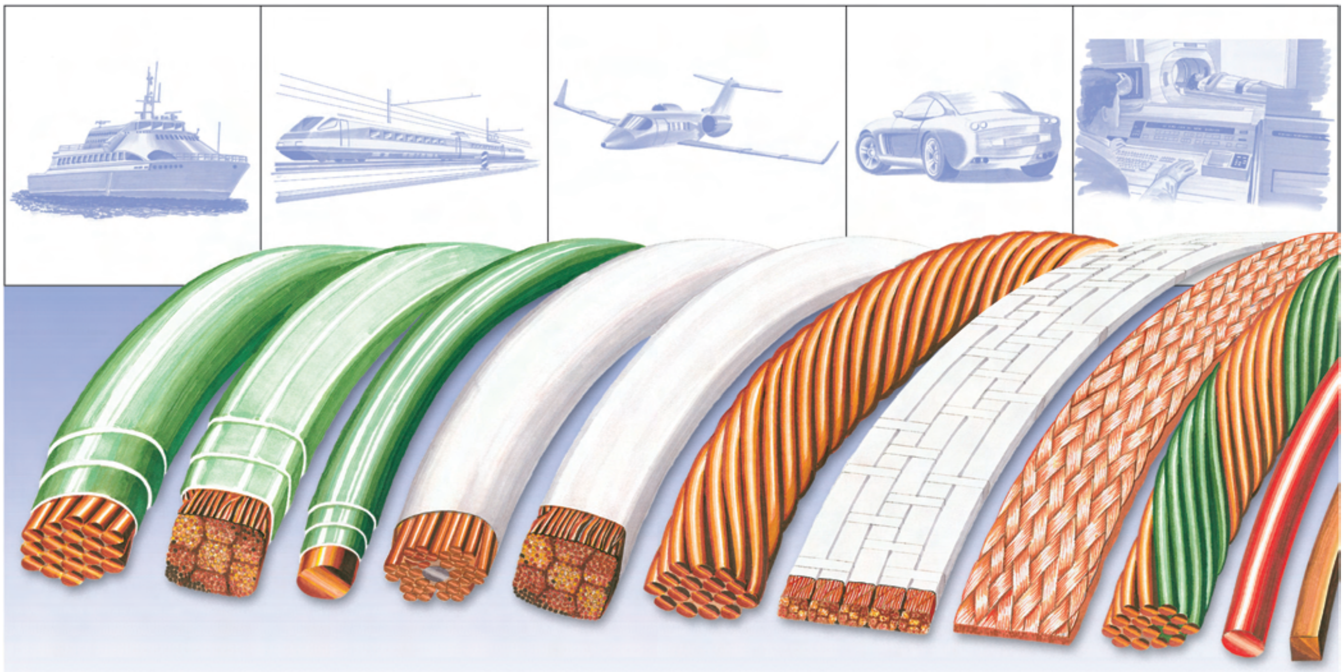

Optimized Winding = Optimum in Power Efficiency

Comparison of losses in litz wires and round wires

In order to minimize converter losses not only semiconductor parts must improve. A key component of converters – no matter if AC/AC, AC/DC, DC/DC or DC/AC – is the magnetic energy storage in form of inductors or transformers. A research project analyzes the electrical characteristics of wires and litz wires in order to reduce the winding losses.

From Prof. Dr.-Ing. M. Albach, J. Patz, Dr.-Ing. H. Roßmanith, D. Exner, Dr.-Ing. A. Stadler
Translated by Marc Döbrönti and Dr.-Ing. Hans Roßmanith
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Inductor and transformer losses in power electronic applications can be minimized by optimizing the cores - size, form, material - and optimizing the winding. The latter indeed mostly consists of copper, but is realized in a large variety of cross sections, reaching from thin foils, rectangular cross sections, solid round wires to the different kinds of litz wires. How winding losses can be reduced using either round wire or litz wire is investigated in the research project „Characterization and Optimization of Litz Wire Windings in Chokes and Transformers for Higher Energy Efficiency“ (see **box** next page), which is funded by the German Federal Ministry of Economics and Technology.

Losses in round wires

The winding losses in round wires can be classified into:

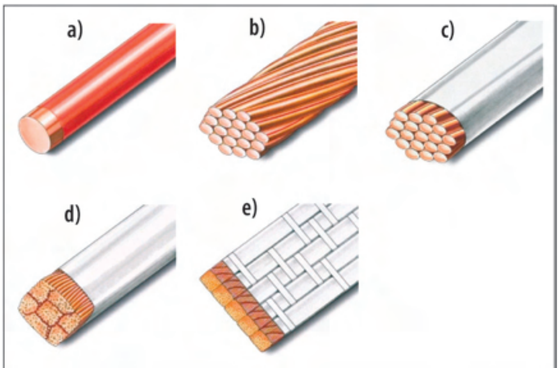
- frequency independent ohmic (rms) losses,
- frequency dependent skin losses,
- proximity losses depending on an external magnetic field

Dielectric losses in the enamel coating play only a minor role in practice. They will be neglected in the following considerations.

