

Loss of Neutral in Low Voltage Distribution Systems – Consequences and Solutions

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Background

In recent years, problems related to the integrity of the neutral in Low Voltage Distribution Systems have been exacerbated due to the unfortunate culture of copper theft that has become prevalent in South Africa. Whilst this kind of problem is not unique to South Africa, it is largely unknown in the developed countries of the world. In general, neutral integrity problems are more common in developing countries due a combination of aggressive environmental conditions, vandalism and in some cases, questionable workmanship.

The consequence of a lost neutral conductor will vary, depending mainly on the load balance conditions in a three phase system, but also on the type of earthing system used and the position of the break in the neutral relative to the load. Worst case scenarios could include both damage to connected loads due to overvoltages on single phase circuits or the creation of hazardous touch voltages on exposed conductive parts.

Systems affected by Loss of Neutral

Almost by definition, the systems and installations that are most adversely affected by the abnormal condition of a lost or broken neutral conductor, are single phase systems and single phase circuits that are derived from three phase star connected supplies. Three phase systems that include single phase loads may experience voltage shifts between the star point and the three phases, depending on the balance of single phase loads across the three phases.

System Voltages

By convention, a solidly earthed neutral conductor is at zero potential to earth. The potential on a correctly installed neutral conductor may rise slightly above this theoretical zero value, depending upon the load current that is carried by the neutral and the consequential voltage drop resulting from the neutral current. In a single phase system that is derived from a single phase source, a break in the neutral conductor will simply result in a loss of the energy supply. However, in a three phase system having a distributed neutral, a break in the neutral conductor may result in undesirable variations of the three (phase to neutral) voltages.

The standard phase to neutral voltage in South Africa is 230V. The resulting voltages between phases are thus $(230V \times \sqrt{3})$ which is equivalent to 400V (nominal). The majority of residential consumers in South Africa are provided with single phase electricity that is derived from a distributed three phase system. Provided the neutral conductor remains continuous, the voltages between each phase and the neutral is largely unaffected, excepting for voltage drops in the circuit, which are load dependent. For the (unusual) case of *equal load distribution* across the three phases, even in the event of a loss of the neutral conductor, the individual voltages from each of the three phases to the star point will remain at approximately the nominal level of 230V.

A break in the neutral conductor can however result in wide excursions of the voltages between each phase and the star point if the three single phase load currents deviate from the ideal balanced condition. Depending on the degree of unbalance between the single phase loads, in the extreme, the three single phase voltages (phase to neutral) could vary from as low as zero volts, to any voltage up to the *phase to phase voltage*. Irrespective of load balance, the voltages *between phases* are not affected by a break in the neutral conductor.

Neutral shift

In both TN and TT electrical distribution systems, the neutral conductor is solidly connected to earth at the source of the electricity supply (transformer or generator). For reasons of safety, this creates a reference point for the neutral (at earth potential). It should be recalled that in a three phase electricity supply system, the three phases are generated at an electrical angle of 120 degrees to each other. When considered in a rotating vector system this can be described as each phase leading the subsequent phase by 120 electrical degrees. As long as the star point of a three phase transformer remains solidly connected to earth, the relationship between the voltage of each phase and neutral (or earth) remains fixed, irrespective of the balance of load between the three phases. However in the absence of this reference, the neutral point at the confluence of the three vectors will be caused to shift depending on the ratio of the *load currents* drawn on the three phases. It is this shift of the neutral that results in the variations of phase to neutral voltages between the three phases.

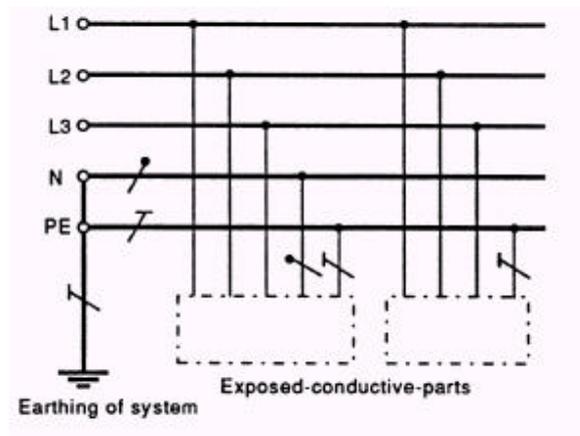


Figure 1 - The TN-S system

Low Voltage distribution systems

There are four main type of earthing systems. These include :-

TN power systems which have one point directly earthed, the exposed-conductive-parts of the installation being connected to that point by protective conductors. Two types of TN system are approved for new installations in South Africa. These are defined according to the arrangement of neutral and protective conductors, as follows:

- **TN-S system:** in which throughout the system, a *separate protective conductor* is used;
- **TN-C-S system:** in which neutral and protective functions *are combined in a single conductor* in a part of the system.

