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Dirty Power – The invisible risk for your electronics

June 2021

Table of contents

Introduction

“Dirty Power” means an unclean supply system. Whereby, this does not concern the means (environmental aspect) how your utility company generates power, but rather how certain electrical/electronic units are “contaminated”, often unknowingly.
What, however, does “contaminate” mean and what does it mean for you to be connected to such a “dirty mains”?

Not only every industrial production plant, but even the simplest electronic units from private households, are causers of “Dirty Power”.
Nowadays, industrial plants almost always contain modern high-performance electronic units and components, including one of the most used components – the frequency inverter.
Frequency inverters (FIs) are normally deployed where an adaptation of the work performance is necessary and so, for example, a speed-regulated drive is deployed. This is the case for handling systems, turning machines, presses, punches, pumps, etc.
The power electronics installed in an FI always cause so-called mains pollutions because of high-frequency switching operations. However, it is possible that other electronic units with switched-mode power supplies also cause such interferences to a limited extent.
Mains pollutions are considered to be interferences that affect the normal sinus voltage of a supply system.

The ideal voltage curve of the alternating voltage corresponds to the graphical characteristic of a sine wave (see Fig. 1).
Whereby, the maximum voltage (peak voltage) is the same as the amplitude value (peak value of the curve).
The single-phase alternating voltage of 230 V supplied by the utility company, as known from the normal household power socket, is the effective value. This is approximately 70.7% of the peak voltage, namely approximately 325 V.
Alternating voltages are mainly specified with the effective value, because this corresponds to the power of an equivalent direct voltage. Direct voltages always have a constant value (e.g. +24 V) and describe graphically a horizontal straight line.
Because the current is proportional to the voltage, it is similar graphically to the characteristics described above.

The oscillation shown in Fig. 1 represents an entire cycle. The cycle duration is the time scale of an oscillation. A cycle so defines an entire oscillation before it repeats itself. A cycle can also be described by 360°. This results from the generation of the alternating current in which the rotor turns in the generator and so one rotation (360°) corresponds to one cycle.

The 230 V mains has a frequency of 50 Hz (hertz) which means that the generator rotor turns 50 times per second. Consequently, 50 successive sine waves are represented graphically for the duration of one second.

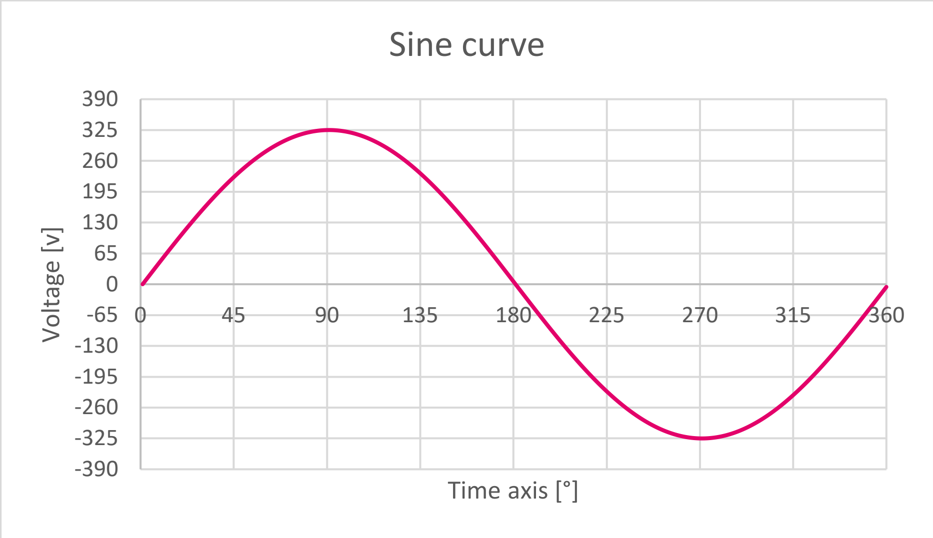

Fig. 1: Sine characteristic

Three phases (conductors) are used for a three-phase system. These three phases are displaced by 120° to each other (see Fig. 2). This displacement is caused by the fact that for the power generation, three coils (to which the individual phases are connected) are placed at 120° angle to each other in the generator. This results in three alternating voltages time-displaced by 120°.

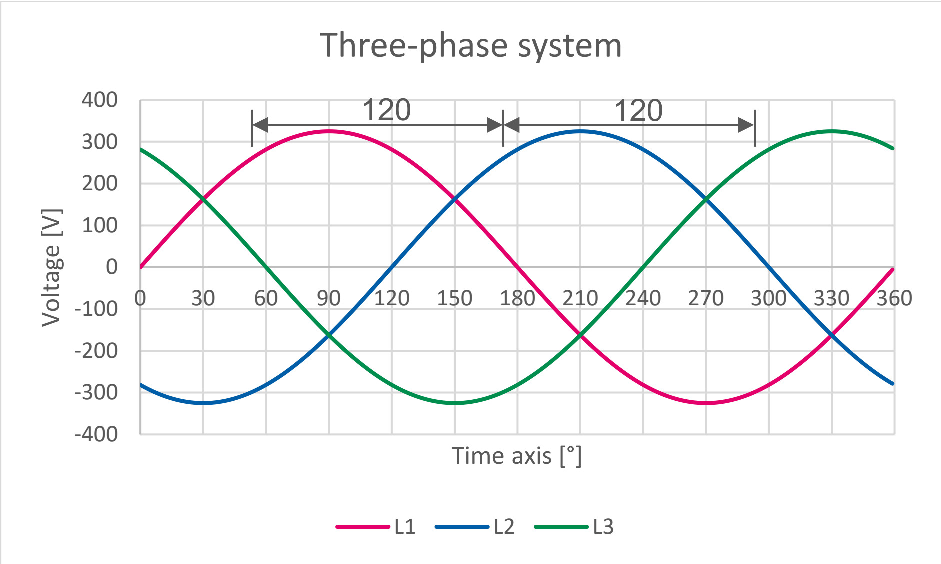

Fig. 2: Three-phase alternating voltage characteristic

Mains pollutions change the typical sinusoidal form. These interference phenomena differ, for example, in

- **Harmonics:** Multiple of the basic sine wave (50 Hz) that distort this by overlaying (no longer pure sinusoidal form). Multiples are, for example, sine waves with 100 Hz, 150 Hz, 200 Hz, etc.
- **Transient surge voltages:** Very short voltage peaks in an interval of a few nanoseconds to milli-seconds. Shown graphically, this can be recognised by the very short, but high “spikes” on the normal sine voltage.
- **Flicker:** Flickering of illumination scarcely detectable by the human eye caused by rising and falling current strengths is well known.
- **Asymmetries:** In the three-phase system, the three phases normally have the same current and voltage characteristic, and are phase-displaced by 120° to each other. Once one of these no longer applies, these are called asymmetries.