Winding losses depend on the winding current, more specific on its rms value, on harmonics included in time dependent waveforms and on the design of the winding layout. Proximity losses additionally depend on the core geometry and the number, geometry and position of optional air gaps. The most simple case will be a straight round wire with radius a, according to **fig. 1a**, and cross section $A = \pi a^2$, which carries the dc current I. With its density of J_0 = I/A the current is distributed homogenously over the wire cross section. The losses can be calculated by $P = I^2 R_0$, where $R_0 = \ell / \kappa A$ is the dc resistance of the wire of length ℓ and conductivity κ.

When a time dependent current, e.g. $i(t) = \hat{\imath}\,\sin(\omega t)$ with amplitude $\hat{\imath}$ and frequency f or rather the angular frequency $\omega = 2\,\pi\,f$, flows through the wire, then the magnetic field inside the wire caused by this current will be time dependent as well. According to Faraday's law, additional eddy currents are generated inside the wire changing the current distribution. The so called skin effect describes the current displacement, concentrating in areas where for dc excitation the magnetic field strength was high. Inside a round wire, the dc magnetic field strength increases linearly with the distance to the wire axis. On the wire surface it reaches its maximum and outside it decreases with the inverse of the distance to the wire axis (**fig. 2**).

In case of time dependent currents, the current density near the axis decreases with increasing frequency, so that the current density is concentrated more and more to the surface of the wire. This effect can be described mathematically in a very simple way by the so called skin depth $\delta = 1/(\pi f \kappa \mu_0)^{1/2}$. With the permeability of copper, which is also the permeability of free space $\mu_0 = 4\pi\ 10^{-7}$Vs/Am, the skin depth will be about 1cm at 50Hz and only about 0.21mm at 100kHz. **Fig. 3** displays the absolute value of the current density over the wire cross section for distance values $0 \leq r \leq a$ from the axis, standardized to the dc value at $a/\delta = 0$. This effect becomes more and more important with increasing frequency or more specific with increasing ratio of a/δ, thus increasing the losses at higher frequencies.



a) RUPOL® b) RUPALIT® Classic c) RUPALIT® Classic d) RUPALIT® Profil e) RUPALIT® Planar

Figure 1: Enameled copper wire (a) and different litz wire from PACK Feindraehte: classical round litz wire „Rupalit Classic" without (b) and with wrapping (c), with square cross section to improve the copper filling factor „Rupalit Profil" (d) and with rectangular cross section as alternative to foils „Rupalit Planar" (e)

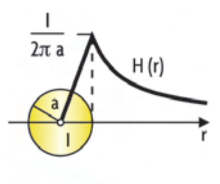


Figure 2: The magnetic field strength H – for a infinitely long round wire – increases linearly inside the wire and decreases by 1/r outside the wire

Search for the optimal winding

In the scope of the German Federal Government's 5th Energy Research Program „Innovation and New Energy Technologies", the Rudolf Pack GmbH & Co. KG (www.pack-feindraehte.de), the Spezial-Transformatoren Stockach GmbH & Co. KG (www.sts-trafo.de) and the Chair of Electromagnetic Fields of the University Erlangen-Nuremberg (www.emf.eei.uni-erlangen.de) joined forces for a research project, with the aim to optimize the winding of inductive components of electronic converters.

The project „Characterization and Optimization of Litz Wire Windings in Chokes and Transformers for Higher Energy Efficiency" started on October 1st, 2008, and is scheduled for 3 years. Its intention is to optimize the layout of litz wires by an extended description of the electrical properties of rf litz wire cables. A better insight into these properties shall lead to the development of new designs of litz wire cables, which reduce the winding losses of inductive components in switched mode power supplies.

In addition, with optimized windings, the partners hope to achieve a better utilization of material and lower product costs. The joint project – with funding managed by Projektträger Jülich (www.fz-juelich.de/ptj) – is attributed to the focus „Energy Efficiency in Industry" and is funded by the German Federal Ministry of Economics and Technology (BMWi, www.bmwi.de) on decision of the German Bundestag, funding identification: 0327494 A,B,C.

