Losses in conductors and inductors: Bibliography

Compiled by David W Knight[1]
Version[2] 1.00, 29th March 2012.

Breit 1922, BS Sci. 430
HF resistance of inductance coils. G Breit.

Hickman 1923, BS Sci. 472
Alternating Current Resistance and Inductance of Single-Layer Coils. C N Hickman. Scientific Papers of the Bureau of Standards, No. 472. 1923, Vol. 19, p 73-104 + corrections. [Available from www.g3ynh.info/zdocs/magnetics/]

Butterworth 1926
Effective Resistance of Inductance Coils at Radio Frequencies. S. Butterworth. Experimental Wireless & The Wireless Engineer, 1926, Vol. 3, April p203-210, May p309-316, July p417-424 and Aug. p483-492.

Hall 1926, BS Tech 330.
Resistance of Conductor of various types and sizes as windings of single-layer coils at 150 KHz to 6 MHz.

Jackson 1937
Measurements of the high-frequency resistance of single-layer solenoids. Willis Jackson. Wireless Section, Proc. IEE, June 1937, Vol. 12, No.35, p133-138

Abstract: Describes an attempt to determine the accuracy of Butterworth's formulae for the HF resistance of single-layer solenoids. Measurements were made on 4" diameter air-spaced coils of 10, 30, and 50 turns over the frequency range from 200kHz to 2.025 MHz. The coils were wound with bare wire of 1.63mm dia. (16 SWG), with a distance of 2.60mm. between the centres of adjacent wires. The method of measurement described was based on the use, for each coil shape, of a series of identical coils wound with Cu, Al, brass, German silver, and eureka wire. There is some uncertainty in the interpretation of the results, but it is evident that of the two formulae with which a comparison is made, one of them is correct to within about 4% for the 30- and 50-turn coils over the frequency range considered. This formula is inapplicable to the 10-turn coils; but for these the second formula gives reasonably good agreement with the experimental results.

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2 The most recent version of this document can be obtained from: http://g3ynh.info/zdocs/magnetics/ .
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Wheeler 1942
Formulas for Skin Effect. H A Wheeler. Proc. IRE, Vol. 30, No. 9, Sept. 1942, p412-424.
Abstract: The 'incremental-inductance rule' is given for determining the effective resistance of a circuit and the added resistance caused by conductors in the neighbourhood of the circuit. Simple formulas are given for the resistance of wires, transmission lines, and coils; for the shielding effect of sheet metal; for the resistance caused by a plane or cylindrical shield near a coil; and for the properties of a transformer with a laminated iron core.

Medhurst 1947
H. F. Resistance and Self-Capacitance of Single-Layer Solenoids. R G Medhurst . Wireless Engineer, Feb. 1947 p35-43, Mar. 1947 p80-92. Corresp. June 1947 p185, Sept. 1947 p281.

High frequency resistance measurements for solenoid coils are in good agreement with Butterworth's theoretical values when the turns are widely spaced. For closely-spaced coils, the measured values are considerably below those of Butterworth.

Medhurst's raw measurements are given in **Arnold 1951**.

Phillips 1950
The eddy-current and screen losses of a screened single-layer solenoid. F M Phillips, Proc. IEE - Part III, Radio and Communication Engineering, Vol. 97, No. 46, p77-87, March 1950.

Abstract: Outlines Butterworth's method for the determination of the HF resistance of an isolated single-layer solenoid. This tends to exaggerate the resistance, and accordingly a modification is suggested. The HF resistance of a particular coil is computed and it is shown that the losses are less than those which would be obtained using Butterworth's formulae. Comparison is made with Jackson's measurements, which show that Butterworth's formulae tend to underestimate the resistance, and it is consequently noted that there must be a further underestimation by the method given in the paper. When the coil is surrounded by a concentric screening-can, not only are the losses in the coil altered, but further losses arise in the screening-can itself. Butterworth's method still applies to the coil, and an expression is derived for the can. This expression is compared with Bogle's empirical formula and is found to agree very well, provided that the coil is not too short. Finally there is a worked example where a particular screened coil is taken for which all the losses are calculated, and the effect of the screening-can on the Q-factor of the coil is determined.

