TRAINING DOCUMENTATION

Electromagnetic compatibility

and

inductive components

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Table of Contents

Introduction to electromagnetic compatibility

1 Radio interference and radio interference suppression

1.1 Definition, origin, propagation and effects

Radio interference is the term used to designate unwanted emitted electromagnetic interference which may e. g. interfere with radio reception or other electronic equipment. The currently applicable standards cover the frequency range between 9 kHz and 400 GHz. Here, a general differentiation is always made between the conducted interference ("interference voltage") and radiated interference ("interfering radiation" resp. "interference field strength").

Radio interference suppression is the reduction of such interference to usually below the limits specified in the applicable standards, resp. if concrete interference exists, to the extent that the operation of the equipment affected will again be guaranteed.

Radio interference is created as a result of spark gaps, e. g. collectors in motors, switching contacts in mechanical switches and relays, by rapid voltage resp. current variations in electronic circuits (phase control, digital integrated circuits) as well as by oscillator frequencies, their harmonics and mixed products (integrated microprocessor circuits, switching controllers, frequency converters). The electronic components with ever increasing speeds are capable of realizing ever higher clock frequencies and steeper rising slopes which may very well be the source of radio interference in the VHF and TV ranges.

Electronic circuits with amplificating components may also oscillate totally unnoticed and unintentionally and thus create radio interference. Previously stable integrated circuits may display a tendency to oscillate, e. g. as a result of an alteration of the printed conductor routing. Due to the above, it is indispensable for the developer to also ensure that his electronic circuitry will not oscillate unintentionally.

The electromagnetic interference generated by interference sources will initially start to propagate via all lines connected (usually the mains supply line) as a so-called conducted interference ("interference voltage") and may interfere with other equipment connected to this specific line, e. g. via the AC low-voltage network in a specific building. Depending on the frequency of the interference and length of the lines, this radio frequency will also be radiated and may interfere with radio reception in the form of interfering radiation.

In former times, radio interference almost exclusively interfered with the reception of radio transmissions and other radio services. The increasing utilization of electronic equipment in everyday life, however, results in more and more electronic equipment which may react sensitively to radio interference, although it has nothing to do with radio whatsoever. A switching click caused by the switching ON resp. OFF of an electric motor may thus e. g. result in the crashing of a component equipped with a microprocessor control which is not sufficiently immune to interference or the high-frequency interference caused by a non-interference-suppressed phase control may e. g. inject into an adjacent temperature sensor line, thus corrupting the measured value to an extent where the controlling function as such is interfered with.

1.2 EC Directives, German EMC law, standards and methods of measurement

In Germany, the Radio Frequency Equipment Law was effective until 12/31/1995, which was the expiration date of the transition period for the German EMC Law (EMVG), a law with the help of which the German legislator had implemented the European EMC directives into German law. This law provided limits for radio interference suppression, i. e. emitted interference only.

The legal responsibility for adherence to these limits was with the operator, not with the manufacturer resp. importer of the respective equipment! This meant that if e. g. a personal computer with inappropriate interference suppression was operated, it was the unsuspecting user operating the equipment who committed an offense and not the manufacturer resp. importer of the equipment! As a result of this, the adherence to the standards and limits was handled rather nonchalantly by the industry.

Since 01/01/1996, only those units may be marketed within the EU which meet the protection requirements of the European EMC Directives, i. e. the German EMC Act for Germany! What is new is the fact that the above protection requirements not only include radio interference suppression, but additionally the immunity to interference as well! The legal responsibility for the adherence to the protection requirements of the EMVG is also no longer with the operator, but rather with the manufacturer resp. importer of the equipment.

With respect to the EMC Directive and the Telecommunications Terminals Directive, the supervision of the adherence to the directives in Germany is the responsibility of the Federal Network Agency (Bundesnetzagentur), formerly known as Regulation Authority for Telecommunications and Postal Services (RegTP), as the successor of the BAPT which was meanwhile dissolved. The Federal Network Agency in Germany is attached to the Federal Ministry of the Economy. For futher information see www.bundesnetzagentur.de.

Search for standards and supply sources, questions referring to the contents of the standards (with respect to Germany):

Since most of the European EMC standards are also classified as German VDE Standards, it is recommended to first inquire with
- VDE Verlag GmbH, Bismarckstr. 33 in D-10625 Berlin, www.vde-verlag.de.

It may, however, be possible that a certain period of time elapses between the passing of a European standard and its publication as a VDE standard. In this case, the standard is available in the form of a manuscript from
- DKE (German Electro Technical Commission in DIN and VDE), Stresemannallee 15 in D-60596 Frankfurt a. M., www.dke.de. Other international electrotechnical standards are also available from DKE.

For the sake of completeness, we would like to mention that international resp. European standards also exist in view of EMC which are generally not published in the form of VDE, but rather as DIN standards, e. g. DIN EN ISO 14982: EMC Agricultural and Forestry Machinery and Equipment. These standards, among others, are available from
- Beuth Verlag GmbH, Burggrafenstr. 6 in D-10787 Berlin, www.beuth.de.

Competent information dealing with the contents of European standards are usually available from DKE, organized in the various specialist departments, as well as from the EMC Enquiry service of the Federal Network Agency, see www.bundesnetzagentur.de > Telecommunications > Stakeholder Information > Technical Regulation > EMC > EMC Enquiry Service

Generic emission standards:

EN 61000-6-3:2007 VDE 0839-6-3	Generic emission standard; Part 1: Residential, commercial and light industry
EN 61000-6-4:2007 VDE 0839-6-4	Generic emission standard; Part 2: Industrial environment

Product family standards (emitted interference, selection):

EN 55011:2009 VDE 0875-11	ISM equipment
EN 55012:2007 VDE 0879-1	Vehicles & devices with combustion engines
EN 55013:2013 VDE 0872-13	Sound and TV broadcast receivers
EN 55014-1:2006 VDE 0875-14	Household appliances, electric tools
EN 55015:2013 VDE 0875-15	Electric lighting
EN 55022:2010 VDE 0878-22	ITE equipment
EN 55025:2008 VDE 0879-2	Automotive internal radio interference suppression
EN 60601-1-2:2007 VDE 0750-1-2	EMC for medical equipment
EN 61800-3:2004 VDE 0160-103	EMC for adjustable speed electric power Drive systems
EN 61326-1:2013 VDE 0843-20	EMC for electrical equipment for Measurement, control and laboratory use
EN 61000-3-2/-3:2006/2013 VDE 0838-2/-3	Mains harmonics and voltage variations (flicker)

The limits for mains harmonic components and mains voltage variations up to now were applicable to household appliances with a power input of up to 16 Amps per phase. Since 01/01/2001, these limits are generally applicable to all (also industrial resp. commercially used) equipment with a minimum wattage of 75 W and a maximum input current of 16 Amps per phase.

Generally it can be said that: As soon as an applicable product (family) standard exists for a piece of equipment, then it will have to be applied. It is only if no appropriate product (family) standard exists, that the generic standard will have to be applied!
Also equipment with interference suppression that meets the requirements of the applicable standards may very well be capable of causing interference if operated in the vicinity of sensitive potentially susceptible equipment (e. g. a radio reception station), i. e. in specific cases the interference suppression or the interference immunity may thus have to be superior to that required by the applicable standards.

1.2 Methods of measurement for emitted interference:

The conducted emitted interference is usually measured with the help of a selective radio interference measuring receiver as interference voltage in the frequency range between 9 (150) kHz and 30 MHz (EN standards), with the supply lines (irrespective of AC or DC) being measured with the help of a line impedance stabilization network ("LISN") and control and signal lines with the help of a probe or special LISNs (e. g. for telecommunication lines).
If a LISN is not applicable, e. g. for supply lines with a very high current or at a "in situ"-measurement in a fixed installation where the supply lines may not be interrupted, the conducted interference may also be measured with a probe.
Conducted interference on supply lines in motor vehicles is usually measured via a specific LISN up to 120 MHz.

A special case is the degradation of the public low-voltage supply system by mains current harmonics and mains voltage variations in the range 50 Hz .. 2 kHz. These in the actual sense of the term are not radio interference, but rather a degradation of the quality of the mains voltage. In order to be able to measure this degradation, specific measuring equipment is required, capable of creating a pure mains voltage via an integrated generator and measuring the mains current harmonics and the mains voltage variations via a defined impedance, usually by means of an FFT-Analyzer.

The radiated emitted interference is usually measured in the frequency range from 30 MHz on up, either by means of antennas in the form of electrical field strength in the free field (resp. in an anechoic chamber) or - for power tools, household appliances and similar products - as interference power with the help of an EMI absorbing clamp.

With some equipment capable of generating strong magnetic fields, e. g. induction-type hotplates, the magnetic field strength is measured in the frequency range between 9 kHz and 30 MHz with the help of a loop antenna.