To determine mains pollutions, we recommend that a detailed mains analysis is performed. The required and very expensive measurement and analysis units are often not always available to everyone. There are, however, various signs of “dirty power” that indicate the presence of an “unclean” supply system, even without the required measuring instruments. These signs are frequently not interpreted as such, but rather they are accepted as being “normal”.
One sign can be sudden and unexplained fault alarms of machines, although no fault cause can be determined. Likewise, the regular burning-through of incandescent bulbs in the building illumination or repeatedly defective electronic components and units as well as failures in the plant area indicate “dirty power”.
Once a part or the entire plant comes to a standstill because of this, it very quickly becomes extremely expensive for the operating company. The often time-intensive troubleshooting, the replacement of defective components and, in particular, production failure, cause the costs to increase rapidly.
By comparison, the expenditures for the associated counter-measures to reduce interferences are low.

Consequently, for example, in the case “Causer: frequency inverter” it is sensible to operate in accordance with the manufacturer's specifications and to use the line filter appropriate for the associated FI.
However, there are frequently cases for which this filter method no longer suffices as sole measure. This is caused by high-performance FIs and/or a large number of FIs or even other units with power switching electronics in the plant mains.

Although filters reduce the mains pollutions to acceptable values for the sensitive electronics, they do not remove them completely. Nevertheless, a small proportion of interferences returns to the plant operator's mains. When many FIs or other electronic power switching units are present in the mains, these small interferences can accumulate (exponentially) and attain values that are no longer harmless for sensitive electronic components in the same mains. This is true even when the filters are correctly dimensioned for each individual FI.

This whole problem can be summarised as one topic area: EMC (electromagnetic compatibility).
Normative directives of the EMC, such as the interference resistance of the units, should counter the above-mentioned problems. The interference resistance describes the protection of the unit against damage and/or malfunction caused by external interferences. Accordingly, manufacturers design their products based on the requirements or even higher than described in the Standards. Even the maximum requirements placed on the emitted interference are observed by the manufacturers (or any necessary filter measures are defined), so for the correct design, all potential interference sources are also standard-compliant.
However, reality is different; this is where theory departs from experience. Nowadays, the real conditions in the mains often significantly exceed the normative directives despite the above-mentioned measures. Thus, although the manufacturers' products fulfil or even exceed their required specifications for the interference resistance and emitted interference, and even the interference-generating units have been designed standard-compliant, additional protective measures must be adopted in some cases in the plant operator's mains.
It becomes clear how "dirty" the mains often is and "dirty power" can affect everyone.

What, however, needs to be done? This is where the plant operators come into play. The objective should be to keep your own mains as interference-free as possible in order to reduce any failures, the associated effort and costs.

The following table provides an overview of the most frequent phenomena for mains pollutions, their detection characteristics, the interference sources and counter-measures.

Phenomena	Characteristics/ Identification features	Interference source	Measures	Standards
Voltage fluctuations / voltage changes (Chapter 2.2 Appendix)	• Flicker • Malfunction of electrical equipment	• Switching large loads • Start up of powerful motors • Switching transformers • Thermostat controllers • Arc furnaces • Welding machines • Directly acting converters • Cranes • Lift systems	(see Flicker)	DIN EN 60038 (VDE 0175-1) DIN EN 50160 DIN EN 61000-2-2 (VDE 0839-2-2) DIN EN 61000-2-4 (VDE 0839-2-4) DIN EN 61000-3-3 (VDE 0838-3) DIN EN 61000-4-14 (VDE 0847-4-14) DIN EN 61000-4-30 (VDE 0847-4-30)
Flicker (Chapter 2.3 Appendix)	• Brightness fluctuations in the illumination (flickering) • Frequently defective lights (incandescent bulb)	• Units with fluctuating current consumptions • Hotplates • Welding units • Presses • Air-conditioners • Flow heaters (as for voltage fluctuations)	• Load distribution • Ensure symmetric distribution of equipment • Prevent rapid voltage changes (e.g. smooth motor start-up) • Start-up current limitation • Staged connecting (e.g. for heating resistors) • Larger conductor cross-sections	DIN EN 50160 DIN EN 61000-2-2 (VDE 0839-2-2) DIN EN 61000-2-4 (VDE 0839-2-4) DIN EN 61000-2-12 (VDE 0839-2-12) DIN EN 61000-3-3 (VDE 0838-3) DIN EN 61000-3-11 (VDE 0838-11) DIN EN 61000-4-15 (VDE 0847-4-15)
Voltage dips / commutation dips (Chapter 2.4 Appendix)	• Malfunction of electrical equipment	• Power inverter • Power controller	• Commutation choke coil in front of the corresponding interference sources	DIN EN 50178 (VDE 0160) DIN EN 60146-1-1 (VDE 0558-11) DIN EN 61800-3 (VDE 0160-103)
Voltage unbalance (Chapter 2.5 Appendix)	• Impermissible heating of motors • Noticeable noise generation for motors • Premature wear on motors	• Unequal distribution of single-phase consumers to the three phase conductors • Connection of loads between phase conductor and neutral conductor • Photovoltaic systems • Heating plants • Filter plants • Arc furnaces • Welding systems	• Avoidance of asymmetric distribution of single-phase loads	DIN EN 50160 DIN EN 61000-2-2 (VDE 0839-2-2) DIN EN 61000-2-4 (VDE 0839-2-4) DIN EN 61000-2-12 (VDE 0839-2-12)
Harmonics/interharmonics (Chapter 2.6 Appendix)	• Impermissible heating and premature failure of transformers and motors • Malfunction and damage of equipment within a system • Accidental triggering of circuit-breakers • Vibrations and noise formation for motors • Failure of IT systems • Risk of fire caused by conductor overload (neutral conductor)	• Equipment with non-linear characteristic (transformers, fluorescent lamps) • Power electronics (rectifiers, triacs, thyristors) • Frequency inverters • Phase-angle control (dimmer) • Coils with iron cores • Power packs	• High-performance consumers as near as possible to the power supply • Filter measures (passive/active) • Chokes	DIN EN 50160 DIN EN 61000-2-2 (VDE 0839-2-2) DIN EN 61000-2-4 (VDE 0839-2-4) DIN EN 61000-3-2 (VDE 0838-2) DIN EN 61000-3-12 (VDE 0838-12) DIN EN 61000-4-7 (VDE 0847-4-7) DIN EN 61000-4-13 (VDE 0847-4-13)
Transients (Chapter 2.7 Appendix)	• Damaged electronics caused by short surge voltage pulses	• Switching actions (contactors, relays, motors) • Lightning strikes • Operation of collector machines • Switch off transformers and reactance coils	• Surge voltage protector • Varistors • Lightning protection concepts • Potential equalisation	DIN EN 61000-4-1 (VDE 0847-4-1) DIN EN 61643-11 (VDE 0675-6-11) DIN VDE 0184 DIN VDE 0100-443 DIN EN 62305-1 (VDE 0185-305-1) DIN EN 62305-4 (VDE 0185-305-4)