The TT power system in which one point is directly earthed, the exposed-conductive-parts of the installation being connected to earth electrodes *electrically independent* of the earth electrodes of the power system. The TT system is not permitted for new installations in South Africa, but still exists in many of the older areas.

The IT power system which has all live parts isolated from earth, or one point connected to earth through an impedance, the exposed-conductive-parts of the electrical installation being earthed independently or collectively or to the earthing of the system. The IT system is not used for the public distribution of electricity, but is used in private installations, mainly for reasons of continuity

of service. Three phase IT systems with a distributed neutral can in certain circumstances, result in hazardous conditions. This latter type of IT system is to be deprecated.

The problems of voltage variations between phase and neutral that can result from a break in the neutral, are common to all types of low voltage distribution systems. The increasing usage of the TN-C-S system has however introduced a further dimension to the consequences of a loss of the neutral conductor.

The TN-C-S power system

Mainly for economic reasons, across the globe, the TN-C-S power system is becoming more and more widely used for the distribution of low voltage electrical power. The concept of combining the neutral and protective functions in a single conductor immediately resulted in the elimination of one of the five distributed conductors that are required for a three phase TN-S system (three phases, one neutral and one protective conductor). South Africa is no exception in this practice.

The combined neutral and protective earth conductor is commonly referred to as the PEN conductor. The effective and safe operation of TN-C-S distribution systems is *critically dependent* on the ongoing integrity of this PEN conductor.

In a TN-C-S system, the separate protective conductor (PE) for each consumer, is created by simply tapping off a second parallel conductor from the PEN conductor at a location that is close to or at the point of supply to individual consumers. The parallel conductor in the installation then becomes the *neutral* conductor.

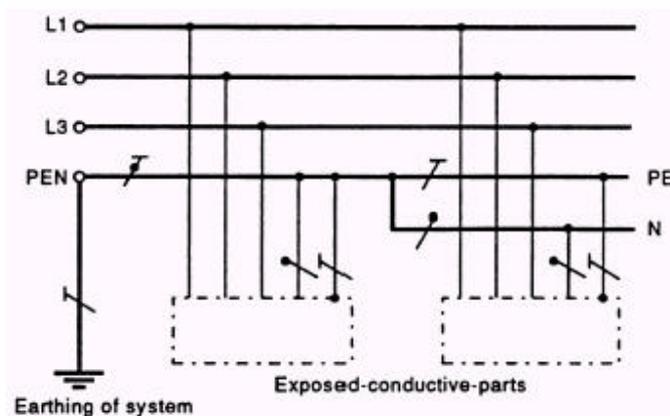


Figure 2 - The TN-C-S system

Broken or lost PEN conductors

Electrical distribution utilities are very conscious of the importance of maintaining the integrity of the PEN conductor. Since the protective earth conductor (PE) has a direct electrical connection to the PEN conductor, this can lead to the creation of potentially hazardous conditions in the event of a break in the PEN conductor. In the absence of a direct return connection to the source other than through the load, a break in the PEN will result in the neutral conductor (downstream of the break in the PEN conductor) assuming the same potential as the phase conductor. Similarly, all exposed conductive parts that are connected to the PE conductor (earth) will also become "live" in such circumstances.

The main disadvantage of the TN-C-S distribution system is this unprotected hazardous condition that could arise in the event of a break in the PEN conductor. This hazard continues to exist independent of the presence of any protection devices that may be installed. In the event of a break in the PEN conductor, all exposed conductive parts will remain "live" irrespective of the operating state of the main switching or isolating device – whether it is ON (closed) or OFF (open).

One possible mitigating solution to this hazard created by a broken PEN conductor, would be the installation of a foundation earth at the service entrance of the electricity supply. This is standard practice under the requirements of the National Electric Code in the USA and is also used to a limited degree in some European countries such as Germany. The effect of the foundation earth is to hold the neutral and PE potentials closer to earth potential even under fault conditions.

It is not a simple matter to retrofit TN-C-S distribution systems with such a facility. This is true for TN-C-S systems (such as those in South Africa) that do not require the installation of a foundation earth at the service entrance. Unless *every consumer* each have their own service entrance foundation earth facilities, in the event of a break in the PEN conductor, the load current of *all other consumers* may find a return path through those foundation earth connections that happen to be present.

An extreme example would be the case of only one consumer having a foundation earth. In such a situation, all the load currents of all consumers connected to that distribution system would try to flow through the single foundation earth present. The consequential overheating together with the related possibilities of incendiary ignition will be obvious.