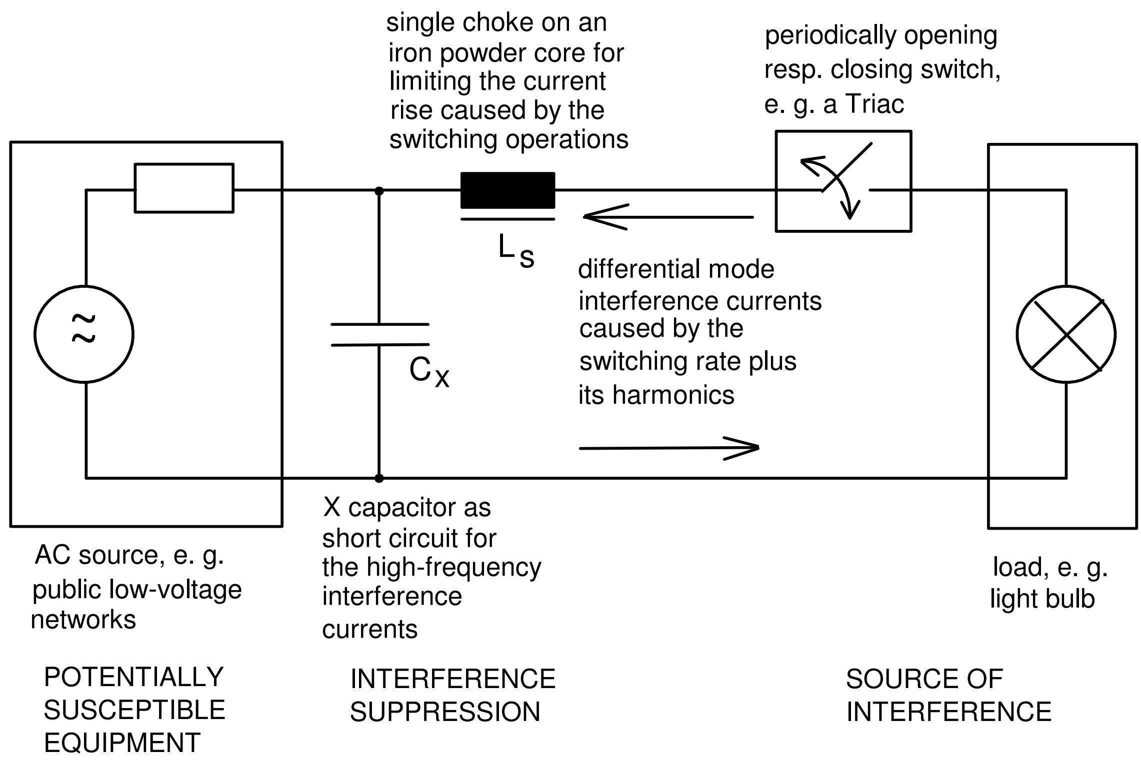
2 Systematic overview - Radio interference and remedies

2.1 Interference voltage (conducted interference):

2.1.1 Differential-mode (symmetrical) interference

(typical < 1 MHz, e. g. as a result of phase controls, rectifiers, semiconductor relays):

Interference suppression by means of X capacitors and single chokes on iron powder cores: The X capacitors will short-circuit the high-frequency interference while the single chokes increase the impedance of the differential-mode interference circuit, thus reducing the interference currents.



Typical example for differential mode interference, here a Triac for the dimming of a light bulb

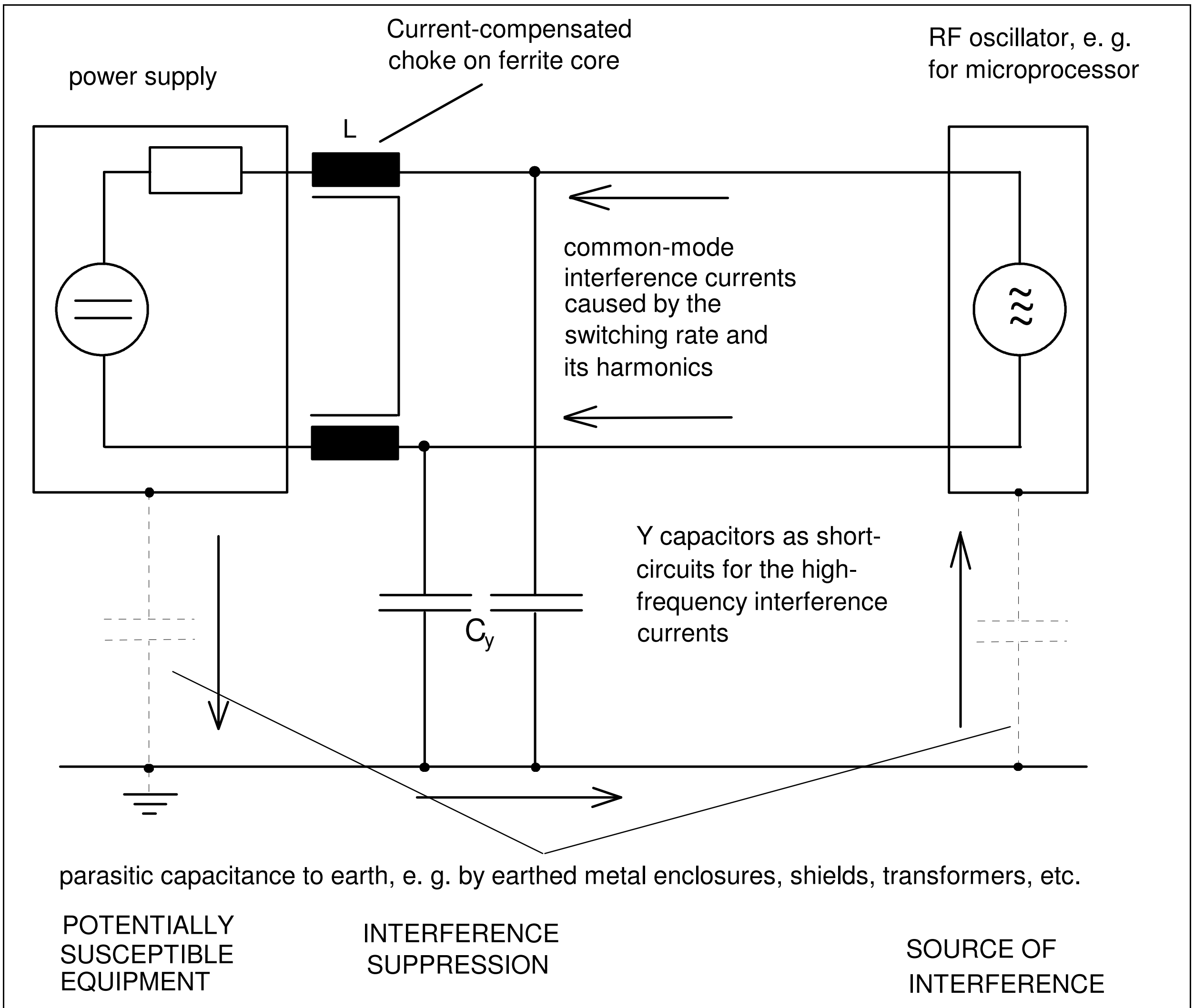
Note on the illustrations on this and on the following page:

From practical experience, it is not necessarily required for the potentially susceptible equipment to be the supply network resp. a different piece of equipment connected to it. It may very well also be part of the interfering equipment as such, e. g. a washing machine equipped with a speed control using a frequency converter, with its unshielded motor line routed in the same wiring harness as the line of the temperature sensor for the suds temperature, thus causing interference with and malfunctions of the temperature control function.

2.1.2 Common-mode (asymmetrical) interference

(typical > 1 MHz, e. g. caused by frequency converters, switched-mode power supplies, RF-oscillators):

Interference suppression by means of Y capacitors, current-compensated chokes on Mg-Zn-ferrite cores (< 5 MHz) and/or Ni-Zn-ferrite cores wound in a single layer (> 5 Mhz): The Y capacitors will short-circuit the high-frequency interference to earth, the current-compensated chokes increase the impedance of the common-mode interference circuit.



Typical example for common-mode interference, here an oscillator for a microprocessor

2.3 Interference field strength (radiation):

Mainly common-mode interference on lines either to or from the equipment (mains, interface, signal lines) which have the effect of an "antenna", more infrequently as a result of radiation of the equipment as such (rule of thumb: In order to produce appreciable radiation, the equipment dimensions must be at least in the order of magnitude of the wavelength). Remedies are Y capacitors, current-compensated chokes or I core chokes, wound in a single layer on Ni-Zn-ferrite cores, shielding, good earth contact, optimized line routing, all equipment components made of metal and connected via large contact areas (ground straps).

2.4 Radio interference suppression

Reduction of interference by adopting the correct interference suppression measures in the right place!
Before specific interference suppression measures are, however, adopted, a check should be made to ensure that the interference as such may not be reduced at the point of origin, e. g. by avoiding unnecessarily steep switching slopes for switching transistors, restriction of high-frequency signals to the smallest possible sector on the pcb resp. in the equipment, selection of the lowest possible clock frequencies, etc. This will usually already make a considerable contribution to reduce the additional interference suppression efforts required!
If specific interference suppression measures are adopted in a piece of electronic equipment, these interference suppression efforts may best be incorporated on the pcb, resulting in a low-priced "interference suppression filter".
Wherever this is not possible, interference suppression may also be achieved by incorporating the appropriate separate filters. In doing so, the following will have to be taken into account: If the interference suppression is achieved by installing a filter at the mains input (e. g. filter with IEC connector), then an accordingly high background noise level will be present within the entire equipment downstream of the filter. It must be prevented that this interference may penetrate to the outside via other lines or missing shields resp. interfere with other electronic components within the very same piece of equipment!

Practical recommendations when working with interference suppression components:

- Suppress interference as close as possible to the point where it originates. Example: In a device with integrated microprocessor circuits and phase control, it usually does not make much sense to suppress interference at the mains input only, since the interference of the phase control may also interfere with the integrated microprocessor circuits. Here, the interference caused by the phase control should first be suppressed directly at the Triac and then the high-frequency interference of the microprocessor electronics should be filtered at the mains connection resp. in the power supply of the electronics components.
- A filter will only work with higher frequencies if it is mounted directly at the source of interference or at the point of transition to a shielded system. Expensive filters in metal enclosures are extremely useless if there is no "clean" transition to a shielded system from an RF point of view, e. g. a conductive equipment enclosure or control cabinet.
- Be suspicious if e. g. a mains filter with an inductance of 2 x 10 mH in the long wave band does not work. In this case you will either have other lines which bypass the filter or you have common-mode pulse noise which saturates the ferrite toroidal core chokes in the filter. In this case what you will need are different materials for the core which do not tend to saturate as quickly, e. g. single chokes on iron powder cores.
- Always take into account the early saturation of ferrite toroidal cores. Also if these are current-compensated, strong common-mode impulses may very well cause a saturation. This applies even more to the new "nano-crystalline" or "amorphous" core materials, which allow for the realization of extremely compact current-compensated radio interference suppression chokes, since the relative permeability of these core materials was increased disproportionately strong in comparison to the maximum saturation flux density.