Fig. 3: Phenomena of mains pollutions

In general, it can be assumed when such interference sources are present in the mains (see table), the described phenomena occur.

The more the listed equipment is present in the mains, the more appropriate the statement that the mains is “dirty”.

Whereby, two trends in industrial control and automation technology from recent years cause users to also become ever more aware to the problem of mains pollutions and EMC interferences.

- For technological, optimisation and automation reasons, even in high performance areas, speed-regulated drives, rather than the previously usual On/Off drive technology, are being increasingly deployed.
- In general, the deployed control and automation technology is also becoming increasingly complex; compared with the still frequently used electromechanical or simple electronic systems of the predecessor generations, the electronics used are significantly more susceptible to such interferences.

Both effects mutually reinforce each other.
This means that users, particularly for technological leaps and generation changes with the newly deployed components, experience interferences that apparently did not exist in the past. As mentioned above, many factors in the EMC topic area affect the sensitive electronics that can be considered only partially by the component manufacturers. Depending on the overall plant design, the plant operator must often adopt supplementary measures.

This statement is also true for the deployment of the current Rittal Blue e+ cooling unit generation.
Also here, compared with the predecessor generation, improved control, frequency-controlled components, etc. result in significant cost savings during operation.
Sensors acquire numerous states that communication modules query and utilise for preventative maintenance.

Rittal has placed high demands on the electronics design; the Blue e+ cooling units are designed and tested far outside the normative requirements with regard to interference resistance.

Nevertheless, for the reasons mentioned, isolated cases can occur in which this does not suffice in a specific plant concept.

Experience shows: When many frequency inverters (or similar power electronics) are present in the plant mains, the mains is particularly affected by mains pollutions. The power of the FIs is also significant. The higher the power, the fewer FIs needed to cause severe mains pollutions.

This is aggravated by cooling units frequently being fed directly from the submains that contain the interfering power electronics. The cooling unit is usually located in the same enclosure in which the components to be cooled are also located.
The high-frequency FI switching operations quickly generate successive transient surge voltages that long-term can damage the surge voltage protective devices (varistors) installed in the cooling units. This concerns the previously mentioned specific cases for which the plant mains is particularly highly contaminated by the mains pollutions (*Chapter 3, Appendix*).
Rittal recommends not only appropriate filter measures specified by the associated manufacturers, but in the case of doubt, to install an additional surge voltage protection as direct equipment protection.
Technical specifications for a suitable surge voltage protection module when using power electronic components (e.g. FIs) up to a power of 800 kVA:

- U_c = 385 V (50/60 Hz)
- I_{max} = 40 kA
- I_n = 20 kA
- U_p = 1.75 kV

The line filters deployed for interference suppression of the power electronics (FIs, power packs, etc.) lead via the protective conductor operational leakage currents to earth (*Chapter* 4, Appendix).
These leakage currents can increase the potential on the protective conductor. What, however, is potential?
Birds can sit on overhead power lines without suffering an electrical shock. How is this possible? The keyword is potential difference.
Current always flows from a higher potential to a lower potential; whereby, the potential difference is the voltage. A bird sits with both feet at the same potential of an overhead power line. Because it does not bridge any potential difference, no current flows through its body.
The overhead power line has a potential of several kilovolts (e.g. 50 kV). In contrast, a mast connected with earth has a potential of 0 V (reference potential). Because the cables are separated from the mast with insulators, no current can flow to the ground.
If a bird would unfortunately theoretically touch the mast and the cable simultaneously, it creates a bridge between the two different potentials. The bird would be subjected to a voltage drop of 50 kV. This corresponds to the difference of the two potentials for the cable (50 kV) and the mast (0 V). The current now flows from the cable, through the bird to the mast into the ground. The bird would burn to death immediately.

This example illustrates that potential differences can be life-threatening.

Potential differences quickly become dangerous, not only for humans, but also for machine electronic components. They can be damaged when the potential equalisation is faulty (*Section 4.1, Appendix*). Thus, it is important that every conductive part of a plant is connected earthed with the main earth busbar and so brought to an identical potential.

Cables (protective conductors) also have an electrical resistance that depends on the cable length and cross-section. To keep the potential differences between plant parts and the various protective conductors as small as possible, they must be connected with earth closely-meshed (= short cable length) and with the largest-possible cross-section. It is also important, that not only the mechanical connections of the electrically-conductive plant parts, but also the protective conductors, are mounted so that a low electrical resistance can be ensured permanently at the connection points. This requires that the screw joint is secured against self-loosening and the necessary corrosion protection appropriate for the environmental conditions ensured.

1. Environments

The environment and the installation location of the plant electrical equipment determines which EMC measures must be adopted. The EMC generic standards of the DIN EN 61000-6 series differentiates between residential and industrial areas.
A low interference resistance suffices for equipment in the residential area, i.e. the electrical appliances used there do not need to be designed to handle extreme interferences. On the other hand, they may themselves have only a low emitted interference, i.e. the appliances themselves must not cause any extreme interferences.
Because of the significantly higher powers of the machines and systems deployed in the industrial area compared with the residential area, larger emitted interferences are permitted in this case. Thus, the electrical equipment may be an interference source because of their function (e.g. frequency inverter). Accordingly, such electrical equipment must itself have an inherently large interference resistance so it is not affected by other units in the mains.
When units observe the limit values for interference resistance in the industrial area (DIN EN 61000-6-2) and the limit values for emitted interference in the residential area (DIN EN 61000-6-3), they satisfy the maximum requirements for both environments. These units then have the smallest possible emitted interference, coupled with largest possible interference resistance, and so can be deployed anywhere.