The losses can be calculated by eq. 1, where $i_{rms} = \hat{\imath} / 2^{1/2}$:

$$P = i_{rms}{}^2 R = i_{rms}{}^2 R_0 \cdot F_s$$

with

$$F_s = \frac{1}{2} \mathrm{Re}\left\{ \alpha a \frac{I_0(\alpha a)}{I_1(\alpha a)} \right\} \qquad (1)$$

and

$$\alpha = \frac{1+j}{\delta}$$

Usually the frequency dependent resistance R is expressed by the product of the dc resistance R_0 and the skin factor F_s. The losses from eq. 1 may be separated into rms and skin losses in a straightforward way

$$P = P_{rms} + P_{skin}$$
$$P = i_{rms}{}^2 R_0 + i_{rms}{}^2 R_0 \cdot (F_s - 1) \qquad (2)$$

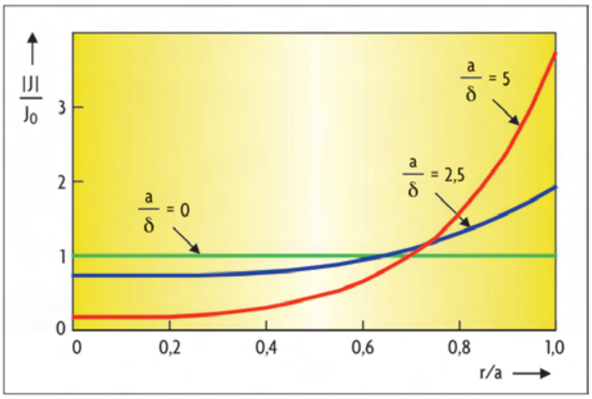


Figure 3: For dc (a/δ = 0) the current is distributed evenly over the cross section. The relative current density – normalized to the current density at dc – is constant from the wire axis to the rim. With increasing frequency (a/δ = 2.5 and 5) the current density decreases at the wire axis and increases greatly at the rim.

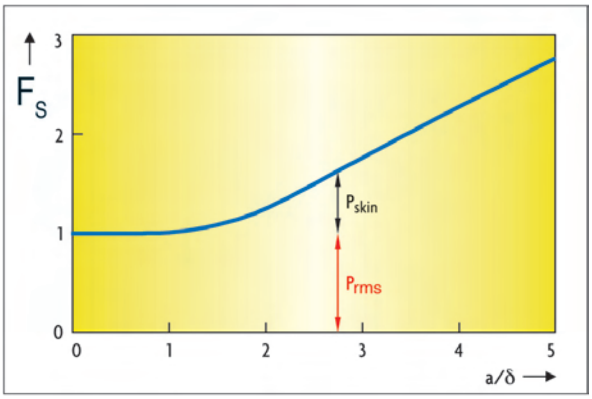


Figure 4: The skin factor F_s is frequency dependent. Starting from the dc value 1 (P_{rms}), the skin losses P_{skin} – after a transitional phase – increase linearly with the ratio a/δ .

If the ratio a/δ is well known, the skin factor is determined by the modified Bessel functions I_0 and I_1. Its separation into the frequency independent part P_{rms} and the additional skin losses P_{skin} can directly be seen in **fig. 4**. For a few selected round wires of 1m length the resistance R is displayed in **fig. 5** as a function of frequency. At low frequencies the resistances are inversely proportional to the cross section areas, i.e. to $1/a^2$. When the skin effect becomes more significant, the current is distributed just over a small rim of the cross section. Thus the resistance will change with the circumference of the wire, which means R is then proportional to 1/a. If the current waveform and the temperature dependent conductivity κ(T) are known, the rms and skin losses for any round wire with the diameter of 2a can be calculated exactly.

The calculation of the previously mentioned proximity losses is a bit more complex. The proximity effect appears if a conductor is exposed to an external time dependent magnetic field, which may be generated e.g. by neighboring wires. It does not matter whether the wire carries any current or not. Proximity effect induces likewise eddy currents, which may contribute considerably to the total winding losses. This external magnetic field depends on:

- the position and number of neighboring strands
- the current flowing through these wires, which means, does the wire belong to the primary or one of the secondary sides
- the core geometry and the air gaps

For the special case of a round wire in a homogenous, time harmonic magnetic field perpendicular to the wire axis, the current density of the induced eddy currents is shown in **fig. 6**, for a ratio a/δ = 5. These eddy currents are diametrically orientated at the upper and lower rim of the conductor. Although the

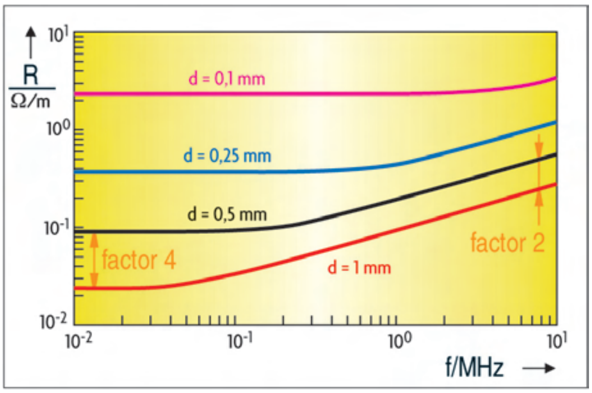


Figure 5: The skin effect is responsible for a frequency dependent increase of resistance of the wire, which varies for different wire diameters d (d = 2a). Thinner wires correspond with higher frequencies, where the skin effect starts increasing the resistance. With higher frequency the resistance changes its dependence from the wire diameter: a quadratic dependency on the radius will change to a linear dependency.