Arnold 1951
The Resistance of Round-Wire Single-Layer Inductance Coils. A H M Arnold (NPL). Proc. IEE Part IV. Institution Monographs, Oct. 1951. Vol. 98, p94-100.

Abstract: Butterworth's two formulae for the resistance of short coils with a finite number of turns and long coils with ∞ turns are merged into a single formula valid for coils of any length and any number of turns. Numerical values of the functions appearing in the formula are tabulated. The formula is shown to give reasonable agreement with the experimental figures of Medhurst and Hickman.
Note: Medhurst's raw measurements, not given in his 1947 paper, are reproduced here.

Dowell 1966
Effects of eddy currents in transformer windings, P L Dowell. Proc. IEE, August 1966, Vol.113, No.8, pp.1387-1394,

Abstract: A method is derived for calculating the variation of winding resistance and leakage inductance with frequency for transformers with single-layer, multilayer and sectionalised windings. This involves dividing the winding into portions, calculating the DC resistances and DC leakage inductances of each of these portions, and then multiplying the DC values by appropriate factors to obtain the corresponding AC values. These AC values are then referred to, say, the primary winding and summed to give the total winding resistance and leakage inductance of the transformer. Formulas are derived and quoted for calculating the DC resistances and leakage inductances of the winding portions. Theoretical expressions are derived for the variation with frequency etc. of the factors by which the DC values must be multiplied to obtain the corresponding AC values. These expressions are presented in the form of graphs, permitting the factors to be read as required.

Ajayi 1973
H.F. resistance of round-wire single-layer inductance coils. O Ajayi, Proc. IEE, Vol.120, No. 9, p1055-1056, Sept. 1973.

Abstract: The elements of a coil cut by two parallel planes are approximated to elements of straight parallel conductors, and equivalence between the coil and the straight parallel conductors is assumed. Resistance of the system of parallel conductors is calculated by the method described in an earlier paper by Arnold and the author. Calculated values of the resistance of the coils used by Medhurst in his experiments are compared with the experimental values of resistance. Results show agreement within 5% for coils having high values of x. This agrees with Butterworth's theory that the field in the coil is uniform for high values of x and a large number of turns. The agreement between experimental and calculated results is therefore within the region predicted by theory when x is large. The method can thus be applied with confidence to coils at high frequencies provided that the frequency of operation is within 5% of the SRF of the coil and x is ≥17.

Smith 1971
The proximity effect in systems of parallel conductors and electrically small multiturn loop antennas. Glenn Smith. Dec 1971. Technical Report No. 624. Division of Engineering and Applied Physics. Harvard Univ. Cambridge, MA 02138.

[Available from www.dtic.mil/dtic/]

Perry 1979
Multiple Layer Series Connected Winding Design for Minimum Losses. M P Perry. IEEE Trans. on Power Apparatus and Systems. PAS-98, No. 1, Jan/Feb 1979. p116-123.

Abstract: The classical one dimensional magnetic field and eddy current distribution ("proximity effect") within a series connected multiple layer coil is re-examined with regard to power losses within the windings. When the length and number of layers in a coil are fixed, the power dissipation within each layer can be minimized by choosing a specific radial thickness for each layer. Above or below this thickness, the losses within the winding increase. The conductor thickness which results in minimum dissipation depends on the relative position of the layer. When compared to a design having a constant thickness for each layer (chosen for minimum total dissipation), it is found that substantial savings in power consumption can be realized by employing a variable thickness of conductor. The one dimensional solution in cylindrical coordinates for the eddy current and skin effect in a multiple layer series connected coil is also presented. By solving the problem n cylindrical coordinates, the effect of curvature on the power consumption within each layer is apparent. This analysis should have application to the design of power transformers, armature windings, and inductors for power transmission lines.

Snelling 1988
Soft Ferrites, Properties and Applications", E C Snelling. Butterworths. 2nd edition 1988.