1.1. Normative specifications for the residential area to DIN EN 61000-6-1/-3

The residential area environment includes operational sites that can be connected to the public low-voltage supply system. Other than typical residential buildings, such as houses, supermarkets, offices, restaurants, service stations and those operations without their own transformer station belong to the residential areas.

- Interference resistance: DIN EN 61000-6-1 (VDE 0839-6-1)
- Emitted interference: DIN EN 61000-6-3 (VDE 0839-6-3)

1.2. Normative specifications for the industrial area to DIN EN 61000-6- 2/- 4

The industrial area environment includes operational sites that can be connected to the public supply system via their own high- or medium-voltage transformer.

- Interference resistance: DIN EN 61000-6-2 (VDE 0839-6-2)
- Emitted interference: DIN EN 61000-6-4 (VDE 0839-6-4)

2. Mains pollutions – Detection and reduction

The individual phenomena, their creation and reduction possibilities are explained clearly below.

2.1 DIN EN 50160 (characteristics for voltage quality) and DIN EN 61000 standard series

The voltage and mains quality is defined in DIN EN 50160. It describes the significant characteristics of the supply voltage. DIN EN 50160 does not specify the compatibility level required for the equipment connected to the mains, but rather the expected value range for the supply voltage characteristics. These characteristics also include mains pollutions.

The structure of the DIN EN 61000 series reflects the topics handled in the basic EMC publications. As the table shows, they cover terminology, descriptions of electromagnetic phenomena and the electromagnetic environment, measurement and testing technology as well as guidelines for installation and reduction.

DIN EN 61000

Part 1: General

- Basic terms (basic principles, definitions, terminology) – interference model
- Functional safety (what is the purpose of a safety function and what measures it fulfils satisfactory)
- Measurement imprecision; measurement uncertainty

Part 2: Environment

- Description of the environment
- Classification of the environment
- Compatibility levels

Part 3: Limits

- Emission limits
- Immunity levels (provided they do not belong to the responsibility of product committees)

Part 4: Measurement and testing technology

- Measurement technology
- Testing technology

Part 5: Installation and reduction guidelines

- Installation guidelines
- Reduction methods and reduction units

Part 6: General standards

- General emission and immunity requirements in various environments

2.2 Voltage fluctuations / voltage changes

Voltage changes are considered to be a single change of the voltage effective value during a half-cycle. In contrast, voltage fluctuations are regular or irregular series of voltage changes.

Typical causes of voltage fluctuations are switching On/Off large loads, switching transformers, start-up of powerful motors, thermostat controllers, arc furnaces, welding machines as well as any equipment that causes voltage changes. The latter differentiates between regular and irregular voltage changes.

Regular voltage changes occur, in particular, during the operation of directly-acting inverters (such as frequency inverters without DC link) or welding machines. In contrast, irregular voltage changes are caused by cranes, lift systems or arc furnaces (during the melting phase).

2.3 Flicker

Flicker are effects of voltage fluctuations which although lying within the tolerance range, are considered as interference, because they can be discerned by humans.

They are the result of fast directly successive series of voltage fluctuations that permanently affect the brightness of illumination equipment. The light begins to flicker. Because the human eye reacts to even smallest brightness fluctuations, they are experienced directly as interference. The shorter the intervals between successive fluctuations, the more distinct and unpleasant sensed by a human. The eye is most sensitive at 18 Hz.

Such flicker can indicate dirty mains. The more lights that exhibit this behaviour, the more probable the assumption that mains pollutions are involved.

Flicker is caused by units with fluctuating consumption currents, such as hotplates, welding units or presses. Because flicker is the effect of voltage fluctuations, the causes are correspondingly identical.

Flicker can be countered by dividing loads or limiting the start-up currents for motors. To do this, it is desirable to ensure symmetrical mains loading. This is because many causes for voltage fluctuations and flicker are also significant for voltage asymmetry.

2.4 Voltage dips / commutation dips

Commutation dips are short voltage dips that normally last 1 ms to 2 ms. Whereby, the voltage dips by up to 40% of the rated voltage. A typical characteristic of commutation dips is that they occur as often as six times per cycle. This is because they normally occur when 6-pulse power inverters (with B6 rectifier circuit) are used. As the name implies, they generate six switching pulses within one mains cycle. The mains-side semiconductor elements (e.g. thyristors) for these power inverters and power controllers briefly short-circuit two phase conductors. Although this short-circuit provides the desired current pulse, it also causes a voltage dip, the commutation dip.

Because these operations occur very quickly, high-frequency harmonics also occur increasingly.

One measure that can be adopted for commutation dips is the deployment of so-called commutation choke coils installed in front of the causing units. The chokes ensure that the commutation dips accept mains-conform values below 20% (voltage dip).

2.5 Voltage asymmetry

The neutral conductor (N) in accordance with DIN VDE 0100-200 serves as return conductor in the alternating-voltage mains and causes no return-conductor current in a three-phase system for symmetrical loading. It normally has the same potential as the protective conductor (earth).

Voltage asymmetry is involved in a three-phase system when the effective values of the three phase conductors to the neutral conductor are no longer identical or their phase relation of 120° to each other is displaced. Voltage asymmetries are caused, for example, by the unbalanced distribution of single-phase consumers on the three phase conductors, photovoltaic systems, the connection of loads between phase conductor and neutral conductor or the connection of industrial loads between the phase conductors. The latter includes heating plants, filter plants, arc furnaces and welding systems. Asymmetric illumination systems (non-uniform distribution of lights on the three phase conductors) also generate non-uniform mains loads.

Voltage asymmetries can be evaluated not only by the angle differences and the deviations of the voltage effective values, but also by the ratio of the negative component (negative half-oscillation) to the positive component (positive half-oscillation) of the voltage. With regard to the three-phase system with clockwise rotation, this means that the positive component has the same rotational direction, whereas the negative component acts against the clockwise rotation.

For symmetrical loading, the two systems (positive system and negative system) counteract each other; the result is the zero phase-sequence system. The zero phase-sequence system does not have any rotation for a balanced ratio of positive system and negative system. Asymmetry results when this is not the case.

Rotating electrical machines (motors), in particular, are affected by voltage asymmetries.

This results in impermissible heating and higher mechanical loading. The emitted interference with regard to harmonics is reinforced for mains-commuted power electronic circuits, such as those for frequency inverters.
The compatibility level (ratio of the negative component to the positive component) for voltage asymmetries is 2% in the industrial area (see DIN EN 61000-2-4 standard).
The most effective measure for voltage asymmetries is to ensure a symmetrical distribution for single-phase loads on the three phase conductors.