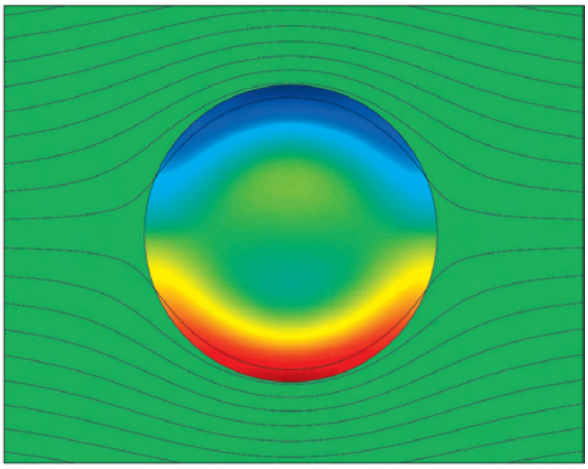


Figure 6: External magnetic fields affect the current density and the field distribution in the wire via the proximity effect. In this example, the magnetic field weakens at the left and right of the wire, but gets stronger at the top and bottom, in comparison to the excitation field.

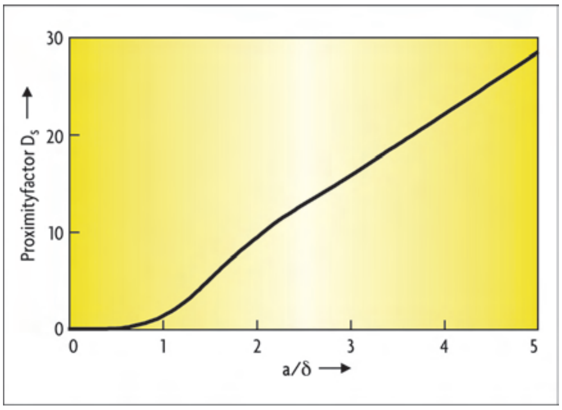


Figure 7: Like the skin factor, the proximity factor D_s depends on the frequency – here plotted as a function of the ratio a/δ . It is responsible for the increase of proximity losses with the frequency.

integral of the eddy currents over the complete cross section is zero, nevertheless extremely high losses can be generated at both rims of the wire. The eddy currents themselves generate a magnetic field – similar to the field of a line dipole – which adds to the original field, so that the resulting field will be displaced from the inside of the wire. Referring to the direction of the external field, the resulting field is reduced in front of as well as behind the wire – to the right and to the left of the wire in fig. 6 – and increased on the sides of the wire – above and below the wire in fig. 6. The proximity effect becomes increasingly important inside a litz wire, because of interactions between the single strands. For the special case of the originally homogeneous external field, the average proximity losses can be calculated by:

$$P_{prox} = \frac{\ell}{\kappa} \hat{H}_{ext}^{\,2} \cdot D_s$$

with

$$D_s = 2\pi \,\mathrm{Re}\left\{ \frac{\alpha a I_1(\alpha a)}{I_0(\alpha a)} \right\} \qquad (3)$$

and

$$\alpha = \frac{1+j}{\delta}$$

The proximity losses are proportional to the wire length ℓ and to the square of the amplitude of the magnetic field $\hat{H}_{ext}$. The dimensionless proximity factor is displayed in **fig. 7**. If the construction of the winding of an inductor or a transformer is known, the magnetic field in the winding window and thus the magnetic field at the position of each single turn can be calculated. Eq. 3 allows an estimation of the proximity losses. A more exact calculation is possible with computer programs which take the inhomogeneity of the magnetic field at the position of the round wire into account.

Losses in ideal litz wires

Reduction of rms losses with a fixed rms value of the current is only possible if the dc resistance R_0 is reduced. The additional skin losses can be reduced, however, if more of the copper cross section can be used as conductor – by a more homogeneous current density enforced to the wire. The current displacement to the wire surface is avoided by interchanging in various ways the single strands of a litz wire, being electrically insulated from each other. Litz wires are characterized by the number of strands, the strand diameter, the diameter or rather the profile of the wire bundle and by the pitch length together with a left or right handed twist.