Approach for interference suppression

- Interference suppression should be attempted prior to the interference immunity test, since the interference media will usually help to achieve an improvement of the interference immunity. After the interfering equipment is connected to the artificial mains network, it is indispensable to first measure the interference before any interference suppression is attempted. Then the lowest frequency at which the limits are exceeded is to be determined, since the lowest critical frequency (e. g. 150 kHz in case of wide-band interference) will be decisive for the efforts required for interference suppression at the individual components!
- The first interference suppression measure to be adopted is the utilization of an X capacitor of increasing capacitance, mains-parallel, up to approx. 0.47 µF at 230 VAC for the attenuation of differential-mode interference. If this is not sufficient, then the common-mode portion of the interference should additionally be limited by means of Y capacitors to earth of increasing capacitance - take into account to the maximum permissible leakage current!
- If the capacitors are not sufficient for interference suppression, then additional interference suppression chokes will be used. In most cases, the chokes are installed on the mains side, since it usually has a lower impedance.
- If this attempt is still not successful, then an investigation is to be carried out as to whether the interference suppression is bypassed as a result of coupling or radiation. The best way to start with the design of the interference suppression is outside the device in a distance of at least four inches. If the components that are necessary are found, they should be built into the device. If the effectivity of the interference suppression is now worse than with the very same components outside the device, there is an internal bypass that must be avoided by optimized placing of the components or wiring inside the device. In some cases an additional shielding inside the device may become necessary.
- If the limits are exceeded only for higher frequencies, then the complete layout will have to be investigated for radiation. If required, RF chokes (wound in a single layer on Ni-Zn-ferrite core material) may have to be used.
- It is not until conducted interference up to 30 MHz is below the limits, that the measuring and interference suppression should be attempted for the higher frequency ranges. Here the layout, shield and a good ground contact play an important role and may have to be modified resp. improved, if applicable.
- At the very end, the final measurement across the entire frequency range is to be made.

Make sure and take into account the fact that any modification of the interference suppression media as such resp. of their arrangement may alter the measurement results. Due to the above, it is indispensable for the final measurement to be carried out in the ultimate state of series production!

3 Improving the interference immunity

3.1 General information:

In modern electronic digital integrated circuits, the control performance required for the execution of commands is so low that pulse-shaped (and thus wide-band) as well as narrow-band high-frequency interference may unintentionally trigger such commands. This means that even a brief individual interference (e. g. caused by a contactor that is actuated only occasionally) may result in the crashing and thus permanent disabling of a microprocessor control.
Also purely analog integrated circuits may react sensitively to this kind of interference, with malfunctions, however, generally occurring only while the interference as such is present, resulting in the fact that a brief individual interference will not be as severe and thus obvious.
Since 01/01/1996, all equipment marketed in Europe must meet the protection requirements of the EMC Directives and thus of the German EMVG, a fact documented by the CE marking. This also includes interference immunity against electromagnetic influence as an essential product feature, i. e. in former times the ensuring of this feature and the proof for interference immunity was submitted voluntarily by the manufacturer, although of interest for the manufacturer - since 01/01/1996, however, it is compulsory.

3.2 Standards (selection)

Generic immunity standards:

EN 61000-6-1:2007 VDE 0839-6-1	EMC - Generic immunity standard - Part 1: Residential, commercial and light industry
EN 61000-6-2:2005 VDE 0839-6-2	EMC - Generic immunity standard - Part 2: Industrial environment

Product (family) standards (immunity, selection):

EN 55014-2:1997 VDE 0875-14-2	Immunity for household appliances, electric tools and similar apparatus (e. g. for gastronomy, shops, as well as electric toys)
EN 55020:2007 VDE 0872-20	Immunity for sound & TV receivers & accessories
EN 55024:2010 VDE 0878-24	Immunity characteristics for ITE equipment
EN 55103-2:2009 VDE 0875-103-2	Immunity of professional audio, video & studio eq.
EN 60601-1-2:2007 VDE 0750-1-2	EMC for medical equipment
EN 61547:2009 VDE0875-15-2	Immunity lighting equipment
EN 61800-3:2004 VDE 0160-103	EMC for adjustable speed electric power drive systems
EN 61326-1:2013 VDE 0843-20-1	EMC for electrical equipment for measurement, control and laboratory use

3.3 General recommendations for increasing the interference immunity

Since radio interference suppression is effective in both directions, a correct interference suppression will already make a major contribution to the increase of interference immunity. Here also, the utilization of a filter at the mains input will make sense only if no major interference is created within the integrated circuits as such. It is furthermore indispensable that all input and output lines be decoupled (slow signals) - either by means of decoupling capacitors to earth resp. to reference ground or by means of chokes - or shielded (fast data lines, sensitive measuring lines) in such a way that no interference may penetrate to the outside or be looped in via these specific lines.

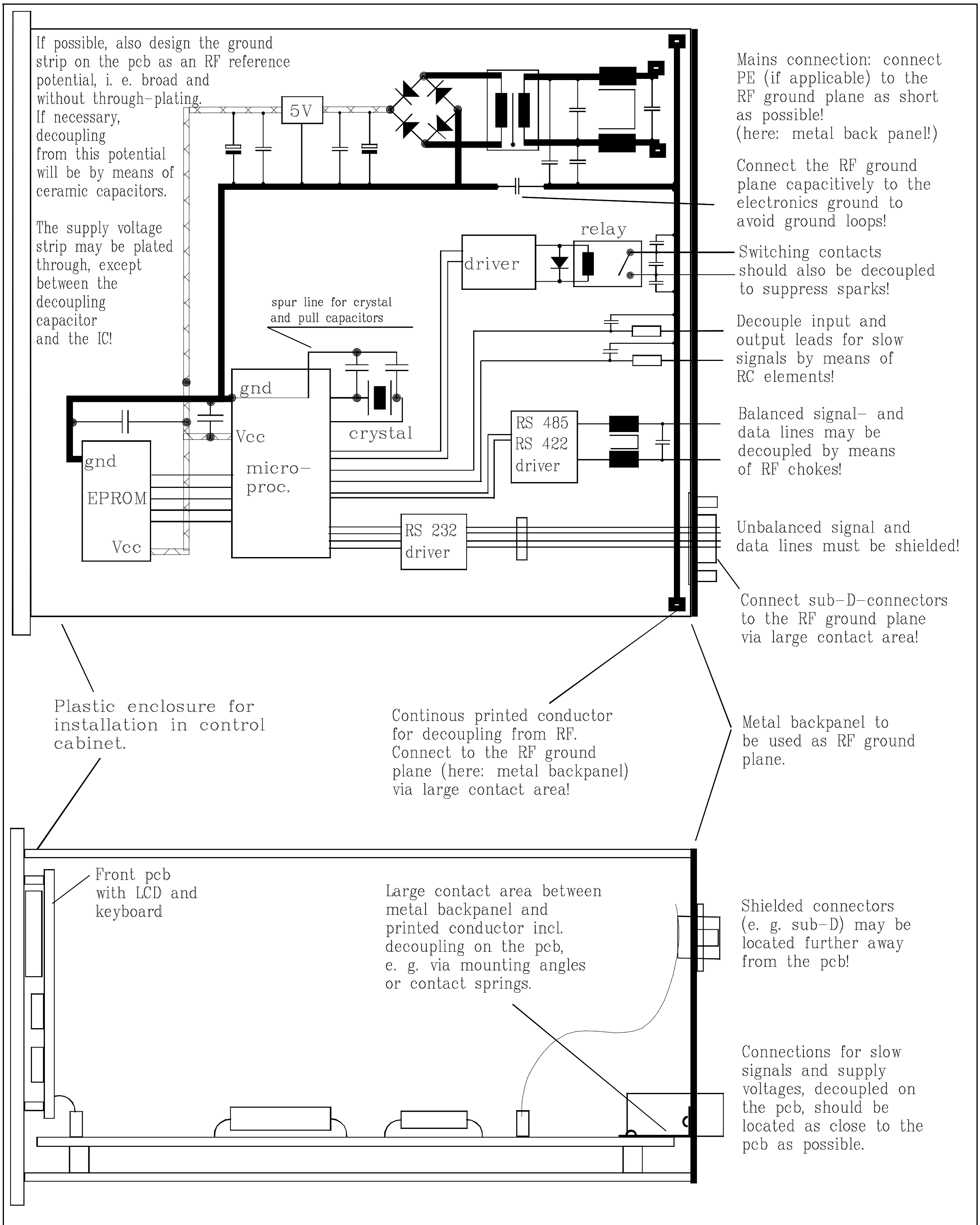
Frequently encountered errors for equipment with shielded enclosures:

In many cases, the incoming mains line is first looped in via switches, fuses or indicator lamps within the respective piece of equipment before the line arrives at the mains filter. This specific section of mains line within the shielded equipment irradiates all interference into the shielded piece of equipment - similar to an antenna - resp. picks up interference created within the equipment and will radiate it to the outside.
This makes the high-frequency interference bypass the mains filter, thus rendering it useless.
The same applies to the control lines - here any existing shields will have to be properly connected to the enclosure directly at the point of entry into a shielded enclosure. It is important to generally ensure that shielded and non-shielded components of equipment are arranged to where they are strictly separated from a spatial point of view.
Attention will also have to be paid to all apertures and slots larger than 1/8 of the wavelength of the maximum critical frequency. Example: Slots larger than 3 cm may cause problems at 1 GHz. Metallic joints which have no low-resistance and large electrical contact areas (key word: shielding resistance), such as joints between painted, anodized or corroded enclosure sections, will frequently be the source of problems. This is particularly true if lines are routed in the vicinity of the joints. They will pick up high-frequency differences in potential at these specific joints and will radiate them again. This is the reason why lines in general (also shielded ones !) should not be routed in the vicinity of enclosure joints.

3.4 Layout design acc. to EMC

Incoming supply lines and signal lines should generally be filtered on the pcb. In case of shielded signal and data lines, connect the shield to a (earthed) enclosures or to a different RF ground plane (e. g. mounting plate in the control cabinet), never directly connect them to the electronics ground! If required, route the electronics ground as an inner conductor!
If possible, avoid ground loops and loops in the supply voltages (ideal: bifilar conductor routing!). In case of multi-layer pcbs, the supply voltages (plus and ground) should be arranged as outer layers. As the reference potential, ground should possibly not be plated-through, since all interference will be capacitively discharged to it. The supply voltage (Vcc) on the other hand may be plated-through, if a decoupling capacitor to ground is provided downstream of each through-plating.
Install a ceramic decoupling capacitor in the operating voltage supply at each IC and do not incorporate any through-plating between decoupling capacitor and IC! ICs with a high interference potential (drivers, multi-vibrators, generators) should have a separate plus and ground line.
Metal enclosures of crystals and the pull capacitors must be connected to the ground connection of the microprocessor via a separate spur line. Provide for ground contact areas beneath the crystals to where no other printed conductors may be routed beneath the crystal or in its immediate vicinity. Make sure and also connect these ground contact areas to the microprocessor ground in the form of a spur line.