2.6 Harmonics and inter-harmonics

Because the sine wave is the most natural form of an oscillation, it is also designated as harmonic oscillation. Other oscillation forms, however, also exist (rectangle, triangle), although they do not normally have a natural origin. If these unnatural periodic oscillations are induced in electrotechnology, the nature behaves as if many harmonic oscillations exist that in total give the apparent other form of an oscillation. When consequently a curve form deviates from the pure sine wave, this is an overlaying of basic oscillations and harmonics. Harmonics are sine waves (namely harmonics) with different frequencies. Whereby, the frequency of a harmonic is always a multiple of the basic sine wave base frequency. This means for a base frequency of 50 Hz, the harmonics have frequencies such as 100 Hz, 150 Hz, 200 Hz. Inter-harmonics are sine waves whose frequency is not a multiple of the basic oscillation of 50 Hz (e.g. 120 Hz, 180 Hz).
Consequently, because once the basic oscillation equals the basic oscillation, the first harmonic does not exist theoretically. Twice the basic oscillation then gives the first harmonic. Thus, the second harmonic is theoretically actually the first harmonic.
Because harmonics can occur in all three phase conductors, a phase displacement exists between them and so also a phase rotation.
Three cases are differentiated:

- *Clockwise harmonics (positive system)*
  - 4., 7., 10., 13., 16., 19., … harmonics rotate in the same direction as a sine wave with base frequency
  - Make motors run unevenly; because of higher speeds due to higher frequencies
  - Noticeable loud noise

- *Counter-clockwise harmonics (negative system)*
  - 2., 5., 8., 11., 14., 17., … harmonics rotate in the opposite direction as a sine wave with base frequency
  - Acts as brake on motors, because they counter the rotational direction
  - Also make motors run unevenly; noticeable noise

- *Non-rotating harmonics (zero phase-sequence system)*
  - 3., 6., 9., 12., 15., 18., … harmonics do not create any phase rotation because they have the same phase in all three phase conductors
  - Do not affect motors

The generators of harmonics are generally all consumers that cause a non-sinusoidal current when a sinus voltage is applied. These include rectifiers as found in power packs or commutation operations, frequency inverters, phase-angle controllers (for dimmers) and magnetisation operations (e.g. a coil with iron core).
The resulting harmonics are distributed by the mains voltage being distorted in the entire plant and have different effects on the equipment present in the plant mains.
Transformers are subject to high losses that result from the higher frequency caused by harmonics. The power factor of the transformers worsens and ageing is accelerated; this causes them to fail prematurely. In addition, there is impermissible heating.
Rotating machines run unevenly; this causes noticeable noise, impermissible heating and also increased losses.
Harmonics can cause circuit-breakers to trigger prematurely.
In particular, the 3rd harmonic (that belongs to the zero phase-sequence system) plays a decisive role for loading the neutral conductor in the three-phase system. For symmetrical loading, the three phase conductor currents in the neutral conductor have zero as sum, namely, counter each other. In contrast, the 3rd harmonic occurs in the neutral conductor because of its triple frequency with triple size. The same also applies to the other harmonics of the zero phase-sequence system (6., 9., 12., …harmonic), although their peak values (maximum values) are significantly lower. Thus, the 3rd harmonic must be considered particularly, because it can overload the neutral conductor. This overload causes heat that long-term can melt the conductor insulation and lead to fire. In particular, the required smoothing capacitors found in frequency inverters and power packs increase especially the 3rd harmonic.
Effects of harmonics can also be divided into short-term and long-term effects.
Short-term effects include malfunctions or damage of plant equipment, IT crashes, vibrations, disturbing noises, and false triggering of fuses. Long-term effects include impermissible heating and overloading of cables, transformers or motors, and so be a fire risk. Line filters and chokes are deployed to reduce harmonics. Likewise, connecting powerful consumers as near as possible to the power supply counters harmonics.

2.7 Transients

Transients are short-term voltage pulses with sometimes significantly higher peak values than the rated voltage. Because the pulse duration is less than 2 ms, transients are also considered to be high-frequency events. Together with lightning strikes, switching operations are one of the major causes of transient surge voltages. The current rises suddenly at switch-on. This extreme current-change speed acts on inductances (e.g. transformers) that cause a corresponding high voltage immediately.

It is possible that a switch “bounces” when switching. This causes a continuously repeating flashover at the switch contact surfaces with switching on and off within a very short time. Such surge voltage pulses are called “bursts”. A “burst” is a brief package of transients that considered as oscillation continue to flatten.

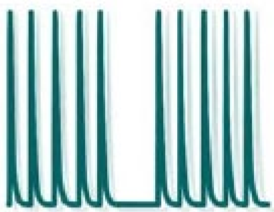

Fig. 4: Burst

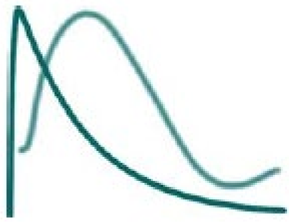

Fig. 5: Surge

A “surge” is caused by various surge voltage events, such as lightning strikes or switching large loads. Such pulses have very high energy and so are the most critical phenomena for sensitive electronics.

The voltage peaks caused by the switching actions are also called SEMP (**S**witching **E**lectro **M**agnetic **P**ulse).

Such voltage peaks can rapidly reach values of several kilovolts that can cause major damage to the sensitive electronics also present in the mains. Although equipment manufactures always provide general protection against transients, these protective measures do not suffice for frequently occurring surge voltage pulses. The more often transient surge voltages occur, the sooner the various protective measures age with loss of equipment protection.

So-called lightning protection concepts provide remedies with varistors and surge voltage protectors to ensure that the voltage at the consumer no longer exceeds the specified limit values and the protective measures installed in the consumer suffice.

3. Surge voltage protection equipment – not only pure lightning protection

Surge voltage events are often linked with direct lightning strikes. The most frequent cause, however, is the surge voltage pulses that result from switching actions.
To permit the appropriate protective measures to respond to surge voltages, DIN VDE 0100-443 and DIN VDE 0100-534 contain four surge voltage categories. They differ in their resistance to impulse voltages, namely, how high the brief voltage pulses can be for specific units without damaging them.
Note that in accordance with the standard, these impulse voltages should occur only sporadically. Because, in reality, the high-frequency switching operations for power electronics (e.g. frequency inverters or large power packs) place a continuous load on the surge voltage protection modules, despite adequate resistance to surge voltage, they can be damaged by overheating caused by the energy of the transients.