The behavior of an ideally twisted litz wire – where every single strand changes its position with every other strand after a very short distance – is characterized by an equal distribution of the total current over all strands. If the copper cross section of a round wire is equal to the copper cross section of a litz wire consisting of N strands, then the radius of a single strand is given by $a_s = a/N^{1/2}$. The skin losses of the litz wire can be calculated likewise by eq. 2, now as sum of the skin losses of the single strands. However the skin factor from fig. 4 is not to be evaluated at a/δ, but at a_s/δ, further left in

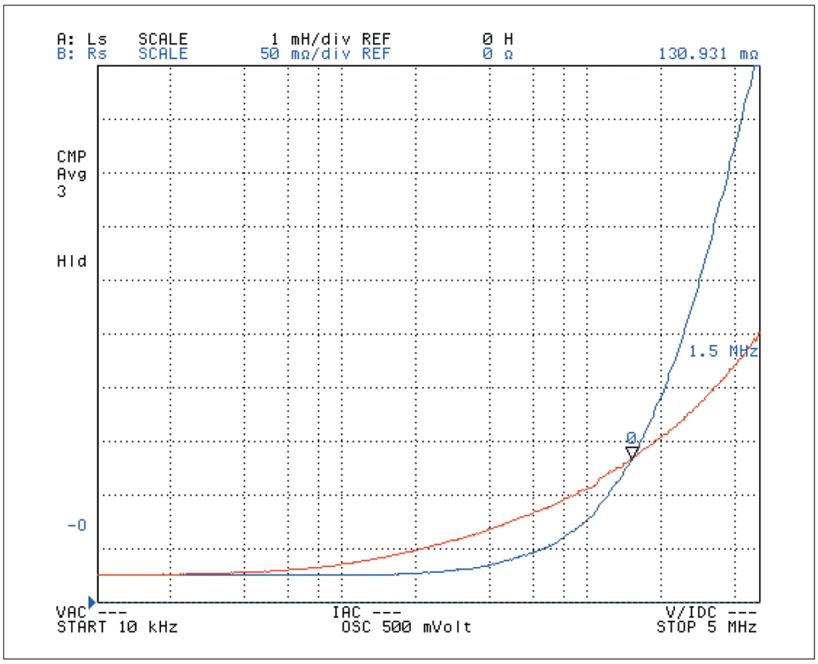


Figure 8: With increasing frequency, the skin effect for litz wires (blue curve) has less negative effect on the resistance than for solid round wires (red curve). But further increasing the frequency, the inner proximity effect in litz wires becomes more and more predominant, so that at very high frequencies solid round wires are to be preferred.

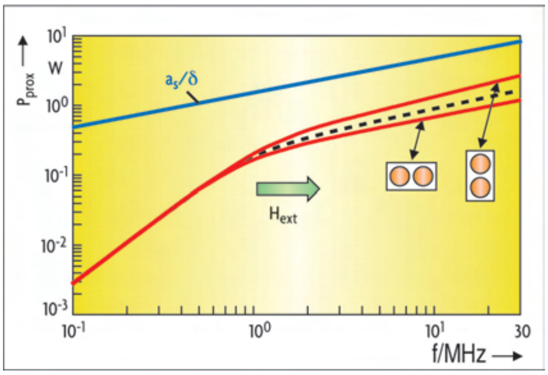


Figure 9: The alignment of parallel wires in an external magnetic field affects the proximity losses. This example shows the proximity losses [W] in two round wires of 1m length and 0.2mm diameter for a homogeneous excitation field H_{ext} = 1kA/m. The configuration on the left – wires in a row along the direction of the magnetic field – produces smaller losses than the configuration on the right, where the wires are exposed to the magnetic field side by side.

the diagram by a factor of $N^{1/2}$. But this obvious advantage is diminished because of the so called inner proximity effect. The inner proximity effect characterizes the losses of every single strand which is exposed to the magnetic field of the neighboring strands. Due to the equal distribution of the current between the strands, the magnetic field increases approximately linearly from the bundle axis to its surface (fig. 2). Using the well known field strength at the position of every single strand, the proximity losses can be calculated by eq. 3 and added up.

Of course, the radius a_s must be used again for the calculation

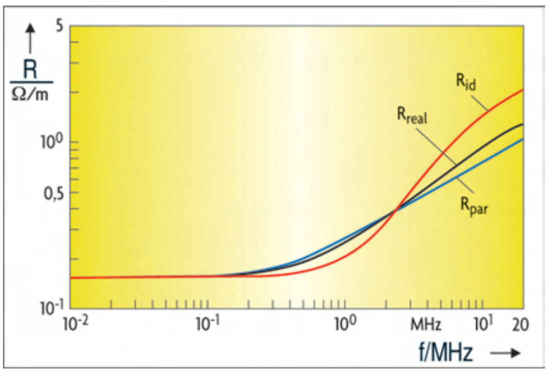


Figure 10: The resistance of real litz wires (R_{real}) due to skin and inner proximity effect stays between the resistance of ideal litz wires (R_{id}) and the resistance of parallel strands (R_{par}).