Electronics ground and earth (shield) should be routed in such a way that a good capacitive coupling will be possible! Do not electrically connect the electronics ground and the earth to one another (earth loops!), but rather via a capacitor 1 ... 100 nF.
Properly connect all metal and metal-coated components of the equipment to one another from an RF point of view, i. e. provide for large contact areas, and connect them to the equipment grounding conductor (if available) at one position!
Select system cycles as slow as possible. Data signals should not display any overshoot. Make all inputs of logic and microprocessor modules as slow as possible by means of decoupling capacitors (mainly reset and interrupt inputs), provide for a low-resistance connection to ground or to the supply voltage for any unused inputs. Use watchdog timers and assign restart commands to unused ROM sectors!
Level-triggered logics are less sensitive to interference than slope-triggered logics!
EMC optimized programming may also contribute to the increase of interference immunity by incorporating multiple inquiries with plausibility checks at critical program positions in order to e. g. filter out brief interference as a result of switching operations which arrive at a digital input.



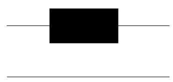
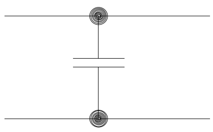
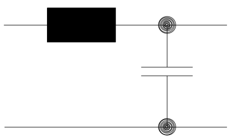
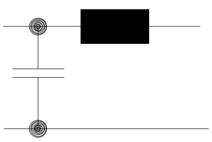
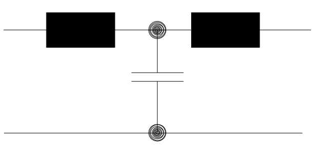
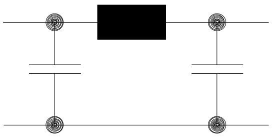
Example of an industrial control designed appropriate for EMC

Interesting facts about radio interference filters

1 General information

Radio interference filters are combinations of several electronic components, usually passive, which attenuate the usable low-frequency signal as little as possible and the unwanted high-frequency interference signals as strongly as possible. Radio interference filters are available as complete units ready to be installed; they may, however, for example also be put together on the pcb of the equipment requiring interference suppression - usually at considerably lower costs.
The filtering effect is based on the fact that for high-frequency interference signals, the interference filters represent the highest possible impedance mismatch of the source of interference to the potentially susceptible equipment. This causes the reflection of the vast majority of interference signals back to the source of interference. Contrary to filters used for the transmission of usable signals, the impedance of which should possibly be adapted as good as possible in order to prevent reflections from occurring, the effect of interference filters is thus based on the highest possible impedance mismatch for the interference signals!

Refer to the following overview for some recommendations for the selection of the proper filter structure:

Impedance of the source of interference	suitable filter	Impedance of the potentially susceptible equipment
low		low
high		high
low		high
high		low
low unknown		low unknown
high unknown		high unknown

Overview of suitable structures of radio interference filters

2 Areas of application

Radio interference filters are used as
- ready-to-install components for interference suppression in equipment, machines and systems, where the user has no influence on the EMC properties of the components and where these will thus have to be adapted to the electromagnetic environment encountered or where an individual interference suppression of all components resp. the modification of these components to ensure interference immunity does not make sense from a cost-related point of view as well as
- discrete circuits constructed directly on the pcb for interference suppression in integrated electronic circuits, being more economic for higher volumes.

3 Notes on the installation

For radio interference filters, it is important that they are positioned as close as possible to the equipment resp. module where the interference is to be suppressed, in order to keep the connecting lines to the equipment as short as possible. This is ever so important, since these connecting lines between interference filter and equipment function just like a receiver resp. transmitter antenna which radiate the interference emitted by the equipment into the environment before it arrives at the filter. The other way round, these lines will also pick up interference present in the environment of the equipment which may then inject into the equipment without any filtration.
An error frequently encountered in practice is that the connecting lines of the filter on the mains and on the load sides are routed to where they intersect or - what is even worse - are partially routed parallel to one another. If this is the case, the filter will become nearly ineffective as a result of a direct coupling via the lines!
In case of interference filters which contain capacitors to ground (Y-Cs - being the case for most filters), the fact that the connection between the earthing point to the equipment resp. control cabinet ground is to be kept as short as possible and made via a large contact area will have to be taken into account. In case of filters with metal enclosures, or metal base plates, these should under all circumstances be connected to the equipment ground, electrically conductive and via a large contact area, e. g. mounting screws with serrated washers.

4 Important criteria for radio interference filters are:

4.1 Nominal current, maximum continuous load current and ambient temperature

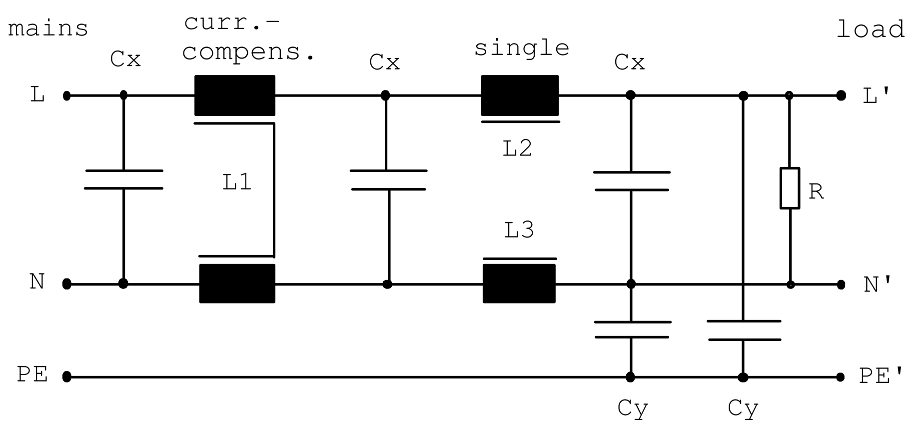
Nominal current is the maximum continuous load current at resistive load, proper installation, 50 .. 60 Hz mains frequency and the maximum permissible ambient temperature (typical: 40 °C). The maximum permissible continuous load current decreases accordingly with a higher ambient temperature. The same is true for loads which create mains harmonics, e. g. phase controls, Triacs, semiconductor relays or primary clocked switched-mode power supplies. The mains harmonics increase the losses, mainly in the inductive components, expressed in a higher temperature development. Brief overcurrents are permissible if an appropriate lower current load follows. This, however, will have to be tested separately for each individual case.

4.2 Enclosures dimensions and type of connections

The lowest priced version are plastic enclosures and flat male connectors. Specific line-through terminals are required for currents in excess of 16 Amps - the extra charge is as much as US$ 5..10 per filter! If straight flat male connectors and insulated flat female connectors are used, these connections are considered as protected against accidental contact in accordance with VBG (German safety standard).
In case of filters for higher currents than approx. 4 x 16 Amps, specific plastic resp. metal enclosures are inevitable, the extra charge will be another approx. US$ 5..10 per filter.

4.3 Filter efficiency

It is primarily the filter efficiency required which determines the efforts to be adopted and the price of the interference filter. It depends on the type of equipment that requires interference suppression, the interference level and other general conditions, e. g. the leakage current permissible.
As a matter of principle, there are two types of conducted electromagnetic interference: differential-mode (symmetrical) interference and common-mode (asymmetrical) interference. In practice, it will usually be a combination of both which occurs.
Common-mode interference is directed to earth and is mainly created by frequency converters, switched-mode power supplies and high-frequency signal sources. It is either short-circuited to earth by means of Y capacitors or decoupled by means of current-compensated chokes. As a matter of principle, Y-Cs to earth or current-compensated chokes produce similar filter effects. Y-Cs will normally cost less than a choke. This is the reason why at first the attempt will be made to exploit the maximum permissible Y capacitance to earth. For this it is, however, indispensable to know the leakage current permissible which may differ, depending on the respective equipment safety regulations applicable. After that is done, the next step is to increase the common-mode attenuation by means of one or more additional current-compensated choke, if necessary.



Basic layout of a single phase radio interference filter with two stages, one each against common-mode and differential-mode interference

In case of differential-mode interference caused by commutation notches of rectifiers or thyristor resp. phase controls, X capacitors of increasing capacitance will first be used. If these are not sufficient or are becoming too large, then additional single chokes on iron powder cores will be utilized. These will usually be incorporated on the load side, while current-compensated chokes are incorporated on the mains side.

The fact that frequently several current-compensated chokes are used should be taken into account for multiple stage filters. It is true that these increase the common-mode attenuation, but not the differential-mode attenuation, which is also important in the industrial sector. We manufacture two-stage filters with typically one stage against common-mode and one stage against differential-mode interference. This procedure involves considerably greater efforts and higher costs than simply connecting two current-compensated chokes in series.

With many other manufacturers, interference filters with additional iron powder cores against differential-mode interference are identified by the designation "very high attenuation also below 150 kHz" or "maximum attenuation", since these iron powder chokes are relatively complex to manufacture and are thus used as the ultimate remedy only.

Please note that the term “filter stage” refers to the inductors only, not the capacitors, so for example a filter with a current compensated choke and two Y-Cs ist still referred to as a single stage filter although it contains two types of components against common-mode interference.

4.4 Attenuation curves

"Attenuation curves" of interference filters or components are frequently rated too high by many developers: They are only suitable to allow for a direct comparison of several components or filters, but the attenuation curve of a filter or component may not be used to directly deduce its suitability for practical applications! When determining the attenuation curves, three prerequisites are assumed to apply which are hardly ever encountered in practice: The filter is operated without any load, i. e. no load current flows, the filter is terminated on both sides with identical impedance (usually 50 Ohms real) and only the filter efficiency at low-level signal operation is measured (measuring signal of only a few mV). This means that particularly those effects which occur in practice as a result of the saturation of the core material of the inductance (operating current resp. strong pulse-shaped interference) are neglected.
This is the reason why a concrete filter efficiency in practice under load may definitely not be deduced from the attenuation curve alone! In practice, a filter with an "inferior" attenuation curve may offer a superior interference suppression efficiency than a filter with the "better" attenuation curve!