3.1 Surge voltage categories

Category I

Sensitive electronic units protected by additional surge voltage protective devices. Such equipment, for example, is located in the power socket where the unit is connected or is installed in the unit plug.
For a rated voltage of 230/400 V, there is a rated 1.5 kV impulse voltage between the active conductors and PE (earth).

Category II

Units that can be operated without additional protection. Household appliances, tools, etc.
For a rated voltage of 230/400 V, there is a 2.5 kV rated impulse voltage between the active conductors and PE (earth).

Category III

Equipment that has increased resistance to surge voltage loads. Such equipment is always permanently installed and so belongs directly to the electrical system, e.g. distributors, power sockets, circuit-breakers, residual current protective devices, busbar systems, terminal boxes, equipment (motors) for industrial plants.
For a rated voltage of 230/400 V, there is a 4 kV rated impulse voltage between the active conductors and PE (earth).

Category IV

Equipment connected near the plant power supply (electricity meters, main fuses, ripple controllers).
For a rated voltage of 230/400 V, there is a 6 kV rated impulse voltage between the active conductors and PE (earth).

The need for a surge voltage protection must be considered when EMC functional failures or damage of sensitive electronic components is involved. In particular, equipment of surge voltage category I (incl. integrated surge voltage protection) must have additional protection for frequent switching actions. The installed protection is not always able to catch all the energy of transient surge voltages.
The manufacturers of such equipment normally assume that higher category upstream surge voltage protective devices handle the major energy load. Thus, the plant operator always has co-responsibility for the surge voltage protection. In addition, transient surge voltages caused by switching actions occur much more often than direct lightning strikes. The consideration for using a general additional surge voltage protection as direct equipment protection is fully justified and is recommended unconditionally for plants in which, for example, many frequency inverters or similar power electronics are installed.

3.2 Types of surge voltage protective devices (SPDs)

Surge voltage protective devices are designated as SPDs. Three types are differentiated:

- Type 1: Lightning current arrestors (coarse protection) placed near the power supply. They prevent lightning currents from entering the building or plant. A dangerous surge voltage, however, remains.
- Type 2: Surge voltage protectors (medium protection) that serve as second protection level and are normally used for remote strikes and switching actions.
- Type 3: Surge voltage protectors used as direct equipment protection (fine protection).

Type 2 and 3 equipment can be considered as additional protective measure for direct equipment protection.
The function principle of the surge voltage protection depends on the associated components. Because the resistance of the varistors reduces to almost zero for surge voltage, they lead the surge voltage pulses to earth.

Whereas measures (arrestor systems or interception devices) to counter direct lightning strikes belong to the so-called external lightning protection, surge voltage protective devices, such as spark gaps, gas-filled surge voltage protectors or varistors belong to the internal lightning protection. They are intended to protect the equipment inside a building. This equipment protection is also generally designated as surge voltage protection.

Although potential equalisation is another significant component of the internal lightning protection, it is important not only because of the lightning protection.

4. Side-effects of filter measures – when a protective conductor becomes a "dirty conductor"

Although line filters reduce the problems caused by harmonics, they themselves cause a new problem. Interferences result that trigger the residual current protective devices (RCDs) or suddenly shutdown a drive during operation. They are caused by so-called leakage currents.
Leakage currents are operational currents that flow to earth over the protective conductor. Line filters create leakage currents because they feed the currents caused by harmonics to the protective conductor. The protective conductor (PE conductor) has the task to rapidly trigger upstream protective devices (e.g. RCDs) in the event of a fault and so protect the operator against dangerous touch voltages (e.g. live equipment housings).
The protective conductor can so carry an operational leakage current or a residual current caused by an insulation fault. To summarise, the protective conductor serves not only personal protection, but also has the task of a functional conductor.
This condition, however, leads to problems. The protective conductor currents must be reduced to a minimum to ensure reliable shutdown in the event of residual currents. Together with the operational leakage currents, the current flowing over the protective conductor quickly exceeds the permitted limits and so falsely triggers the protective devices or, indeed in the event of a fault, does not trigger them.

Thus, DIN 0110-530 prescribes universal current-sensitive residual current protective devices (RCDs type B) for the operation of frequency inverters with line filters, etc.

4.1 Potential equalisation

The operational leakage currents present in industrial plants can cause potential differences dangerous not only for electronic components, but also for humans in extreme situations.
In addition to the protective potential equalisation, a functional potential equalisation can minimise the potential difference. The protective potential equalisation protects humans against an electrical shock. The functional potential equalisation protects machines and other electrical equipment in a plant. It also ensures an EMC-conform environment.

DIN VDE 0100-540 permits not only shared, but also a separate use of earthing systems for protective and functional purposes. The protective function always has priority. If a protective-earth system is already present in an industrial plant, it can also be used for additional EMC measures. DIN VDE 0100-444 specifies that all protective and functional earthing conductors are fed to the main earthing busbars.
The principle task of a potential equalisation is to bring conductive parts to the same potential by connecting them with each other. Whereby, ensure that the associated cables are connected with earth closely-meshed (= short cables) and with low-resistance.

5. Different voltage supply systems

The associated mains system also plays a major role with regard to EMC compatibility. TN, TT and IT systems are differentiated. The TN system is further subdivided into TN-C and TN-S systems, as well as the mixed form from both, a TN-C-S system.
TN systems are typically used in industry.

First letter (Earthing of the current source)	**Second letter (Earthing of the equipment)**	**Suffix (Neutral conductor and protective conductor variant)**
T = “Terre” (earth)	**N** = “Neutre” (neutral)	**C** = “Combiné” (combined)
I = “Isolé” (insulated)	**T** = “Terre” (earth)	**S** = “Séparé” (separated)

TT system: Not only the feeding power supply, but also the equipment connected to the consumer is earthed.