instead of a. For the time dependent current, the sum of rms, skin and inner proximity losses can be calculated by

$$P_{sk,id} = i_{rms}{}^2 R_0 \cdot \frac{1}{2} \mathrm{Re}\left\{ \alpha a_s \left[\frac{I_0(\alpha a_s)}{I_1(\alpha a_s)} + N(N-1)\frac{a_s^2}{a_L^2}\frac{I_1(\alpha a_s)}{I_0(\alpha a_s)} \right] \right\} \qquad (4)$$

where

$$a_L = d\sqrt{\frac{N\sqrt{3}}{2\pi}}$$

In eq. 4, a_L stands for the radius of the bundle of strands forming the litz wire, and d for the average distance between two strands inside the litz wire. $R_0 = \ell/(\kappa N \pi a_s^2)$ is the dc resistance of the litz wire. In **fig. 8**, measurement results for the frequency dependent resistances of a litz wire 80x0.1mm and a solid wire with equal copper cross section are compared. The dc resistances are identical. With increasing frequency, the litz wire has significant benefits because of a less pronounced increase in resistance due to skin effect. Above a certain frequency – in the example of fig. 8 above 1.5 MHz – the inner proximity effect leads to higher losses in the litz wire, and the solid wire is the better choice.

Evaluating the proximity losses in litz wires due to an external magnetic field leads to another problem, concerning the interaction between the single strands as consequence of the eddy currents induced there. To help understand this interaction, two parallel solid wires are examined, which are aligned either in a row, or side by side in relation to the excitation field. According to the explanations to fig. 6, the losses for the first case are expected to be lower. A quantitative example is presented in **fig. 9**. This diagram corresponds to the proximity factor in fig. 7, but now in a loglog scale. The direction of the external field has been indicated by the arrow. Without mutual interaction – i.e. the losses of a single wire are multiplied by factor 2 – there would result the intermediate dotted line. The results in fig. 9 show that for ideal litz wires with only a few strands and also for litz wires with a distinct rectangular profile, the direction of the external field will have significant influence on the winding losses. For round litz wires with many strands these influences compensate mutually. The same holds for litz wires with rectangular profiles, if they are placed next to each other in several layers inside a winding. The average proximity losses in ideal litz wires may be calculated in analogy to eq. 3 by

$$P_{prox,id} = \frac{1}{\kappa} N \hat{H}_{ext}{}^2 \cdot D_{s,id}$$

with

$$D_{s,id} = 2\pi \mathrm{Re}\left\{ \frac{\alpha a_s I_1(\alpha a_s)}{I_0(\alpha a_s)} \right\} \qquad (5)$$

and

$$\alpha = \frac{1+j}{\delta}$$

As before, a_s denotes the radius of a single strand and N the number of strands in the litz wire.

Losses in real litz wires

The loss calculations made before, however, are not yet applicable in general to practical problems. Because litz wires are soldered at both ends, i.e. all strands are electrically connected to each other, loop currents may form, flowing in one direction in some strands and in opposite direction in others. In this case, the integral of proximity currents over the cross section of a single strand will not be zero, i.e. the condition that all strands are equal and the litz wire can be considered as „ideal“, does not hold any more.

As a second limit case, besides the ideal litz wire, a situation will be examined, where the strands do not interchange and therefore run in parallel. This happens, if e.g. the length of a litz wire between the soldered ends is short compared to its pitch. Skin and proximity losses may be calculated in this case like for a solid wire, if the somewhat greater litz wire radius a_L according to eq. 4 and its mean specific conductivity κ_L, which is somewhat lower, are taken into account. Denoting the average distance between strands by d, then by equating the dc resistances, the mean specific conductivity can be expressed as $\kappa_L = \kappa 2\pi a_s^2 / (3^{1/2} d^2)$. The sum of rms and skin losses according to eq. 1 is given by

$$P_{par} = i_{rms}{}^2 R_0 \cdot F_{s,par}$$

with

$$F_{s,par} = \frac{1}{2}\mathrm{Re}\left\{\alpha_L a_L \frac{I_0(\alpha_L a_L)}{I_1(\alpha_L a_L)}\right\} \qquad (6)$$

and

$$\alpha_L = (1+j)\sqrt{\pi f \kappa_L \mu_0}$$

Proximity losses are now

$$P_{prox,par} = \frac{\ell}{\kappa_L}\hat{H}_{ext}{}^2 \cdot D_{s,par}$$

with (7)

$$D_{s,par} = 2\pi\,\mathrm{Re}\left\{\frac{\alpha_L a_L I_1(\alpha_L a_L)}{I_0(\alpha_L a_L)}\right\}$$

Fig. 10 shows the frequency dependent resistances for a 15x0.1mm litz wire. R_{id} denotes the ideal litz wire calculated by eq. 4, R_{par} has been calculated by eq. 6 for the case of parallel wires, and the intermediate curve is the measurement value for the real litz wire. Of course it was to be expected, that the frequency dependent resistance of the real litz wire would stay between both limit cases. Starting from the common intercept point of all three curves, it makes sense to describe the litz wire with a single parameter λ_s by a linear combination of both limit cases:

$$P_{sk,real} = i_{rms}{}^2 R$$
$$P_{sk,real} = i_{rms}{}^2\left[\lambda_s R_{id} + (1-\lambda_s)R_{par}\right] \qquad (8)$$

The value λ_s may be interpreted as quality parameter:

- $\lambda_s = 1$ signifies an ideal litz wire,
- $\lambda_s = 0$ an array of parallel strands.

