

Distribution Transformers and EMC

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Since electromagnetic compatibility (EMC) is governed not only by technical specifications but by legal regulations too, it frequently poses significant questions. What evidence of EMC has to be provided for medium-voltage equipment? What certification of conformity is required? Do we need a CE mark? To what extent does emissions-control legislation apply? The answers concern manufacturers and users alike, for both are jointly responsible for electromagnetic compatibility. The electromagnetic compatibility (EMC) of transformers is determined by their stray magnetic fields. These are influenced, above all, by a transformer's rating and load and by its proximity to other items of equipment. When planning installations, however, it is important to consider not only the transformer's stray field but also the stray field generated by the low-voltage transmission system.

Task definition

In an industrial society, our living and work environments are increasingly influenced by the use of electronic equipment. These include data processing systems with computers and monitors as well as data and measured-value acquisition systems. At the same time, power supply installations move closer to the centres of consumption, i.e. also nearer to people's working environment. Power distribution systems can act as a source of interference causing disturbances in electronic equipment. Transformers are an important element of supplies to a load centre. This article explains the characteristics of transformers which generate electric and magnetic fields and act as a source of interference in terms of electromagnetic compatibility (EMC).

Legal and technical rules

Electromagnetic compatibility is bound up with both technical and legal regulations. Legislation deals with the effect of equipment on the general public, in a wide range of contexts.
Technical aspects include a description of the electromagnetic phenomena involved; the treatment thereof is covered by standards containing the relevant design-related and test specifications. Since certain equipment gives off electromagnetic fields into the environment, the German Federal Emissions Control Ordinance (26. BImSchV) imposes limits in order to prevent impermissible effects on people. German EMC legislation (derived from the European EMC directive) pursues a different objective. To ensure free trade, the law specifies EMC protection targets and governs the topic of conformity rating, i.e. what products should bear a CE mark.

EMC legislation and the CE mark

Do distribution transformers have to bear a CE mark? This is a frequently asked question, and sometimes the CE mark is mistaken for a kind of quality symbol. The European directive on electromagnetic compatibility [1] states that equipment should be constructed and operated such that it neither causes interference to other devices, nor is subject to any interference itself. That effectively sums up the idea behind the German law on the electromagnetic compatibility of devices (EMVG) [2]. According to EN 60076-1/A1:2000 and IEC 60076-1, amendment 1, power transformers constitute passive elements in terms of electromagnetic interference emission and interference immunity. Passive elements are declared to be not capable of causing electromagnetic interference, and their operating characteristics to be not affected by such interference.
A further aspect is conformity rating (a statement and evidence that a product complies with the protection specifications).

Distribution transformers require no CE mark
Devices have to meet the EMC protection targets. A device in the sense of the EMC directive means any electric or electronic system, network or item of equipment. But not all devices require a CE mark or declaration of conformity. The reason is comprised in the very sense of the EMC directive. Its intention is to prevent everyday use of commonplace electrical devices from interfering with radio transmission or telecommunications, and to avoid the risk of such devices having any mutually adverse effect on each other.
Distribution transformers are precisely not "commonly" available; they are set up and operated only by experts. It can be assumed that anyone dealing with them will possess sufficient knowledge relating to EMC. There is consequently no need for any declaration of conformity, nor for the CE mark.

26th German Federal Emissions Control Ordinance
Distribution transformers produce electric and magnetic fields (at system frequency) that can spread into the surrounding area. Since this surrounding area may well be accessible to the public, any risk to humans (resulting from such fields) must be ruled out. The 26th German Federal Emissions Control Ordinance (26. BImSchV) [3] therefore imposes limits on electric and magnetic fields. Compliance with these limits is cogent under law; the ordinance takes precedence over VDE and other standards.

Scope of validity
The ordinance applies to stationary systems for the transformation and transmission of electricity:

- Overhead power lines and buried cables with a frequency of 50 Hz and a voltage of ≥ 1000 V.
- Overhead power lines and overhead contact lines, including the traction substations and switchgear, with a frequency of 16 2/3 Hz or 50 Hz.
- Transformer substations, including switchgear, with a frequency of 50 Hz and a high voltage of ≥ 1000 V.