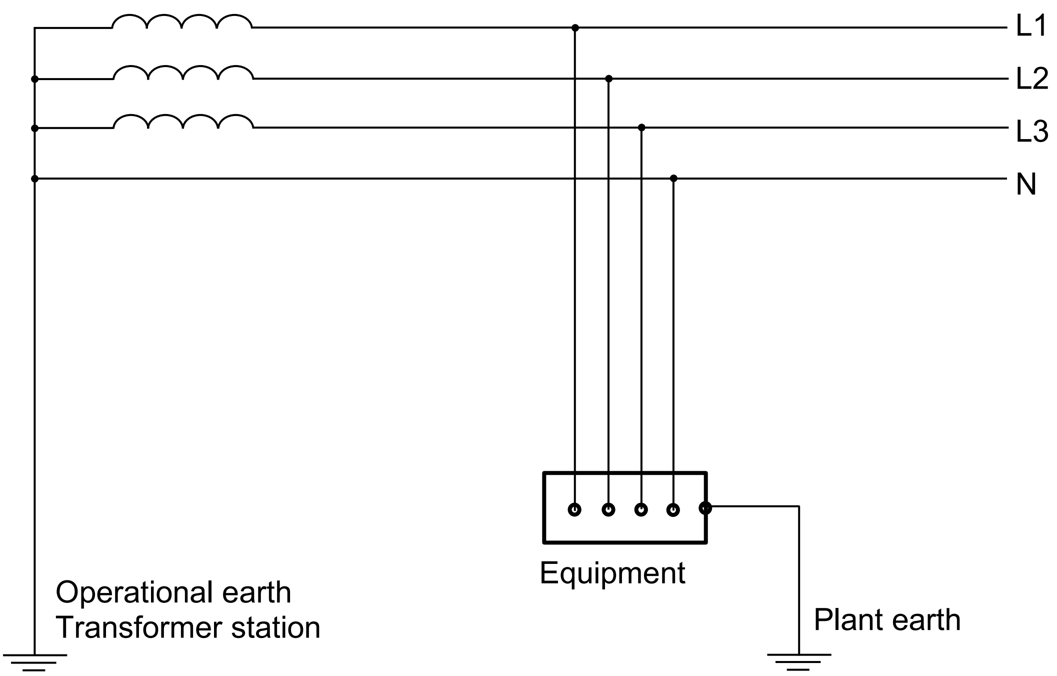

Fig. 6: TT system

IT system: Although the feeding power supply is insulated against earth, all equipment connected to the consumer is earthed.

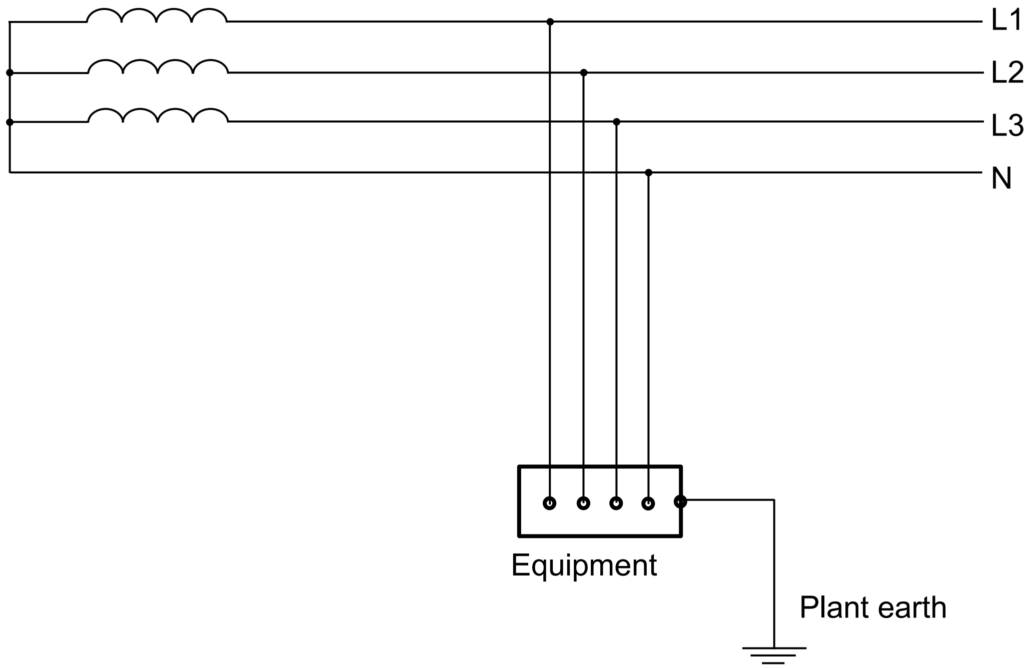

Fig. 7: IT system

TN-C system: The feeding power supply is earthed and the equipment connected to the consumer is connected with earth via a combined neutral and protective conductor.

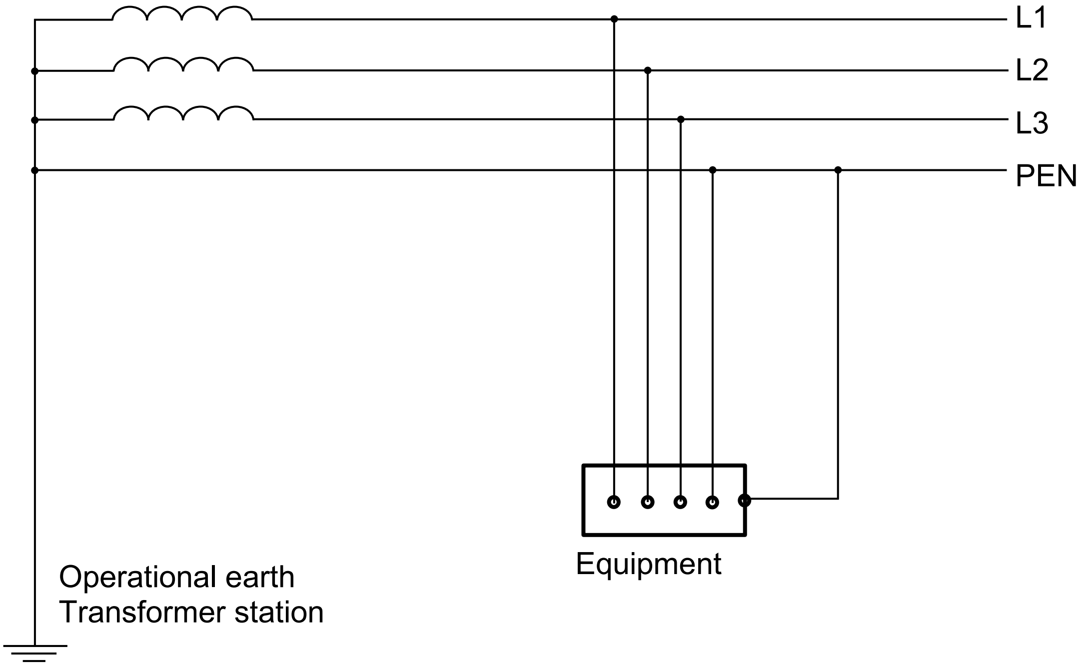

Fig. 8: TN-C system

TN-S system: The feeding power supply is earthed and the equipment connected to the consumer is connected with earth via the protective conductor. The neutral conductor is laid separately.

