TN-C-S network.

Current generated by the Remote Property flows into building A, B and C. Some of the current flowing through the load in building B goes into buildings A and C and vice-versa. Currents going back and forth between the buildings will sum and cancel depending on the magnitudes and phase angles. We haven't added loads in A or C yet. And in a 3 phase system, these relationships are even more complex.

From Kirchhoff's laws, the net 'return' or neutral current of balanced 3-phase loads is effectively zero. Where the load on a 3 phase 4 wire system is not balanced the un-balanced part of the current appears as neutral current. Triplen harmonics make the situation worse. They sum on the neutral, rather than cancelling. On one site (approx. 110 Amps 3-phase demand), the phase currents were balanced to within a few amps. Yet the installation still had a neutral current of more than 30 Amps due to the harmonics.

Installations, if they are 3 phase with some form of connected earthing, then share their neutral current with each other due to the interconnections. Here, harmonics and phasing of the current on the neutral become important. The relationship between the loading of the network at any given time and the cancelling effects of the currents flowing becomes incredibly complex. There are then many scenarios which could be in play – so diagnosis becomes very, very difficult.

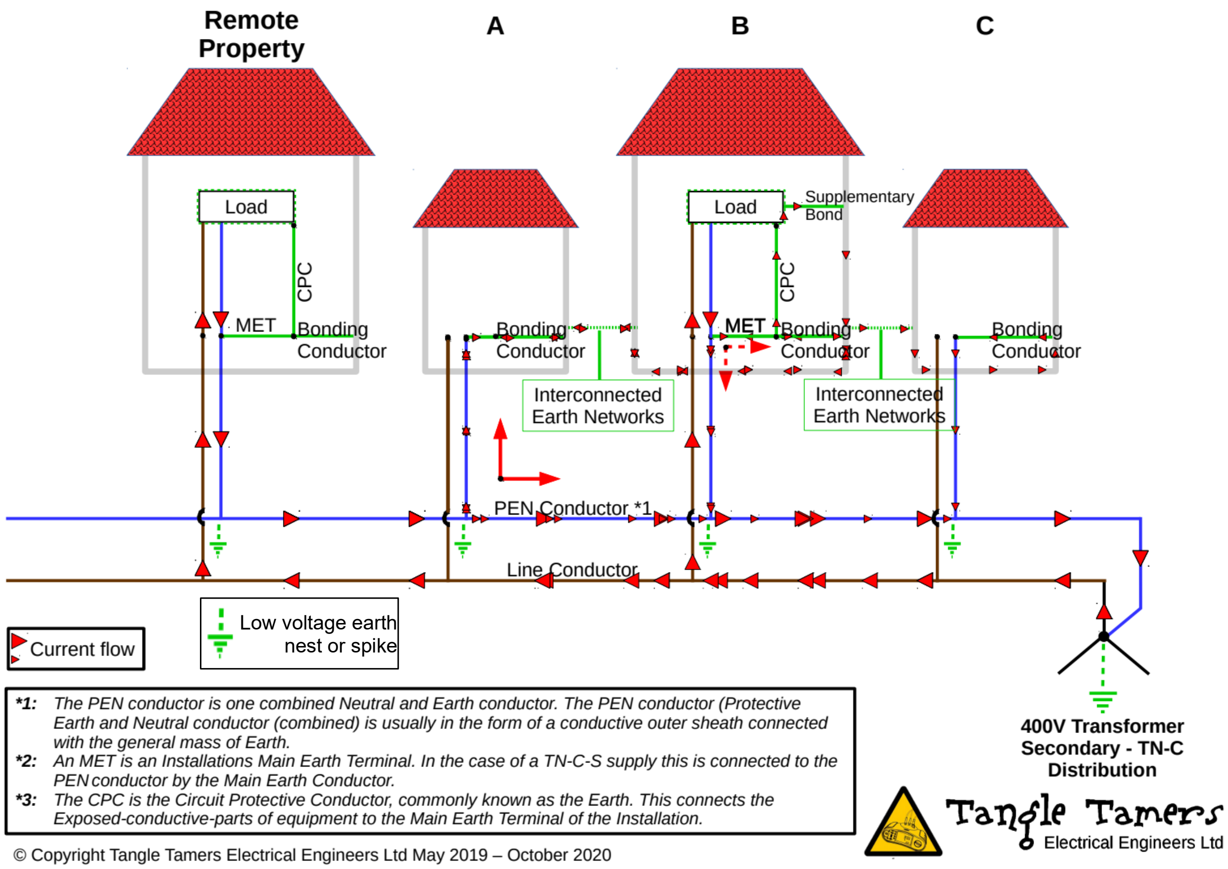

Illustration 9: The combined effects of multiple cross linked TN-C-S supplies with multiple loads on a distribution network

Some definitions – Also see BS7671

BS 7671: "Requirements for Electrical Installations" – The IET wiring Regulations. The Regs.