5 CE Marking

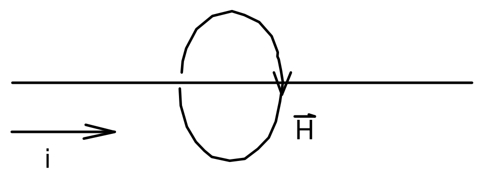
Typical radio interference filters are strictly passive components and require neither a CE marking in accordance with the low-voltage nor with the EMC directives! Filters with active components or surge voltage protectors may be an exception to this rule.

As a matter of principle, our radio interference filters for mains voltage are designed and tested in accordance with VDE 565-3 resp. EN 133 200.

Coils and chokes - an introduction

1 General information

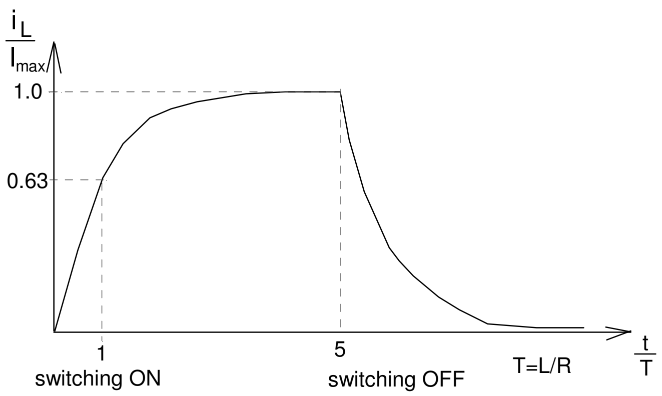
Coils resp. chokes are passive electronic components that
- feature a frequency-dependent reactance which increases with the frequency, i. e. displays an inductive behavior and
- are capable of storing and supplying electrical energy.



Magnetic field around a conductor through which a current flows

The simplest form of a coil is an electrical conductor around which a magnetic field is built up as soon as a current flows through it.

If the current is switched ON, then it will not immediately arrive at the other end of the conductor with full strength, but will rather rise with a time delay (cf. the fig. below), since the magnetic field will first have to be built up around the conductor.



Flow of current through a coil when switching ON resp. OFF

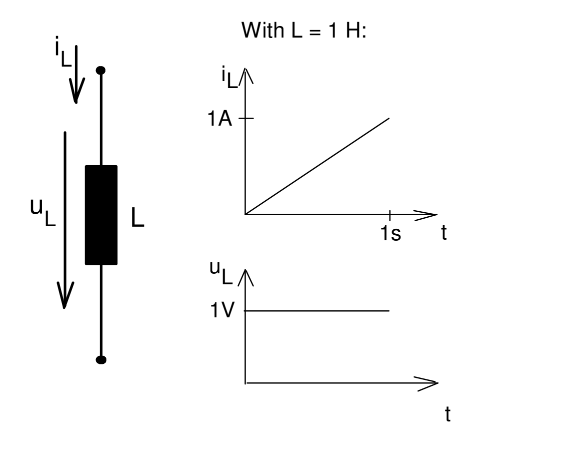
If the current is switched OFF, the magnetic field will again be extinguished. During this process, a current is induced into the conductor which decreases with time until the magnetic field is fully extinguished, i. e. the coil will briefly become a current source. The magnetic field around the conductor is thus full of energy and represents an electromagnetic inertia, which attempts to oppose any alteration of the flow of current through the conductor.

The inductance is a measure for this inertia. The higher the inductance, the higher is the ability of the coil to oppose an alteration of the current flowing through it.

Usually the conductor is wound around a coil core several times in order to increase the inductance. The increased number of turns results in an addition of the individual magnetic fields and thus in a concentrated magnetic flux combined with the smallest possible volume.
If a substance ("core"), which contains more elementary magnets than the vacuum resp. the air, is inserted into the space through which the magnetic field flows, then this effect will again be amplified.
The extent to which this effect is amplified and thus also the energy stored in the magnetic field, is referred to as relative permeability μ_r. $\mu_r = 1$ corresponds to a vacuum, $\mu_r = 85$ means that the energy stored in an identical volume is 85 times higher than that in a vacuum.

Summary of the most important formulas for coils:

1.1 Inductance (also referred to as "coefficient of self-induction"):



Example of the voltage induced in a coil

The inductance of a coil is 1 Henry if a voltage of 1 V is induced in it with a uniform change of the coil current of 1 A in 1 second.

$u_L = L \frac{\Delta i}{\Delta t}$ [V] with

u_L: voltage across the coil
Δi: current change
Δt: time duration of current change

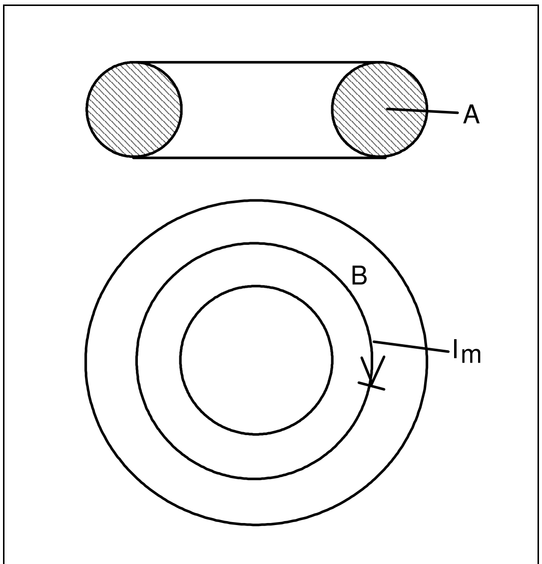
The sign and the arrow symbols in the opposite drawing correspond to the load reference arrow system.

The A_L value ("coil constant") indicates which inductance one turn on the respective core has and is usually specified by the core manufacturer in specifications books. In practice it usually serves for the determination of the required number of turns for a targeted inductance on a given core.

$L = N^2 A_L$ [H = Vs/A = Ωs]

$A_L = \frac{\mu_0 \mu_r A}{l_m}$ [H]

N: number of turns
L: inductance
A_L: coil constant (A_L value)
μ_0: magnetic field constant $1.256\ 10^{-6}\ \frac{Vs}{Am}$
μ_r: relative permeability
A: cross section of coil area
l_m: mean length of magnetic lines of force



A and l_m in the example of a toroidal core

Example:

Target: an inductance of approx. 300 µH.

Given: a toroidal ferrite core with an A_L value of 2250 nH. How many turns are required on the core in order to obtain the targeted inductance?

Solution: $N = \sqrt{\frac{L}{A_L}} = \sqrt{\frac{300\mu H}{2.25\mu H}}$ = 11.5 turns.

In practice this means 12 turns.

Caution: The turns are always counted on the inner side of the core, i. e. also if a conductor is just pushed through the core, it already counts as one full turn!

1.2 Inductive reactance:

$Z_L = j\,\omega\,L$ [Ω] ω: angular frequency = $2\,\pi\,f$

1.3 Relation between inductive reactance and attenuation

$Z_L = 2Z_S(10^{\frac{a}{20}}-1)$ [Ω] Z_L: inductive reactance of the choke
Z_S: circuit impedance (e. g. 50 Ω)

$a = 20 \log (\frac{Z_L}{2Z_S}+1)$ [dB] a: attenuation

1.4 Energy in the magnetic field:

$W = 1/2\, L\, I^2$ [Ws]

1.5 Magnetic field strength:

$H = N\,\frac{I}{l_m}$ [A/m] l_m: mean length of the magnetic lines of force

1.6 Magnetic flux density (also referred to as "magnetic induction"):

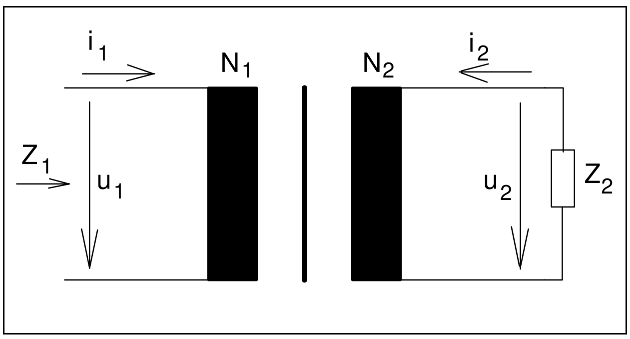
$B = \mu_0\mu_r H$ [T = Vs / m²] μ_0: magnetic field constant $1.256\;10^{-6}\,\frac{Vs}{Am}$
μ_r: relative permeability (vacuum: $\mu_r = 1$)

1.7 Time constant of the coil

Important for the calculation of ON and Off operations: After one period of the time constant, the current through the coil has increased or decreased by a factor of 0.63, after 5 periods by a factor of 0.99.

$\tau = \frac{L}{R}$ [s] R: equivalent resistance of the coil (winding resistance)

1.8 No-loss transformer



Transformation ratio:

$r = \frac{N_1}{N_2} = \frac{u_1}{u_2} = \frac{i_2}{i_1}$

N_1, N_2: number of turns in winding 1 resp. 2
u_1, u_2: voltage at winding 1 resp. 2
i_1, i_2: current through winding 1 resp. 2

Impedance ratio: $r^2 = \frac{Z_1}{Z_2}$ Z_1, Z_2: impedance at the connections of winding 1 resp. 2

Example:

Given: transformer with Z_2 = 100 Ohms real, $N_1 = 2\,N_2$.
Target: impedance Z_1, i. e. the transformed impedance of Z_2 which appears at the connections of winding 1.
Solution: $r = N_1/N_2$ with $N_1 = 2\,N_2$ follows r = 2. The result is $Z_1 = r^2\,Z_2$, i. e. 400 Ohms real.

2 Areas of application

In the following, you will find a description of coils mainly for the attenuation of high-frequency signals, i. e. so-called "chokes", as well as transformers and storage chokes.

For the suppression of radio interference, one or more chokes are connected to form filters, usually together with capacitors. The intention is to allow for an unrestricted passage of the usable signal, e. g. the operating current and, from a specific frequency on up, to attenuate the interference generated within the equipment as efficiently as possible, e. g. clock frequencies of digital circuits or switched-mode power supplies and their harmonics. Filters naturally also work in the opposite direction, by preventing interference which originates in the mains or signal lines connected from effectively injecting into the equipment.