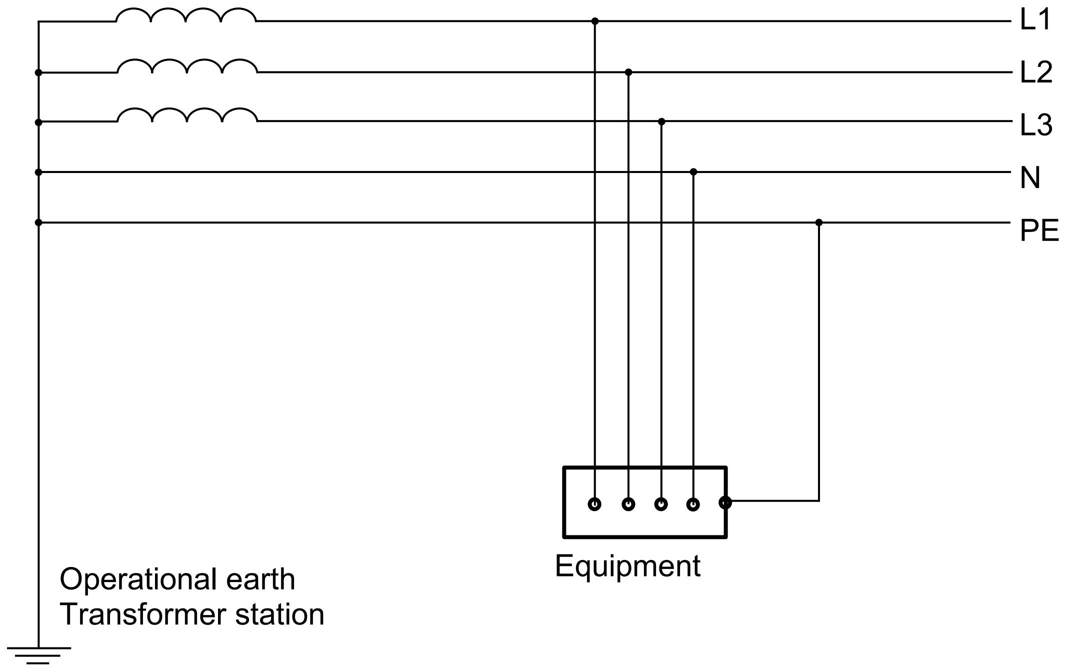

Fig. 9: TN-S system

TN-C-S system: The feeding power supply is earthed; the neutral and protective conductor (PEN) is initially combined, but separated later.

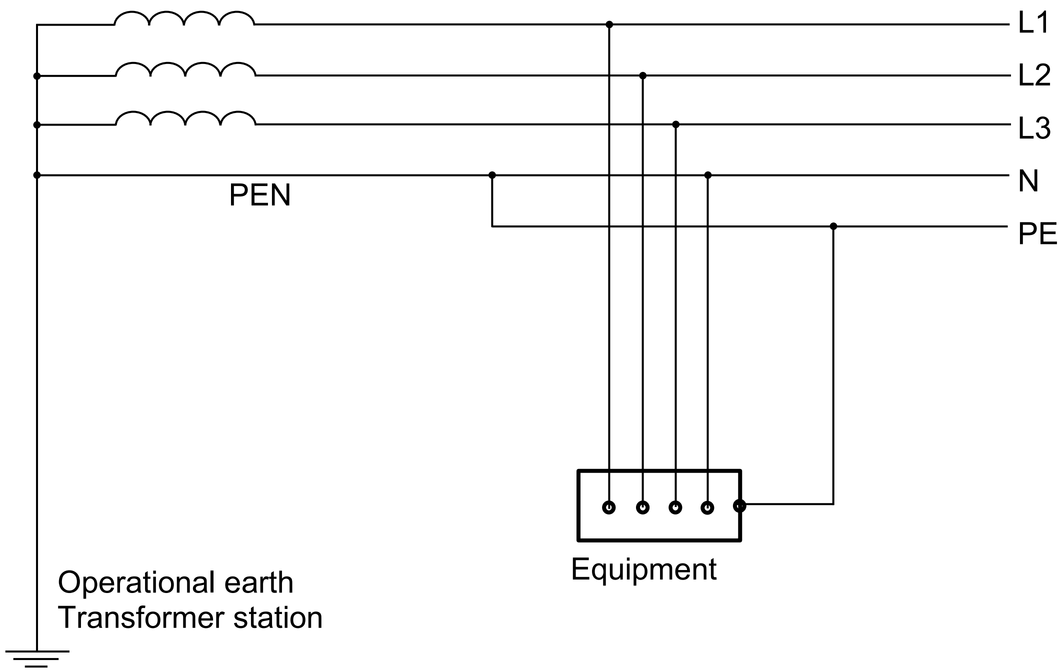

Fig. 10: TN-C-S system

5.1 The PEN conductor

The PEN conductor is the combination of protective conductor (PE) and neutral conductor (N). Thus, in the event of a fault, it carries the residual current and the operational return conductor currents (neutral conductor currents), e.g. for asymmetrical operation of a motor on three phase conductors.
With regard to the EMC compatibility, this conductor causes major problems. DIN VDE 0100-100 specifies that the PEN conductor may be connected more than once with earth. This provides new paths for the returning current (operational neutral conductor current) back to the current source (feeding transformer). These are so-called vagrant currents (stray currents). Stray currents can flow over earthed metallic parts of a machine, conduits and similar conductive parts, whereby they generate an electromagnetic alternating field. This affects the proper function of electronic components in the mains. Thus, EMC compatibility is not given in a mains with PEN conductor.

Because it is not desirable to fully prohibit the PEN conductor, it is possible either to connect the PEN conductor only at a single point with earth or to separate the PEN conductor for a TN-C system early into a separate protective conductor (PE) and neutral conductor (N), and then no longer connect with each other.
This produces a TN-C-S system; the mixed form from the TN-C and TN-S systems.
The TN-S system is suitable for critical EMC applications, because the neutral conductor is laid insulated back to the current source. The return conductor currents do not flow through conductive parts or earth, and the critical electromagnetic alternating fields are minimised.

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