Early solutions

During the mid to late 1980's and early 1990's ageing electrical installations that showed increasing instances of poor electrical connections encouraged researchers to address the phenomenon of lost neutral conductors. The more commonly used distribution systems at that time were the so-called Protective Multiple Earthing (PME) or Multiple earthed neutral (MEN) systems. In most cases these types of distribution system also included an earth rod at or near to the point of supply to individual consumers. The main purpose of the local earth rod was to ensure that the neutral conductor would be held at earth potential in the event of a high impedance or break in the neutral conductor. In the event of such a break in the neutral conductor, the load current would return via the earth connection.

It was however conceded that in the typically dry South African conditions, the probability of obtaining low resistance earth connections was not particularly good. Any significant load current could result in a rise of potential in the local earth circuit. In extreme cases the development of hazardous touch potentials on the exposed conductive parts of items such as water taps and fences was possible. The problem became further aggravated by the increasing use of non-metallic pipes and fittings in water supply and plumbing systems. A further problem was the possibility of electrolytic corrosion of cable armouring and other buried metalwork in the event of such a condition remaining undetected or uncorrected for any significant time period.

It should be recalled that all intentional earth connections on the neutral were made upstream of the earth leakage circuit breaker (if fitted). The provision of sensitive earth leakage was therefore not a solution to this problem, since even though the load current returned via the earth rod, the live and neutral currents through the earth leakage circuit breaker remained balanced.

The proposed solution at that time was to monitor the level of neutral current that found a return path via the provided earth electrode, and to interrupt the supply mains in the event of this current exceeding some predetermined level. One immediate problem was that for the case of a very efficient earth rod together with a very low earth return loop impedance, *even in the absence of a*

fault, a significant level of current would return to the source via the earth circuit. A crude solution to this situation was to decrease the sensitivity of the monitoring device.

The over-voltage problem

Overvoltages in single phase installations that result from a break in the neutral conductor will invariably result in damage to most appliances and other connected electrical equipment. As a general rule, any protection system that is designed to detect such overvoltages will be arranged to disconnect the affected part of the installation from the source of electricity. Furthermore protection systems have to be designed such that they are not too sensitive, since this would result in unacceptably high levels of what is termed as “nuisance” operation. In South Africa, according to the Electricity Act, electricity supply utilities are permitted to deliver electricity at the nominal voltage up to 110% of the nominal voltage. For this reason, devices that are designed to detect overvoltages on standard 230V single phase systems are usually preset at an operating value that exceeds ($230V \times 110\% = 253V$) plus some additional margin, in order to cater for the not uncommon probability of short duration temporary overvoltages.

The standards to which most appliances are built, rarely require an overvoltage withstand level that exceeds a value of 110% of their rated voltage. It becomes obvious therefore, that for practical reasons, in most cases, an unprotected “window” of overvoltage may remain. Even for the case of very short duration temporary overvoltages, it is highly unlikely that any form of guarantee of survival could be obtained from the majority of appliance manufacturers. As a consequence, it needs to be clearly understood that devices that are designed as “Overvoltage protection devices” may not necessarily be able to *guarantee* the survival of appliances or equipment in the event of an overvoltage. Such devices will however mitigate such conditions and provide a reasonably high degree of protection to the entire circuit and to equipment connected to the circuit.

A new cost effective solution

Earth leakage circuit breakers are manufactured using two distinct and differing technologies. Modern devices that employ solid state electronic sensing systems already include all the basic elements for the provision of additional protection facilities other than that of the basic sensitive earth leakage protection. It is a relatively simple matter to extend these functions in order to include the additional function of *overvoltage protection*.

South African manufactured earth leakage circuit breakers have recently become available with two discrete optional additional protection facilities. These include –

- Devices that include facilities for detection and operation in the event of the phase to neutral voltage rising above a predetermined critical level.
- Devices that include facilities for detection and operation in the event of a rise in the potential of the neutral conductor above a preset permitted level.

In the event of a break in the neutral conductor upstream of the point of supply, the former type will operate and open the protected circuit in the event of an increase in the phase to neutral voltage. In the event of “neutral shift”, such a voltage increase could result due to a higher load being drawn on one of the *other phases* in the network.

A break in the upstream neutral conductor will also result in the appearance of a voltage between *neutral and earth*. This neutral to earth voltage will also increase in the event of an increase in load on a different phase to the phase that is being monitored.

Applicability of Overvoltage protection systems

Overvoltage detection and protection systems that are based on standard earth leakage circuit breakers are most suited to consumer level protection. With the installation of sensitive earth leakage protection having been a mandatory requirement in South Africa for the past quarter century, this can be achieved easily and cost effectively by simply replacing the existing earth leakage circuit breaker with a device that includes the chosen type of overvoltage protection.