The limits for electric field intensity and magnetic flux density are:

- 5 kV/m and 100 µT at 50 Hz,
- 10 kV/m and 300 µT at 16 2/3 Hz.

These figures apply to continuous operation and highest system operational load. The defined limits apply in the area affected by complete systems of varying design – depending on customer requirements and spatial conditions. The electric and magnetic field intensities for a particular installation therefore cannot be transposed onto another. Specific evidence relating to an overall system must ultimately be produced.
26. BImSchV permits both measurement-based and theoretically calculated evidence of compliance with the relevant limits.

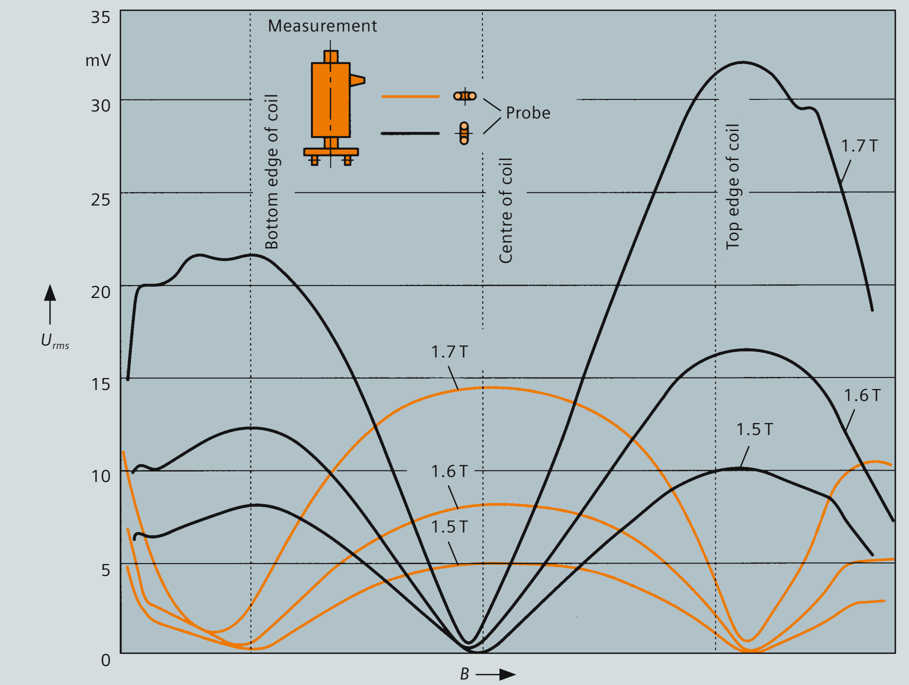

Fig. 1: Voltage induced by no-load stray field at the surface of a 630 kVA cast-resin-encapsulated transformer; parameters: limb induction 1.5 T to 1.7 T (measurement probe with 2900 turns, A_{eff} = 1.53 cm² and distance from surface of the winding 20 cm)

Fields occurring in the proximity of transformers

Electric and magnetic fields which occur in the frequency range of the public supply network – 16 2/3 and 50 Hz – can be decoupled and therefore considered separately [4]. Higher frequencies which emit electromagnetic fields occur only in conjunction with partial-discharge processes in and around the transformer. These partial-discharge pulses can contain frequencies of 0.1 to 50 MHz. Distribution transformers do not generally produce partial discharges at supply voltage, however. In such cases, it is merely necessary to design the high-voltage connections so that the field intensity in air which is critical for partial discharge inception is not exceeded at any point. High-frequency electromagnetic fields are therefore of only secondary importance in the case of transformers and will not be discussed here.