An examination of proximity losses in a real litz wire shows, that the real case may be combined in a similar way from both limit cases, too. It leads to the approximation for a real litz wire:

$$P_{prox,real} = \lambda_p P_{prox,id} + (1-\lambda_p)P_{prox,par} \qquad (9)$$

Measurement techniques to characterize litz wires

For a description of litz wire behavior, two independent measurements are necessary to determine the parameters λ_s and λ_p. On the one hand, the frequency dependent behavior of the wire plays an important role for rms, skin and additional internal proximity losses in litz wires, which means, that the impedance of different solid and litz wires must be described as a function of frequency according to fig. 8. On the other hand, a major part of the winding losses is caused by the proximity effect, which means, that here the design of the winding and thus the position of each turn in the winding area plays an important role. Indeed, knowledge of the field distribution inside the winding area is necessary in order to calculate the proximity losses. However, independent of that, the behavior of litz wires in an external field has to be characterized – similar to solid round wires as shown in fig. 6. The second challenge to measurement and test engineering therefore consists of determining the losses of a litz wire located in an external magnetic field.

The frequency dependent resistance of a solid or litz wire may be measured easily by connecting a section of length e.g. 1m to the terminals of an impedance analyzer. Although the instrument can be calibrated for short and open circuit initially, there arise some inherent measurement errors. The magnetic field produced by the wire loop generates losses in all neighboring metal structures, like housings of measurement devices, but also the wire loop itself. To avoid these proximity losses, the measurement setup shown in **fig. 11** may be used, where the outside is shielded completely against the magnetic field. The test sample is fixed by spacers in the axis of a brass pipe acting as return conductor and is electrically connected to it at the far end. The frequency dependent resistance of the pipe may be subtracted mathematically. Calibration of this setup is easily done with a solid round wire.

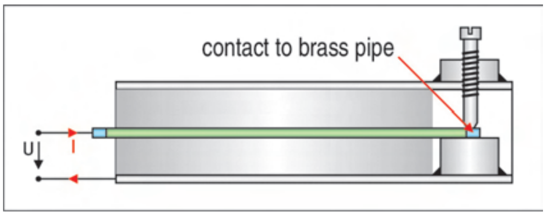


Figure 11: In order to measure the skin effect in solid wires as well as in litz wires, a setup similar to a coaxial cable has been developed, which eliminates external influences and ensures reproducible measurement conditions.

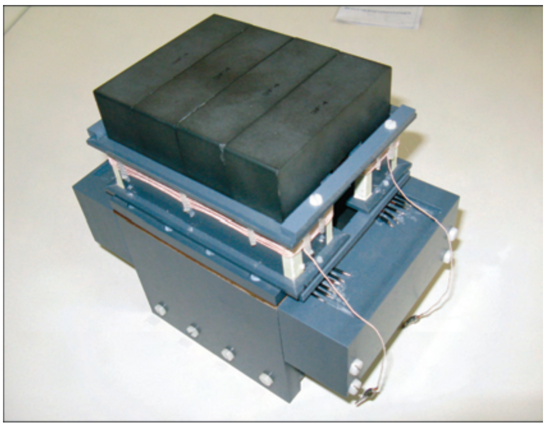


Figure 12: In order to measure the proximity effect, a transformer was constructed, which allows aligning several wire samples (solid or litz) of a determined length in its air gaps. The proximity effect can be derived from the difference of two resistance measurements in the excitation winding – with or without test samples in the air gap.