Protection Sensitivity

The alternative option of monitoring the voltage increase on the neutral conductor relative to earth would result in closer protection than monitoring the voltage increase between phase and neutral. Depending upon the neutral conductor impedance between the system earth point and the consumer and of the system load current being drawn, it is quite common for the neutral to rise several volts above earth. This is particularly so in the case of single point neutral earthing, or where the last neutral earthing point is relatively distant from the consumer. In general, this neutral voltage elevation is usually only a few volts and rarely exceeds about 10 to 15 volts.

SABS 0142-1:2001 annex K requires notification of potential danger should the elevation of voltage on a supply neutral exceed 25V. From the above, it can be concluded that for neutral elevation detection devices, an operating level of about 20 volts might be appropriate.

Computer simulations have shown that at a preset operating level of 20V any interruption of the neutral conductor will almost immediately be detected. It can also be shown that even for the case of a balanced load on all phases, a load unbalance as low as 20% in any one phase would elevate the neutral by at least 20 volts.

Sub-station level protection

The problems of copper theft together with the consequential widespread damage to single phase equipment connected to TN-C-S distribution systems precipitated the development of further devices for application in utility and consumer sub-stations. In most cases the theft of copper neutral and/or earth connection busbars takes place on the low voltage side of the sub-station transformer. Whilst it is recognized and accepted that no such protection device can always guarantee the protection of all connected appliances, a significant reduction in such damage has been demonstrated.

One such device comprises a sensor that is arranged to monitor current between an earth connection and a predetermined location on a conductor of the neutral pole of the supply. It is designed to generate an output when the current exceeds a predetermined value. The device also includes a switch that is responsive to this output and is arranged to disconnect the live conductors from the respective loads in response to such an event.

For the case of interference with the copper busbars in sub-stations, the sensor is arranged to detect changes in current due to removal or damage to the busbar. In a typical sub-station, it is a reasonably simple matter to anticipate which copper busbars or cables are most vulnerable to vandalism of this kind.

With the operating sensitivity of the sensing device set to a relatively low value of some amperes, the two pilot wires used with the device need only be of relatively small cross sectional area. In addition, the pilot wires are arranged in such a way that they will be self protected through isolation, once the sensing device has operated. In practical applications, the pilot wires are discretely connected at convenient locations between which it can be anticipated that the vandalism and theft would occur.

The sensor arrangement is connected across the neutral busbar in the sub-station and effectively monitors this conductor for continuity. Any removal or interruption of the system neutral busbar will result in a current flow in the sensor due to the potential difference between the earth and the supply neutral that results from removal or damage to the neutral busbar.

Since the pilot wires are connected in parallel with the anticipated break in the neutral conductor, even in the event of such a break occurring, an alternative ohmic connection is provided to complete the neutral circuit. This has the additional benefit of (to some extent) restricting the neutral shift and consequential excursions in the phase to neutral potentials.

In the event of a neutral break, an auxiliary switch that is included as part of the sensing device is arranged to activate the shunt tripping mechanism of a circuit breaker connected so as to isolate the low voltage circuits from the supply transformer.

In practice the installation of the sub-station level lost neutral detection device always requires the presence of a shunt trip operated circuit breaker. Should the substation already include a main transformer low voltage circuit breaker, it is simply necessary to add a shunt trip device to that circuit breaker and to install the patented current sensing device. With isolation of the low voltage distribution circuits being a prerequisite for protection systems such as this, older sub-stations that include fuse protection on the transformer secondary, would require the installation of a trippable protection device such as a shunt trip equipped circuit breaker.

The performance of the device described above was fully studied in a SPICE simulation, the results of which were confirmed in a laboratory test program.

Conclusions

Intensive investigations in several technical working groups of the International Electrotechnical Commission (IEC) have shown that in first world developed countries, the incidence of a break in the neutral conductor of low voltage distribution systems is so low as to not even deserve any consideration. In normal law abiding societies, the justification for the development of devices such as those described in this paper would as a result remain questionable.

It is regrettable that in the new South African democracy for various reasons, similar criteria do not apply. This paper has attempted to identify the causes and consequences of a break in the neutral conductor in low voltage distribution systems. Whilst it is recognized and accepted that protection devices such as those described cannot always guarantee the protection of all connected appliances, a significant reduction in such damage has already been demonstrated in pilot test sites.

In recognition of the widespread equipment damage implications resulting from a broken neutral, together with the need for economically viable solutions, three different solutions have been proposed in this paper. Since the unfortunate culture of copper theft occurs mainly in substations, the relatively low cost zone monitoring solution is more appropriate to sub-station applications.

Consequential to the high cost of insurance claims for damaged appliances, it is not inconceivable that insurance companies may start to demand the installation of means to mitigate against the effects of overvoltage damage to appliances. The voltage sensing devices described, offer affordable solutions involving only relatively minor modifications to standard freely available Earth Leakage Circuit Breakers.

References

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