Electric fields occur between live conductors and between the conductors and earth. The magnitude of the electric fields depends on the supply voltage, distances and electrode geometry. A field intensity of around 10 kV/mm may be present in the internal structure of an oil-immersed transformer, with intensities ranging from 0.5 kV/mm to 3 kV/mm inside dry-type transformers. Transformer tanks, for example, which act as Faraday cages, shield the electric field of enclosed fluid-filled or dry-type transformers. Dry-type transformers without enclosures are generally installed in compartments without walls and ceilings of electric insulating material. These compartments therefore also represent Faraday cages in a first approximation. The same applies to the electric fields generated by connections and incoming cables which are thus virtually inactive inside buildings.

Magnetic fields, by comparison, are a far greater source of disturbances. These are normally not shielded by building walls, not even steel-lined concrete walls. This article therefore concentrates on these fields.

Stray magnetic fields in transformers

It is necessary to analyze different sources of stray magnetic fields in transformers. These sources have the following ascending order of importance:

- Stray field in no-load operation;
- stray field from the terminal leads under load (particularly on the low-voltage side because of the greater current) and
- stray field from the current-carrying windings.

These three-dimensional fields are complicated, because they are generated in time and space by the three-phase system and are affected by the iron contained in the enclosing structural elements.

The magnetomotive force which the no-load current generates in the primary winding produces the **stray field in no-load operation**.

The magnitude and waveshape of no-load current depend on the magnetization requirement of the iron core. Because of the curved shape of the magnetization characteristic, the no-load current contains harmonic components which are consequently also present in the stray field. The effective value of the voltage induced in a measurement coil was therefore plotted in **Fig. 1** as a function of the measurement location on a cast-resin-encapsulated transformer.

The no-load field is emitted mostly at the top and bottom end of the primary winding and from the transition points of the iron core. However, the no-load field is smaller by a factor of about 10 than the stray field generated by the load-current-carrying windings so it can generally be disregarded.