Combined Neutral Earth (CNE) Cable: One where a separate circuit protective conductor (CPC) is not included in the cable structure. Instead the cable combines the functions of the Neutral and the Protective Conductor into one CNE conductor. Hence a single phase cable in an installation is commonly 3 core or 2 core plus armour, to include a separate CPC. However, in many common distribution systems a single core plus CNE armour cable would be used as a single phase cable – a "CNE cable"

Diverted Neutral Current (DNC): A DNO's or a consumer's neutral current which flows partly or wholly in a path other than its own circuits' neutral conductor(s). Commonly these flow in earth networks, earthed structures, service pipes, rebar and drainage systems, together with a variety of CPCs and their associated equipment structures, CNE conductors *and also the mud of earth itself.*

Electrical Installation (abbr: Installation): Ref BS7671 (The "Regs"): *An assembly of associated electrical equipment having co-ordinated characteristics to fulfil specific purposes.* In practice, commonly understood as being the fixed electrical system of one user or company, in one location.

Earth Leakage Current (Protective Conductor Current): Ref BS7671 *Electric current appearing in a protective conductor, such as leakage current, or current from an insulation fault*. In practice, commonly taken to mean a residual current e.g. in equipment and its CPCs (Circuit Protective Conductors), bonding and earthing, bonded services and structures.

Main Earth Conductor: Ref *BS7671: **Earthing Conductor**: A protective conductor connecting the main earthing terminal of an installation to an earth electrode or other means of earthing.* In practice, we use the term "Main Earth Conductor" instead of Earthing Conductor, for clarity, when talking about earthing systems. This helps avoid confusion between an earth conductor and the earthing conductor (because those latter expressions are so very close to each other, causing misunderstanding in discussions).

MUD, MoE, Mass of Earth: The electrical industry talks of the Mass of Earth, and Earthing and Earth and Ground and Grounding and many similar words: Yet everyone seems to have a bit of confusion and lack of clarity in discussions about Earthing systems. About 10 years ago we started using the term "Mud" to denote the Mass of Earth – remote from the zone of influence of the earth electrodes under discussion, the stuff of which Terra Firma is made – to try to avoid misunderstandings. We therefore use it here.

REC / DNO / DSO / IDSO: The DNOs (Distribution Network Operators) are the successors to the distribution arms of the **RECs** (Regional Electricity Companies). Their geographical operating areas reflect the boundaries of the old electricity boards prior to deregulation back in the 90's. There will be increasing implemented of micro-generation technologies in future: Hence DNO's will progressively to take on DSO (Distribution System Operator) responsibilities. IDSOs are independent. Relevant acronyms may include:

LEB - London Electricity Board

DNO - Distribution network Operator

IDNO - Independent Distribution Network Operator

EDNO - Licence Exempt DNO

REC - Regional Electricity Companies

BNO - Building Network Operator

DSO - Distribution System Operator

Residual Current: Ref BS 7671 *Algebraic sum of the currents in the live conductors of a circuit at a point in the electrical installation*. In practice, commonly understood to mean the net difference or imbalance between the phase and neutral currents in a single phase circuit. By extension, the net difference in the currents in a 3 phase circuit's 3 or 4 live conductors. Note that some of this current may go down paths other than the CPCs (Circuit Protective Conductors), such as metal pipes connected to equipment. Some of this current can also leave the installation via extraneous-conductive-parts such as service pipes.

Triplen Harmonics: Ref BS 7671 *The odd multiples of the third harmonic of the fundamental frequency (e.g. the 3^{rd}, 9^{th} ,15^{th} 21^{st}).* In practice, commonly understood to mean 150, 450, 750, 1050 Hz etc. on a 50 Hz system.