The structure of such a filter is as follows: Contrary to conventional telecommunication technology, the attempt is made to achieve the maximum possible mismatch of impedance for the interference signals to the equipment resp. the environment at the input and output of the filter, in order to reflect unwanted frequencies at the filter back into the equipment resp. into the lines connected.

Another frequent application is the storage of energy by means of so-called storage chokes in switched-mode power supplies. They furnish the current required during the switching breaks of the switching transistor.
Coils with several windings are used as transformers for an electrical isolation, e. g. an electrically isolated triggering of switching transistors, or for the impedance adaptation of signals.

So-called current transformers on toroidal core base are used for the current detection resp. recognition of alternating currents. They consist of a core with a secondary winding and a high number of turns, while the conductor - the current of which is to be detected - is inserted through a central hole as the primary winding.

No further reference will be made in view of additional areas of application of coils, e. g. for oscillating circuits, RF filters, electromagnets or e. g. for the deflection or focussing of electron rays in cathode-ray tubes.

3 Core materials

3.1 Iron powder

Iron powder cores are made from compressed iron powder and are often used as single chokes (i. e. with typically one winding) for radio interference suppression and as storage chokes for switched-mode power supplies. The typical relative permeability is between $\mu_r = 35$ for storage chokes and $\mu_r = 85$ for radio interference suppression chokes.
The maximum saturation flux density for iron powder is about 1.5 T. It is important to take into account the fact that the core will already be partially saturated by the operating current and that the inductance thus decreases with an increase of the operating current. The specifications sheet will typically state the no-load inductance which does not correspond to the inductance at nominal current! Exceptions are storage chokes: Here the inductance is normally specified at a given nominal current, sometimes even the course of inductance as a function of the operating current.
For radio interference suppression purposes, the chokes are used for the attenuation of differential-mode (symmetrical) interference which usually occurs in the lower frequency range up to about 1 MHz. Typical applications are e. g. phase control circuits (dimmers), which create a strong differential-mode interference up to about 500 kHz. Special versions are the iron powder chokes with inserted toroidal iron cores, which deliberately increase the core losses and decrease the ripple. Since the differential-mode interference plays a role only for relatively low frequencies, radio interference suppression chokes may be wound in multiple layers on iron powder cores in order to achieve a high inductance. The capacitive coupling via the winding will play a role only for higher frequencies, where differential-mode (symmetrical) interference is practically unknown.
Typical values for the no-load inductance of our radio interference suppression chokes are 50 .. 1000 µH, the nominal current ranges from 0.5 .. 300 Amps.

Core material with a relatively low permeability is typically used for storage chokes to ensure that the inductance does not decrease too strongly when subject to current load. The working point of the current is typically specified at 60 .. 75 % of the no-load inductance. It is important here that eddy-current losses occur in the iron powder whenever the direction of current and thus the magnetization of the core is reversed, which could heat up the core very strongly. This is the reason why the current ripple across the choke may not become too high. The rule of thumb which applies here is: High inductance will cause a low ripple, a low inductance will cause a high ripple.
Overview of meaningful applications for the different iron powder core materials:

relative permeability	switching frequency of min. core losses	rel. price index for identical core size
$\mu_r = 35$	200 .. 500 kHz	3.5
$\mu_r = 55$	50 .. 250 kHz	2.5
$\mu_r = 75 .. 85$	DC .. 50 kHz	1.0 (std. mat. f. radio interf. suppr.)

The chokes are typically wound with normal copper wire. It is true that the rarely utilized flexible RF leads will reduce the skin effect. This, however, will be effective only for frequencies in excess of 200 kHz for the typical wire diameters (up to 2 mm). The higher parasitic capacitance of the winding will furthermore increase the switching losses in the transistors, not to mention the production-related difficulties encountered during the winding process.

3.2 Molypermalloy powder (MPP)

These cores are made from compressed nickel- and iron powder and are mostly utilized for storage purposes, similar to the iron powder cores. The maximum relative permeability is slightly higher than is the case for iron powder (μ_r = 25 .. 300). The essential difference is the fact that when compared to iron powder, this specific material displays very low eddy-current losses, i. e. the direction of current across the choke may also be reversed without the core being heated up too strongly.
The typical applications for these chokes are the so-called power factor correction controllers, which limit the reactive component mainly of primarily switched-mode power supplies, in order to adhere to the limits for mains harmonics applicable in the future. In individual cases, MPP cores will also be used as storage chokes in switched-mode power supplies with high clock frequencies (up to approx. 300 kHz).
With respect to the price, these cores are very expensive due to the high amount of nickel.
The price in comparison to a standard iron powder core of the same size is about 10 times higher (μ_r = 75 .. 85).

The "Kool Mµ" resp. "Super MSS" cores are specific versions which allow for a similar flux density than that of MPP. These are, however, somewhere between iron powder and MPP when it comes to the core losses and the price. They are also utilized for the correction of the power factor.

3.3 Soft Ferrites

Soft ferrites are ceramic materials that are very hard, brittle and chemically inert. They are made of a mixture of different metal-oxydes that are pressed and sintered. In comparison to iron powder they offer a much higher maximum permeability but a lower saturation flux density. On account of its high relative permeability, ferrite allows for reaching high inductance values with a compact design. Ferrite cores are typically used either as single chokes with air gap or as current-compensated multiple chokes, since the ferrite is magnetically saturated very quickly by the operating current on account of its high permeability, resulting in its inefficiency as an inductance. This is the reason why either the magnetic resistance of the core is increased by introducing an air gap or by incorporating several windings, which are electrically connected in such a way that the magnetic fluxes induced into the core by the operating currents mutual compensate one another. The result is that practically only the common-mode (asymmetrical) interference currents will be attenuated.

With respect to ferrites used for interference suppression coils, a differentiation is made between two frequently used material combinations: Manganese-zinc-ferrite (Mg-Zn) and nickel-zinc ferrite (Ni-Zn). The typical relative permeability for Mg-Zn ferrite is in the range of μ_r = 4300 .. 10000, for Ni-Zn ferrite it is μ_r = 250 .. 1200. The typical maximum saturation flux densities are 380 mT for Mg-Zn ferrite and 270 mT for Ni-Zn ferrite (each at 25 °C operating temperature).

Caution: These maximum saturation flux densities are almost independent of the relative permeability of the ferrite!
Example: An Mg-Zn ferrite with μ_r = 15 000 will feature a saturation flux density which is only insignificantly higher than that of μ_r = 5000. This means that on a core of identical size with an identical number of turns, a highly permeable ferrite allows for the creation of a choke with an inductance that is three times as high, but the highly permeable material will inevitably already be saturated at one third of the interference current, i. e. it may very well become inefficient in view of interference suppression. This connection is frequently neglected by the developers, who are laboring under the misapprehension that the interference suppression efficiency depends on the inductance alone, overseeing the problem of saturation!

Mg-Zn ferrite is the standard material for the manufacturing of current-compensated radio interference suppression chokes. It not only offers a higher permeability than Ni-Zn ferrite, but also a slightly higher saturation flux density. Since it is very conductive electrically, increasing eddy-current losses occur with higher frequencies (> 1 MHz), which make this material not suitable for applications above approx. 5 MHz. For high-frequency applications, i. e. with the focus above 5 MHz, only the high-resistance Ni-Zn ferrite will be suitable. Generally the following can be said for both ferrite types: The higher the relative permeability, the lower will be the upper cut-off frequency.

Another specific feature of ferrites is their sensitivity against mechanical stress. If a ferrite core is compressed, its inductance will decrease strongly. This is the reason why ferrite may be wound with solid wire up to a specific diameter only. If a larger cross-section is required, then a stranded flexible line will have to be used, since it is easier adapted to the shape of the core and will not exert excessive pressure onto the core as such. This, however, requires considerably higher production efforts and a higher price, since it is practically not possible to wind stranded flexible lines mechanically. Also when embedding the finished choke in an enclosure, attention will have to be paid to ensure that the sealing compound will remain flexible enough in order to allow for the compensation of the core's expansion when heated up. If this is not the case, the core may bust as a result of the pressure or the choke may lose the vast majority of its inductance. If large ferrite cores are used, the core will have to be bandaged with textile tape in order to obtain a flexible intermediate layer between the winding and the core.

The influence of the temperature on the properties of the ferrite should also not be neglected:

The permeability initially increases continuously as the temperature rises and with it the inductance increases linearly. From a temperature of approx. 130 °C on, the typical "Curie temperature", it will drop abruptly. This is the reason why the temperature of the ferrite core should possibly never exceed 125 °C in order to ensure that the intended attenuation is achieved. Contrary to it, the maximum saturation flux density decreases with rising temperature! Example: Mg-Zn ferrite with a nominal permeability of μ_r = 6 000 at 25 °C and a saturation flux density of B_S = 350 mT. At a temperature of 40 °C below Zero, μ_r will drop to 3 000, at a temperature of 125 °C, it will increase to approx. 12 500, B_S on the other hand will drop to 150 mT at a temperature of 100 °C. This means that e. g. with a choke that was dimensioned at a core temperature of 40 °C, the attenuation will initially increase slightly as the temperature rises. As a result of the decreasing saturation flux density, the core will suddenly enter into saturation at a higher temperature, causing the attenuation to suddenly break away. Due to the above, the interference suppression efficiency of a current-compensated ferrite choke should definitely be verified under realistic load conditions and at the maximum temperature. With Ni-Zn ferrite, the same connections basically apply. They are, however, not as pronounced.

3.4 Nano-crystalline materials ("amorphous" cores)

These cores consist of a nano-crystalline magnetic material, manufactured in a toroidal strip-wound form. The basic properties are similar to those of manganese-zinc ferrite, i. e. just like these, the cores are utilized mainly for the production of current-compensated radio interference suppression chokes. The specific feature of these cores is the very high relative permeability possible, typically ranging from 30 000 to 80 000. This means that with these specific cores, distinctly higher inductance values may be achieved with a considerably smaller volume than is the case for the conventional Mg-Zn-ferrites (μ_r = 5000 .. 10000).
Caution: Since the maximum saturation flux density is typically 1.2 T, i. e. only 3 times higher than that of Mg-Zn ferrite, the relative permeability, on the other hand, typically being 5 ... 10 times higher, there is a danger that the chokes will enter into saturation before those with the very same nominal inductance on Mg-Zn ferrite - primarily in case of pulse-shaped interference - thus rendering them ineffective. This problem mainly occurs if previously utilized current-compensated chokes on ferrite cores are to be replaced by chokes with identical inductance on smaller, nano-crystalline cores on account of spatial reasons.
The fact that "nano-crystalline" core material is distinctly more expensive than ferrite and that currently only few manufacturers of this specific material exist, i. e. longer delivery periods will possibly have to be expected, should also be taken into account.