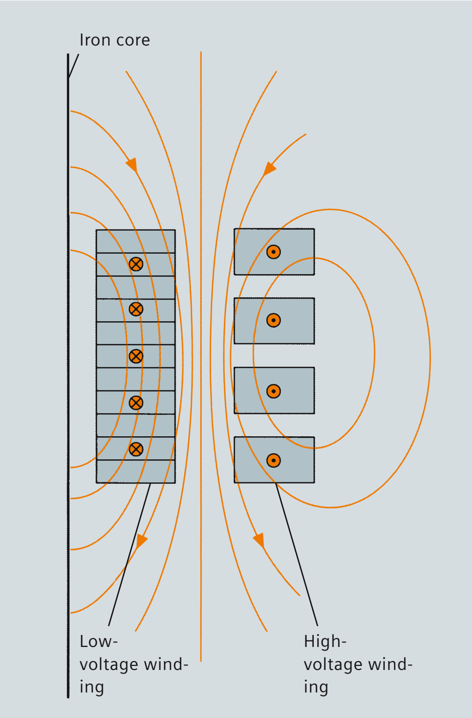

Fig. 2: Basic stray field of a transformer under load

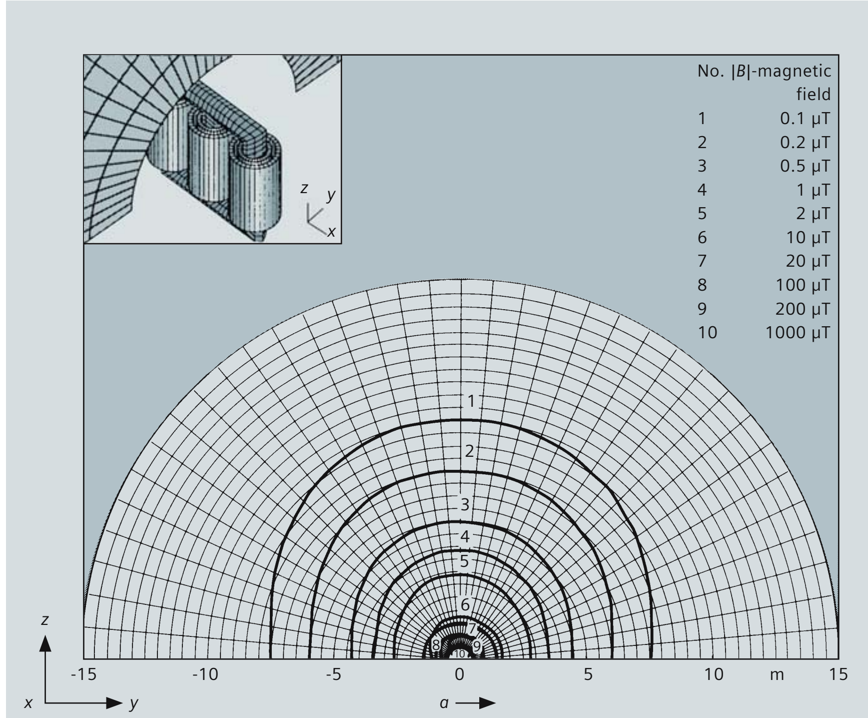

Fig. 3: Spatial calculation of stray field for a 630 kVA GEAFOL transformer

As with every current-carrying conductor, leads such as connecting cables and busbars also generate a **stray field** [5], which, at every point in space, is a function of the vectorial sum of field intensities generated at that same point by the current-carrying conductors. In conductor configurations where the sum of currents equals zero, as in the supply and return lines of an AC circuit, or in a three-phase system, for example, the more tightly these conductors are bunched, the smaller the resultant field will be. The transformer's load-current-carrying **primary and secondary windings** generate a stray field which is emitted from the space between the windings **(Fig. 2)**. This stray field causes interferences mainly in the vicinity of the transformer. Leakage from the low-voltage leads, particularly where these are not tightly bunched, is an additional factor.

Stray field of the transformer under load

Fig. 3 shows the results of a model calculation performed to ascertain the stray field of a rated current-carrying 630 kVA resin-encapsulated transformer in the event of a short circuit. The stray field spreads outwards in a virtually hemispherical form at even a relatively close distance. When distance a is approximately 10 m, the short-line function roughly proportionally follows $1/a^3$. In the near field, i.e. from 0 m to 1 m, field density tends to be proportional to $1/a^2$. Up to about 10 m, this produces a function of between $1/a^2$ and $1a^3$. The measured values for a 630 kV transformer and the computed values for a busbar system are both plotted in **Fig. 4**. If we assume that the stray field measured at a distance of 3 m is B_3, we obtain the following equation for the actual transformer (without leads):

$$B(a) = B_3 \cdot (3\,\mathrm{m}/a)^x \text{ where } 2<x<3$$

Using the same measured values, for the distance range between 1 m and 10 m we obtain:

$$B(a) \approx B_3 \cdot (3\,\mathrm{m}/a)^{2.8}$$

For the distance range above 10 m the equation is as follows:

$$B(a) = B_{10} \cdot (10\,\mathrm{m}/a)^3$$

By comparison, stray field induction in the busbar system varies only as the square of the distance, and therefore has a more powerful effect under certain circumstances than the transformer stray field. The stray field generated by the busbar system is also a function of conductor proximity, i.e. it decreases with increasing proximity. The transformer stray field is influenced by

- the transformer's load factor k_T (directly proportional to $k_T = I/I_r$),
- the design of the transformer and
- the design data.