Q-factor: Section 5.7, p175 - 178
Power loss due to eddy currents in the winding. Section 11.4. p317 - 330.
References: p338

Fraga et al. 1998
Practical Model and Calculation of AC resistance of Long Solenoids. E Fraga, C Prados, and D-X Chen. IEEE Trans. on Magnetics, Vol 34, No. 1. Jan 1998.

Abstract: In order to study the impedance of long solenoids, a tube model has traditionally been used. The model resistance is expressed in terms of the Bessel functions. We show how to relate the model resistance to the resistance of the actual solenoid, so that the model can be better used in practice. Since the computation accuracy when using the Bessel functions may decrease quickly with increasing the magnitude of their argument, the model results can be calculated only for thin solenoids at low frequencies. This problem has traditionally been solved by using the asymptotic expressions of Bessel functions. We show the appreciable error owing to this and propose a simple approach to make a very accurate correction. Practical formulas for the ac inductance of solenoids are also given.

Sullivan 2001
Sullivan, C.R.; , "**Computationally efficient winding loss calculation with multiple windings, arbitrary waveforms, and two-dimensional or three-dimensional field geometry**," Power Electronics, IEEE Transactions on , vol.16, no.1, pp.142-150, Jan 2001

Abstract: The squared-field-derivative method for calculating eddy-current (proximity-effect) losses in round-wire or litz-wire transformer and inductor windings is derived. The method is capable of analyzing losses due to two-dimensional and three-dimensional field effects in multiple windings with arbitrary waveforms in each winding. It uses a simple set of numerical magnetostatic field calculations, which require orders of magnitude less computation time than numerical eddy-current solutions, to derive a frequency-independent matrix describing the transformer or inductor. This is combined with a second, independently calculated matrix, based on derivatives of winding currents, to compute total AC loss. Experiments confirm the accuracy of the method.

Sippola and Sepponen 2002
Accurate prediction of high-frequency power-transformer losses and temperature rise, M Sippola, R E Sepponen, IEEE Trans. on Power Electronics, vol.17, no.5, pp. 835- 847, Sep 2002

Abstract: The high-frequency power-transformer design equations for winding and core losses and temperature rise were reviewed from literature and formulated for spreadsheet calculations using material (Steinmetz loss coefficients, ferrite resistivity, copper resistivity), geometry (core area, core length, winding area, winding length), winding (number of primary turns, copper fill factor, primary to secondary area ratio) and excitation (input voltage, switching frequency, duty cycle, current harmonic components) parameters. The accuracy of each design issue was first validated and quantified separately using regression analysis. Calculated core losses, winding AC-resistance equations and heat transfer capacity calculations were compared with the results from calibrated heat sink measurements, finite-element method (FEM) analysis and measurements using thermal test blocks, respectively. Finally three EFD20 type transformers (solid wire, noninterleaved foil and interleaved foil winding) were fitted into an active clamp forward converter (100-300 kHz switching frequency, 0-78 W throughput power) for comparison between the theory and experiments. Standard error of predicted core losses and heat transfer capacity were determined to be 0.0581 and 0.15 W, respectively. The results of the in circuit tests suggests that the transformer total losses can be predicted with the average standard error below 0.2 W with datasheet type information only. The most significant uncertainty was heat conduction through and losses generated in the interconnecting wires between the test transformer and other converter components.

Podoltsev, Kucheryavaya, Lebedev 2003
Analysis of effective resistance and eddy-current losses in multiturn winding of high-frequency magnetic components, A D Podoltsev, I N Kucheryavaya, B B Lebedev, IEEE Trans. on Magnetics, vol.39, no.1, pp. 539- 548, Jan 2003

Abstract: This paper develops a numerical model for calculation of eddy-current losses in a multiturn winding of a high-frequency transformer. The model assumes periodic arrangement of conductors, and uses the repeat elementary cell concept. The paper proposes analytical expressions and graphic dependences to determine effective frequency-dependent resistance of the winding. It computes the leakage field in the transformer window, taking into consideration the effective magnetic permeability of the multiturn winding as a heterogeneous medium. Finally, it analyzes the values of the resistance at various frequencies for two types of winding (solid conductor winding and Litz wire winding) by numerical and experimental methods.