3.5 Strip-wound toroidal cores

These cores are made of wound metal strip, similar to transformer sheet metal. This allows for very high permeability values to be reached, however, only with very low frequencies, e. g. 50 .. 60 Hz. The main application for these cores are current transformers for current measurement at 50 .. 60 Hz alternating current. For this purpose, the current-carrying conductor is routed through the core. Its current then induces a voltage into the winding of the strip-wound toroidal core at a defined load resistor ("burden"), which accurately corresponds to the current (CVCC transformer) resp. an appropriate current for short-circuit operation (CC transformer). These strip-wound toroidal cores are occasionally also used in single chokes for interference suppression in phase controls with specific loads.

4 Typical designs

4.1 I cores

I cores consist of a longitudinal, cylindrical ferrite core and are usually wound in a single layer. This means that this particular core shape features a very large air gap, which on the one hand keeps the achievable inductance low (typically 5 .. 20 µH), practically excluding a saturation on the other hand. The air gap, however, makes the stray field very large. I cores may also be subject to differential-mode operating current without any appreciable reduction of the inductance. Typically they are utilized together with the respective capacitors in collector motors for the reduction of the radio interference caused by the brush sparking, not so frequently for interference suppression in data lines, since - unlike current-compensated chokes - they also attenuate the usable signal. I cores also exist with multiple windings, which may also be of the current-compensated type. They are, however, very rare and utilized for specific applications only. With the usually single-layer winding - the beginning and the end of the winding spaced far apart - and the low coupling capacitance resulting from it, the I cores are suitable for a very wide frequency range, also in excess of 100 MHz. I cores may be manufactured in a fully automated process and thus offer a relatively low price in comparison to other designs if produced in high volumes.

4.2 Toroidal cores

Toroidal cores consist of a core bent to form a circle, the cross-section of which corresponds either to a circle or a rectangle with rounded edges. Since the magnetic lines of force form a closed circle within the core, toroidal core chokes have the smallest stray field of all choke designs and the highest density of the magnetic flux. This, however, brings along the danger of a rapid saturation for the ferrites. This is the reason why usually several windings are provided for toroidal ferrite cores. These are connected in such a way that the differential-mode operating currents resp. the usable signals are compensated and the choke becomes fully effective with its full inductance for common-mode (asymmetrical) (interference) signals only, while only the stray inductance (typically 1 % of the nominal inductance) will be effective for the usable signals resp. the operating current. One exception are the so-called "equipment grounding conductor chokes", which feature only one winding on a closed ferrite core, since no operating current will normally flow through them, but rather a leakage current only (a few mAmps only).
With identical electrical specifications, toroidal cores are the most compact design for a closed coil core. What is disadvantageous, however, are the increased production efforts required and thus a higher price, since toroidal cores may not be wound in a fully automated process.

5 Types of windings

5.1 Single-layer winding

This winding is mainly used for RF chokes in order to keep the coupling capacitance from one winding to the next as low as possible. The beginning and end of the winding should furthermore be spaced as far apart as possible from one another.

5.2 Multiple-layer winding

Two versions exist for the multiple-layer winding:

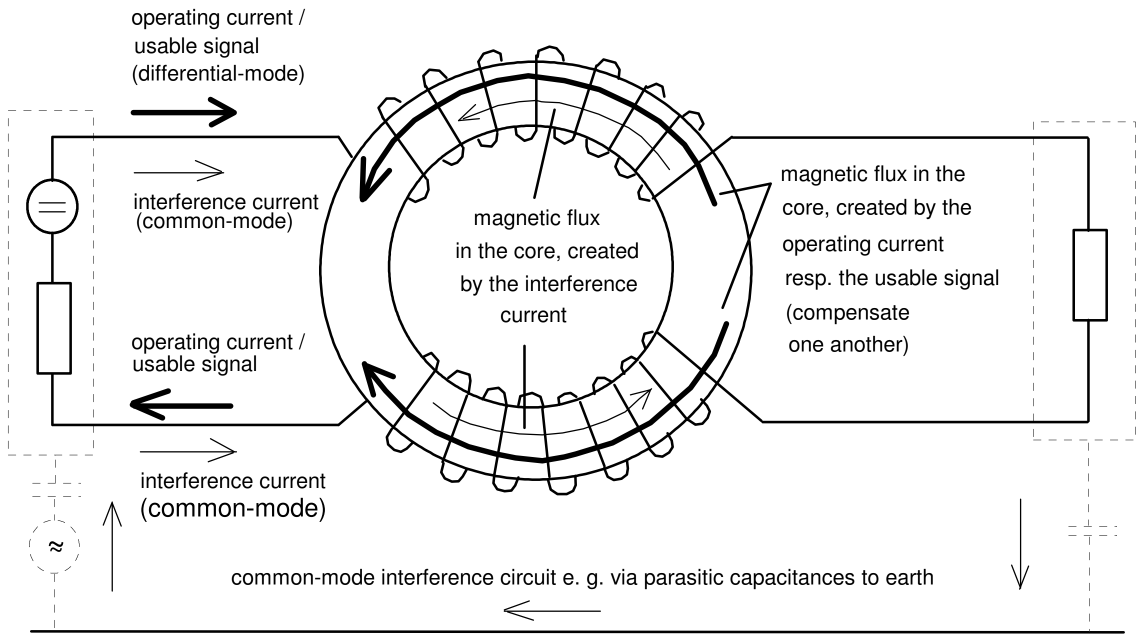
The visually "cleanest", the layer winding, where one layer is wound forward and the next backwards, from an RF point of view is not the best solution, since the beginning and the end of the winding may possibly be close together (even on top of one another), resulting in a strong coupling of the input and output of the choke and thus a decrease of the choke's efficiency at higher frequencies.

The so-called "wild winding", where several layers are immediately placed on top of one another and where the choke is wound in one direction only, is not as nice from a visual point of view, but is more suitable for higher frequencies than the layer winding.

5.3 Multiple windings on one single core

5.3.1 Current-compensating

This procedure is usually used for ferrite and other highly permeable core materials in order to compensate for the magnetic flux in the core created by the operating current resp. the usable signal for data line chokes. This means that the choke will be fully efficient with its full inductance for common-mode (asymmetrical) interference currents only, for differential-mode (symmetrical) currents with its stray inductance only.



Mode of operation of a current-compensated double choke on a toroidal core

This principle may be applied to a random number of conductors. The only thing that is important is that the sum totals of operating currents truly compensate one another. Typical are two-way to four-way current-compensated chokes.

With chokes for mains voltages, it is important that the electric strength between the individual windings is ensured in accordance with the applicable safety regulations. This is typically achieved by a suitable safety distance between the windings. The usual way to ensure this is a separating web or are separate winding chambers.
In specific cases this may, however, result in a sensitivity against magnetic stray fields located in the vicinity, which in turn may interfere with the current-compensated choke just as is the case for a loop antenna. If this problem may not be solved by positioning the components differently, then apart from considerable shielding efforts, only a bifilar winding will help. First all wires are twisted together and then wound on the core together. The use of varnished copper wire will be possible only for lowest voltages on account of the thin insulation, flexible PVC insulated lines will e. g. have to be used for higher voltages.
Current-compensated chokes are not only used for a frequency-dependent attenuation of high-frequency signals, but also for the separation of differential-mode (symmetrical) and common-mode (asymmetrical) interference signals.

Data lines, such as e. g. current loops (4 .. 20 mAmps), RS 485, CAN, telephone, etc. Here, only the stray inductance which results from the difference between the series resp. nominal inductance of the windings will be effective for the usable signals. The full nominal inductance will, however, be effective for the common-mode interference signals.
With current-compensated chokes with spatially separated windings, e. g. for mains voltage, the stray inductance is typically 100 times lower than the nominal inductance. If the attenuation against common-mode interference signals is to be effective already at lower frequencies, then a relatively high nominal inductance is required, which will inevitably result in a higher stray inductance, allowing for an attenuation of the usable signal even more than permissible, despite the current-compensation. Since the usable signals on data lines, however, are usually in the extra-low voltages sector, a bifilar wound choke may be utilized to solve the problem. With this kind of choke, the stray inductance is 5000 .. 10000 times lower than the nominal inductance.

Example:
NKL choke *R1405X11 2 x 6 mH (bifilar winding) 1 Amp:*
- typ. stray inductance 0.8 µH, ratio L_{rated} / L_{stray} = 7500
- upper 3 dB frequency limit for differential mode signal: 22 MHz
- example for application: increasing immunity of a CAN bus in parallel to a motor cable of a frequency converter carrying strong interferences

NKL choke *R1405XB1 2 x 27 mH (2 chambers) 0.5 Amps:*
- typ. stray inductance 250 µH, ratio L_{rated} / L_{stray} = 108
- upper 3 dB frequency limit for differential mode signal: 0.1 MHz

5.3.2 Transformer

Transformers serve for the electrically isolated transmission of electrical signals resp. the transformation of electrical signals to a more favorable current / voltage ratio. For this purpose, two or more windings are wound onto one single core to where a current in the primary winding will create a current in the secondary winding which is to be as identical as possible from a time sequence point of view. Frequently current-compensated two-way chokes are used for a 1:1 transformer for reasons of simplicity, with the connections wired differently. In case of transformers with an additional impedance adaptation, it may be necessary to select different numbers of turns, depending on the desired transformation ratio. Designs with one primary and two secondary windings are typical for an electrically isolated triggering of switching transistors in bridge circuits.