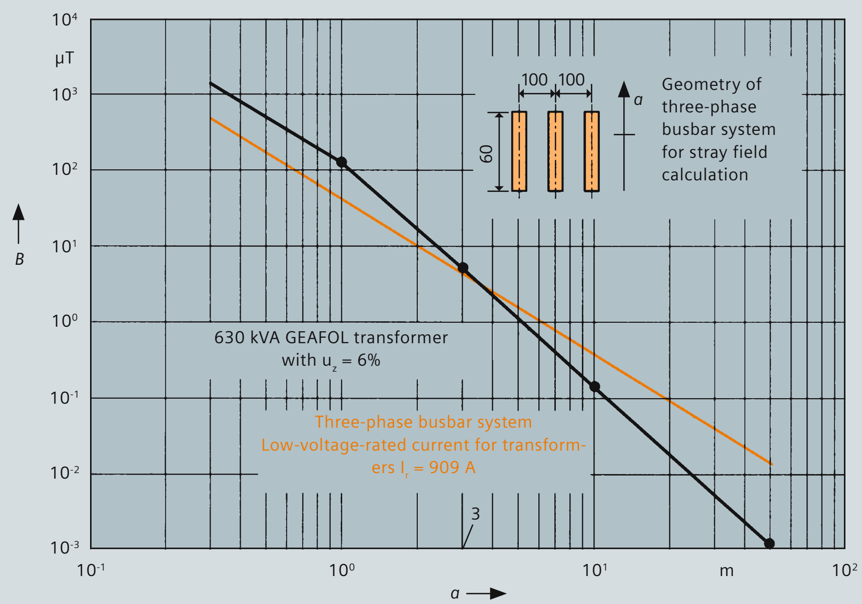

Fig. 4: Stray field measurement for a 630 kVA GEAFOL transformer and stray field calculation for a busbar system

In the case of a 630 kVA cast-resin transformer where u_z = 6%, a peak value of B_3 = 5 µT must be expected at rated load. This value is reduced by a factor of 2 to 3 in the case of oil-immersed distribution transformers and also sheet-steel-enclosed, dry-type transformers because of the shielding effect of the transformer tank. The stray field can be considered in a first approximation as a function of the transformer's leakage flux. This in turn determines the relative impedance voltage u_z of the transformer with the result that the stray field is roughly proportional to the impedance voltage. From the laws of propagation applying to the transformer, it can be inferred that leakage flux is a function of apparent transformer power S_r arrived at via a root function. From this we obtain:

$$B \sim B_0 u_z \sqrt{S_r} \left(\frac{a_0}{a}\right)^x k_T \quad \text{or}$$

$$B = B_0 \frac{u_z}{u_{z0}} \sqrt{\frac{S_r}{S_{r0}}} \left(\frac{a_0}{a}\right)^x k_T$$

where B_0 denotes induction at distance a_0; the exponent is $2 < x \leq 3$.

Related to the available measured values for the 630 kVA transformer, we obtain the following equation for rated load (k_T = 1)

$$B = 5\,\mu\text{T}\, \frac{u_z}{6\%} \sqrt{\frac{S_r}{630\text{ kVA}}} \left(\frac{3\,\text{m}}{a}\right)^{2\text{ to }3}$$

or for the range *a* = 1 m to 10 m

$$B = 5\,\mu\text{T}\, \frac{u_z}{6\%} \sqrt{\frac{S_r}{630\text{ kVA}}} \left(\frac{3\,\text{m}}{a}\right)^{2.8}$$

The stray field is thus a product of the transformer's technical specifications and is virtually impossible to alter without changing those specifications.

Stray Field in the Transformer during Short Circuit or Connection to the Supply

The short-circuit state is a rare but extreme loading state of the transformer. The stray fields resulting from such short circuits are likewise proportional to the current. The short-circuit current corresponds to a function of impedance voltage:

$$I_c = I_r / u_z \cdot 100$$

or, according to [10]:

$$I_{cmax} = I_c \cdot K$$

A short circuit may therefore briefly produce stray fields which can exceed the rated values by a maximum factor of 25·1.8 = 45 for u_z = 4 % and impulse-to-AC-strength ratio K = 1.8, or by a factor of 16.7·1.8 = 30 for u_z = 6 %.

By comparison, virtually the entire useful flux of the transformer may occur in the air space inside the primary winding **at the moment the transformer is energized** due to saturation of the iron core [6]. However, this maximum value is only obtained if the transformer is connected to the supply at the zero crossing of the voltage wave. The ratio of useful flux to leakage flux is $1/u_z$, i.e. values for u_z = 4 % or 6 % would be 25 times or 16.7 times higher respectively than nominal leakage flux. Magnification of the stray field is far less pronounced, however, due to damping of the inrush current as a result of leakage impedance and ohmic resistance in the winding. The stray field is therefore likely to attain values about 15 to 10 times higher than the rated stray field during the initial cycles of the inrush current.