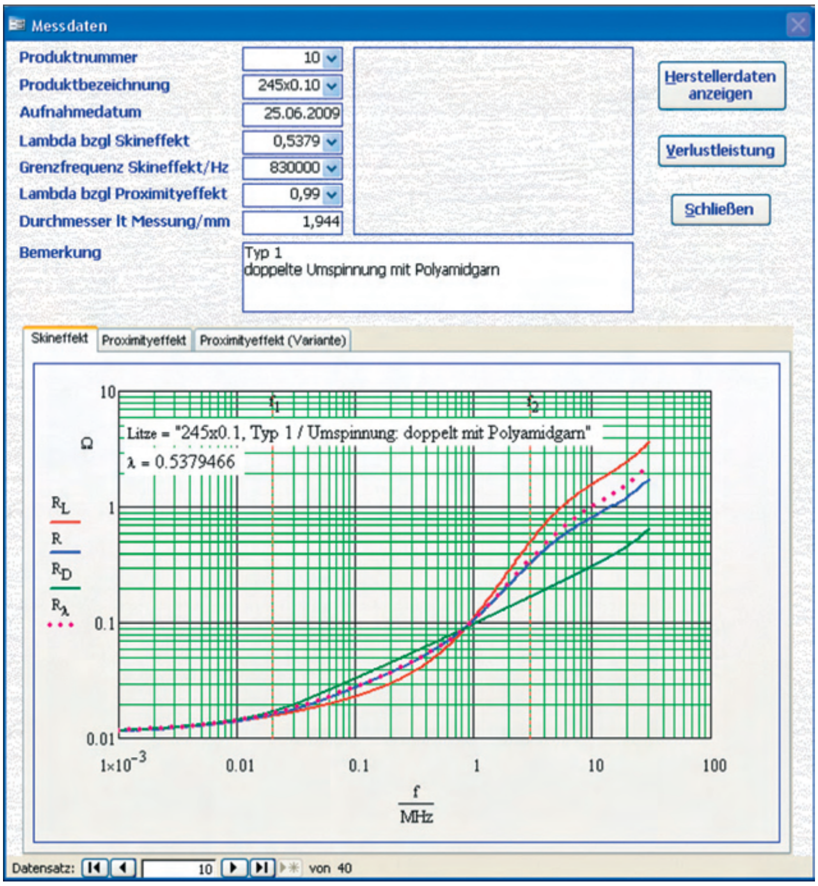


Figure 13: Test results have been collected in a data base, which allows e.g. to calculate winding losses directly from the test results when looking for the optimal wire type.

Fig. 12 shows the test setup to determine the proximity losses in solid and litz wires. In the air gap of a UI-core combination – consisting of four parallel U93 cores of material 3F4 – a magnetic field is generated by means of an excitation coil. From a reference measurement without test sample, the loss resistance of the setup is determined, produced by winding losses in the excitation coil and core losses. For the final measurement, several lengths of the test sample are placed in the air gap, and the loss resistance of the setup is determined again. From the difference of both loss resistances and a model of the magnetic circuit, the proximity factor for one strand of the test sample is calculated. The model of the magnetic circuit may be further corrected by evaluating the reactive parts of the impedances, which are measured in both cases. Several sections of the litz wire under test are placed into the air gap, where the soldered ends are not exposed to the magnetic field. Allowing for some inherent measurement errors, this setup provides quite useful results in the frequency range between 3 kHz and about 8 MHz. Below this range, proximity losses become too small compared with the dc losses of the excitation coil. Above 8 MHz the core losses become too dominant.

Measurement results

Measurements of a great number of different litz wires show that the parameter λ_s can vary within

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a wide range of values between 0.15 and 0.9. The resulting value depends in particular on the following criteria:

- In which way are the strands twisted together to form the litz wire?
- How many strands are twisted in advance and then bunched together with each other?
- Which pitch lengths were chosen?

In general can be stated, that better litz wires are characterized by a more uniform distribution probability of the strands on the litz wire cross section, over to the litz wire section length. This can be achieved by an appropriate stranding of bundles forming subsets of the litz wires.

A different picture appears when looking at the parameter λ_p. All measured values exceed 0.95. Whether a litz wire shows „ideal“ or rather „real“ behavior, is determined essentially by the distance between its soldering points, i.e. by the litz wire length in the corresponding winding. For litz wire sections with lengths above the pitch length, λ_p approaches the value 1. The smallest and thus least desirable value λ_p appears if the litz wire length exposed to the field matches approximately half the pitch length. In this case the currents in the single strands, which close over both soldered ends, will assume a maximal value. The parameter λ_p reduces then to about 0.9. Another factor influencing the quality parameter λ_p is the form stability of the litz wires. Litz wires without wrapping change their form during the winding process to a more elliptical cross section. If the larger side of the cross section is oriented

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vertically to the magnetic field, the magnetic flux through the areas between the strands increases, and thus increase the induced currents which close over the soldered ends. Litz wires with double wrapping have the highest quality parameter with regard to the proximity effect. In real winding packs there adds as an additional advantage for these types of litz wires the greater distance between neighboring turns. For rectangular profiles the direction of the external field has great influence on the quality parameter λ_p. If the external field enters the litz wire through the narrow side of the profile, it is shielded better by the induced eddy currents of the strands than if it enters through the long side. In winding packs this effect is reduced, however, by neighboring litz wires.

The road to the optimal winding

A number of different parameters must be kept in mind when choosing an optimal litz wire for a given application. When the harmonic content of the currents in coils or

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transformers is known, then, starting from the litz wire profiles, the position of the turns in the winding area can be determined and so the anticipated field distribution can be calculated. With this information, from the wide range of different rf litz wires – e.g. of type RUPALIT® – may be chosen. The manufacturer Pack Feindraehte can take advantage of a detailed characterization of standard litz wires, stored in a database (**fig. 13**).

The most important parameters for the choice of litz wire types are the number of strands and the strand diameter, as well as pitch length and direction of twist. The pitch length is influenced by the outer wrapping of the litz wire, consisting of natural silk or polyamide yarn. With increasing number of strands in a litz wire bundle, the number of options for forming bundles of multiple subsets of strands increases.