5.3.3 Special cases

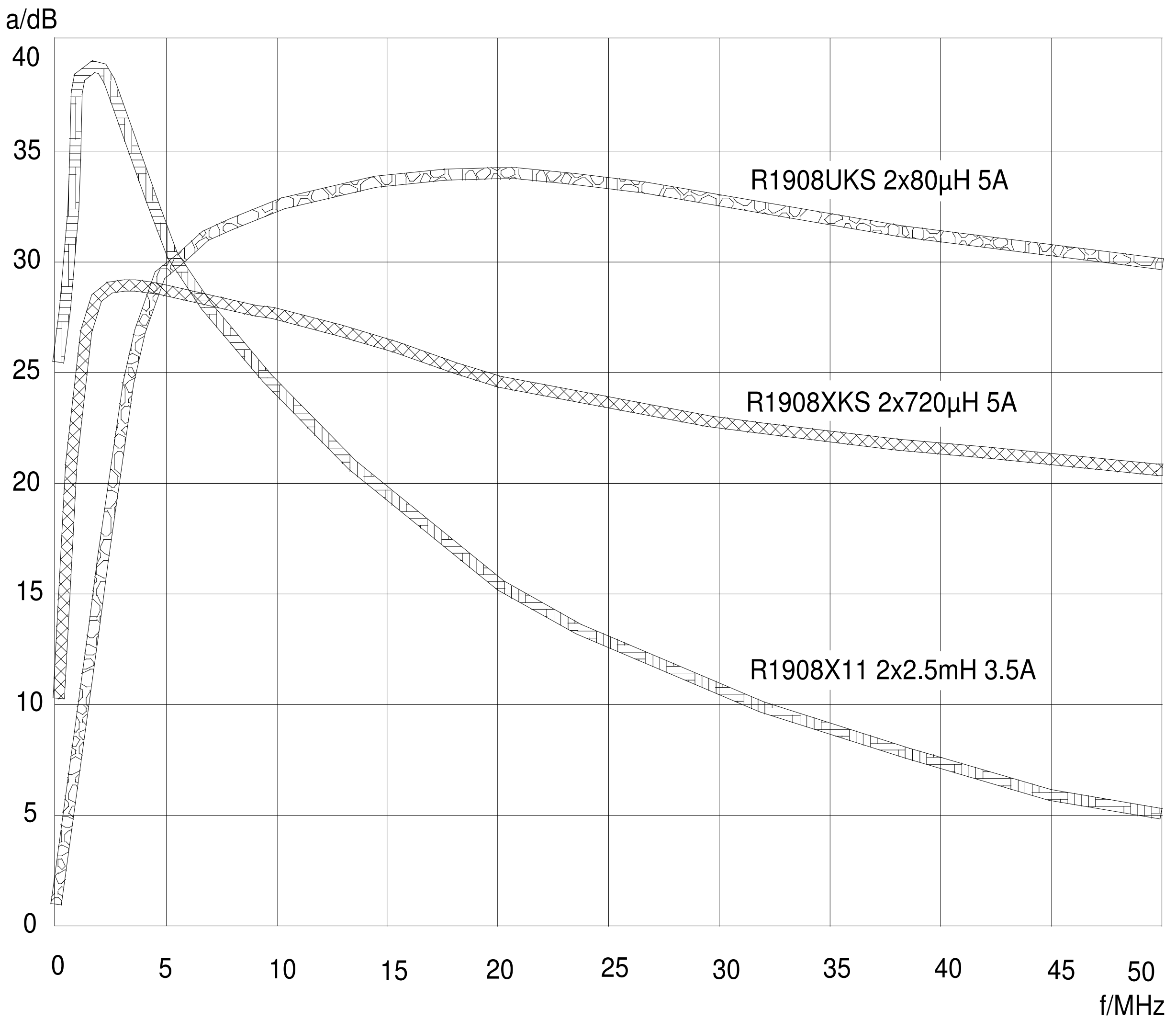
Other cases exist where several windings are wound on one single core, e. g. in case of PFC chokes, to supply the PFC controller with energy or to detect specific voltage resp. current ratios in the inductance. Occasionally, interference suppression chokes on iron powder cores are also equipped with several windings in order to avoid having to insert a separate choke into each printed conductor track. What will have to be taken into account, however, is the fact that the windings in this specific case may not be wired to where they are current-compensated, thus causing a higher premagnitization as a result of the operating current resp. a reduction of the inductance effective for interference suppression.

6 Other specific features

In special cases it may very well make sense e. g. to place two cores with a different material composition onto one another and to wind them together, e. g. a manganese-zinc ferrite core and a nickel-zinc ferrite core, in order to combine the specific properties of the two different core materials.

7 Typical attenuation curves of interference suppression chokes and their application

Attenuation curves serve for a comparison of different components in view of their RF properties. The attenuation curves specify the insertion loss in a 50 Ohm system with no load, i. e. without operating current and with low signal operation. The components are terminated to ground on both sides with 50 Ohms real. Due to the above measuring conditions (low signal operation, no load and termination on both sides with 50 Ohms real), which normally do not apply in practice, it already becomes quite clear that the attenuation curve alone may not be used to deduce the suitability of a component for a specific application!



Attenuation curves of current-compensated interference suppression chokes in a 50 Ohm system

The three attenuation curves shown in the above diagram are recorded from three different standard NKL common-mode interference suppression chokes, all of which were wound on toroidal ferrite cores with identical geometrical dimensions:

1. RX1908X11 2 x 2.5 mH 3.5 A

This type is a commonly used standard radio interference suppression choke on a manganese-zinc ferrite core (μ_r = 6000), also typical for many other manufacturers. It is wound in multiple layers to achieve a high nominal inductance. The attenuation values increase strongly already at low frequencies and reach their maximum at about 1.5 MHz with 38 dB. A relatively steep decline of the attenuation follows, the attenuation reached by the choke at 50 MHz is only approx. 5 dB.
These interference suppression chokes are used for interference suppression of mainly common-mode sources of interference with the main interference level located in the lower frequency range up to a maximum of approx. 1 MHz. Typical examples are switched-mode power supplies and frequency converters. Here, a high attenuation already at low frequencies is required, the residual higher-frequency shares of the interference spectrum are mostly discharged to ground by means of the respective Y capacitors.

2. R1908XKS 2 x 720 µH 5 A

This choke possesses exactly the same core as the first one. Contrary to it, the windings are wound in a single layer only, resulting in an accordingly lower nominal inductance. The rising of the attenuation curve of this choke is initially somewhat flatter and the maximum attenuation of 28 dB is reached at approx. 2.5 MHz. The single-layer winding and the consequently reduced parasitic coupling across the winding is the reason why the drop of the attenuation values towards the high frequencies is distinctly flatter, the choke reaches an attenuation of as much as 22 dB at 50 MHz. The application for this choke is similar to that for the first one, mainly for common-mode sources of interference, however, with a higher clock frequency, e. g. in equipment with a fast switched-mode power supply or a microprocessor up to a clock frequency of approx. 12 MHz: Here, the attenuation at lower frequencies must not be as high but must cover a wide bandwidth in order to also sufficiently attenuate the harmonic of the switching resp. clock frequencies.

3. R1908UKS 2 x 80 µH 5 A

This choke possesses a core made of nickel-zinc ferrite with a relative permeability of μ_r = 900. The size of the core is identical to that of the above chokes, the winding is identical with that of the second one, i. e. also a single-layer winding. The rising of the attenuation curve is again flatter than is the case for the first two chokes, the maximum of 34 dB attenuation is reached at 20 MHz and distinctly drops towards the higher frequencies, 30 dB attenuation are available at 50 MHz.
The main application for this choke is the interference suppression of high-frequency common-mode interference, such as microprocessor clock frequencies or RF oscillations and their harmonics as well as the enhancement of the interference immunity of integrated electronic circuits against strong sources of RF interference - such as radio signals - or protection against wide-band disturbing pulses, such as e. g. electrical fast transients ("burst"). This choke is frequently used in addition to a choke of the first or second type, e. g. if a piece of equipment is not equipped with an equipment grounding conductor connection towards which high-frequency interference may be discharged to ground effectively by means of Y capacitors.

8 Some comments on storage chokes

In switched-mode power supplies, the stored energy of these chokes serves for the bridging of the switching breaks of the transistor. Due to this, different conditions apply to these chokes than is the case for interference suppression chokes. The core is magnetized and should be capable of storing the maximum energy possible with a small volume in order to be able to output this energy during the switching breaks. The calculations for such a choke specify the inductance required at the highest current. In case of a low driving, the inductance partially increases considerably, depending on the core material used. This will have to be taken into account for testing with no load. In case of frequency-controlled circuits, this is a desirable effect. In case of pulse-width modulated circuits, however, this may be disadvantageous. It is consequently important to exactly know the mode of operation. The losses within the core material should furthermore be taken into account. They are created by the current ripple. When determining the core losses, the current ripple and the frequency are to be taken into account.

Many years of practical experience have shown:

1. That the core losses are usually not more than 25 % of the total losses. Due to this, the main focus should be directed towards the reduction of the ohmic resistance of the winding.

2. It does not make sense to wind storage chokes with flexible RF lines. The disadvantage of the higher winding capacitance to the core as well as across the winding (in case of multiple layers) is by far more detrimental. This parasitic capacitance is charged and discharged with high current peaks which increase the losses within the switching transistor. The fact is added that the higher capacitance results in significantly higher radio interference, which in turn makes increased efforts for radio interference suppression necessary.

3. The current ripple is responsible for the core losses and should thus be as low as possible. If the current in the choke chops with alternating load and then returns and again flows with full power, the core losses will be considerable. If the core is heated, the permeability will increase and the saturation will occur earlier. Due to this, a snowballing effect may occur in case of an overheating: The current is too high, the core heats up, the saturation starts earlier, the regulator attempts to compensate this by means of a higher frequency or extended ON times. This in turn will result in still higher losses, etc., until a failure occurs.

4. The fact that particularly the magnetization of iron powder cores should not be reversed must be taken into account, since very high losses are created in the core. This is the reason why these cores may hardly be used for differential-mode circuits. Toroidal ferrite cores may be used for lower power only on account of their earlier saturation. Here, the utilization of ferrite cores with air gaps is indispensable. The air gap should be located inside to ensure that the stray field will remain low. For special applications, where the polarity of the operating current must be reversed by means of a choke, but where the benefits of the toroidal core are nevertheless desirable, e. g. correction of the power factor (PFC), higher-grade MPP or Kool-µ cores are used, where the core losses are distinctly lower than is the case for iron powder and which are, however, distinctly more expensive.

5. In order to prevent an unwanted coupling of the interference, interference suppression chokes should - if possible - not be located parallel to one another or in the immediate vicinity of the storage choke.