Measuring the stray field

There are various methods of measuring the stray fields of transformers including Hall probes or measurement coils as defined in DIN VDE 0107 [7]. In the latter example, the voltages induced in the coil by the stray fields are recorded with an oscilloscope and their waveform is analyzed.

The maximum value or direction of the field can be clearly determined and recorded by rotating the measurement coil. If the load current, for example, has a harmonic component, it is also possible to ascertain the harmonic content of the field using a harmonics analyzer. It is also possible to take the frequency response of the measurement coil ($U \sim Bf$) into account and to distinguish this from the frequency spectra of other sources of interference. By measuring stray field induction at different intervals it is possible to plot an induction curve versus the distance from the source of interference.

Limits

The EMC limits to be observed depend on the sensitivity of the instruments which can be affected by these stray magnetic fields.

In **medical** applications, DIN VDE 0100-710 limits the maximum permissible readings in the vicinity of a patient to 0.4 μT for electrocardiograms (ECGs) and 0.2 μT for electroencephalograms (EEGs).

These are peak-to-peak values. The electromagnetic susceptibility of display screens becomes important in technical applications. Screen manufacturers specify an interference immunity of around 1 μT [8] with field strength limits as low as 0.1 μT for electron microscopes.

Protective Measures

Since field strength declines roughly in proportion to the cube of the distance from the transformer, the most important measure is to site the transformer sufficiently far away from the anticipated source of interference. In medical applications, DIN VDE 0100-710, for example, considers a distance of 6 m to be sufficient.

The data and curves presented here can be used to calculate or select acceptable distances for a certain field intensity limit. This simple measure should be taken into account at the planning stage [9]. Subsequent damping measures, such as laying low-voltage leads in a bunched configuration or use of shielding covers, are usually expensive and demand detailed investigations. Monitor screens which offer protection against stray magnetic fields are already available as factory-assembled products. With these it is essentially possible to reduce interference resulting by stray magnetic fields even as a subsequent refinement.

Literature

[1] Council Directive 89/336/EEC of 3 May 1989 on the approximation of the laws of the Member States relating to electromagnetic compatibility; amended by Directives 91/263/EEC, 92/31/EEC, 93/68/EEC, 93/97/EEC.

[2] Gesetz über die elektromagnetische Verträglichkeit von Geräten (EMVG) vom 18. September 1998. Veröffentlicht im Bundesanzeiger am 25. September 1998.

[3] EMVU-Verordnung. Sechsundzwanzigste Verordnung zur Durchführung des Bundes-Immissionsschutzgesetzes (Verordnung über elektromagnetische Felder – 26. BImSchV) vom 16. Dezember 1996. Auszug aus dem Bundesgesetzblatt, Jg 1996 Teil I Nr. .66, ausgegeben zu Bonn am 20. Dezember 1996.

[4] Haubrich, H.-J.: Biologische Wirkung elektromagnetischer 50-Hz-Felder auf den Menschen Elektriz.-wirtsch. 86 (1987) H. 16/17, p. 697–705

[5] Hadrian, W.: Leitungen, Transformatoren und Schaltanlagen als Störquellen. Elektrotech. und Masch.-bau 101 (1983) H. 1, p. 21–28

[6] Schäfer, W.: Transformatoren. Sammlung Göschen Bd. 952/952 a. Berlin: Walter de Gruyter, p. 104–108

[7] DIN VDE 0100-710 Errichten von Niederspannungsanlagen – Anforderungen für Betriebsstätten, Räume und Anlagen besonderer Art

[8] Kohling, A.; Zimmer, G.: Beeinflussung von Bildschirmarbeitsplätzen durch Magnetfelder. etz Elektrotech. Z.114 (1993) H.12, p. 758–763

[9] Kohling, A.: EMV – Planung für Krankenhausneubauten. etz Elektrotech. Z. 106 (1985) H. 9, p. 428–430

[10] IEC 60076-5:2006 Power transformers – Ability to withstand short-circuit

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