Popular Magnetic Cores And Wires: Their Properties, Accessories And Tables

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Magnetic components such as inductors and transformers are usually designed for a specific application. However, certain applications of these components are sufficiently popular that they are offered as standard products. More commonly, though, magnetic components are custom-designed, resulting in thousands of magnetic parts variations designed from more basic components: cores and conductors (wire).

Although core and wire components also have multiple variations, the number of them is manageable for stocking the inventory of a power-electronics laboratory or prototyping facility. This article describes how the Innovatia laboratory is stocked as an example of how relatively few cores and wire sizes can suffice for a wide range of typical magnetics designs. What not to stock (much of) is also recommended.

Along the way of this virtual tour of my stockroom, I'll review some of the magnetics design theory that underlies the various choices of cores and wires kept on hand. I'll also recommend some selections based on the results of a study conducted by one of the leading power magnetics programs. A series of tables appended to this article list my favorite cores and their properties along with a specialized wire table I have developed.

Core Materials

One of the core properties that can be derived from core catalog data is the optimal ripple factor of a core. Although the magnetics industry has yet to list this important design parameter in core catalogs, core materials have an optimal ripple factor of

$$\gamma_{opt} = \frac{\Delta B/2}{\overline{B}} = \frac{\hat{B}_{\sim}}{\overline{B}}$$

The magnetic field density, *B* ripple (~) amplitude (^), or $\hat{B}_{\sim}$, is the horizontal-axis quantity on core material power-loss graphs. In the γ_{opt} expression, $\hat{B}_{\sim}$ is the maximum allowable value based on frequency and thermal design that determines maximum average power-loss density $\overline{p}_c$, the vertical axis on the power-loss graph. Average *B*, or $\overline{B} = \mu \cdot \overline{H}_{sat}$ relates to maximum core saturation. When a core is driven to both its power-loss and saturation limits, ΔB and $\overline{H}$ are both maximized, and maximum transfer-power density is achieved resulting in the smallest size of core of that material.

Not only does core material have γ_{opt}, power-transfer circuit design conditions determine the circuit γ related to winding current;

$$\gamma_{ckt} = \frac{\Delta i/2}{\bar{i}} = \frac{\hat{i}_{\sim}}{I}$$

where $\hat{i}_{\sim}$ = the ripple amplitude and $I = \bar{i}$ = the average current. The winding current ripple amplitude to average on-time current ratio is γ. Whenever $\gamma \le 1$, the current waveform is CCM and for $\gamma > 1$, it is DCM. Transformer waveforms are bipolar; for the whole waveform, $\gamma \to \infty$ (I = 0 A), but γ is only meaningful when applied to each half-cycle during which *I* is the average on-time current—the average current when $i \neq 0$ A.

By combining circuit design with a choice of magnetics material, the optimal condition,

$$\gamma_{opt} = \gamma_{ckt}$$

is achieved and the power-transfer circuit will have maximum power transfer for a given size of core made of the material. (This is one instance of why circuit and magnetics designs should be optimized together.)

The optimal core material for transformers in SMPS applications is ferrite because ferrites have the highest γ_{opt} and are closest to optimum for bipolar waveforms. Each half-cycle of a symmetric bipolar waveform of any waveshape has γ = 1. Then whatever core material is closest to γ_{opt} = 1 maximizes transfer-power density. Appended to this article is the Innovatia MnZn ferrite core list (Appendix 1). This expresses what is inventoried by Innovatia and is not necessarily optimal for a new laboratory—more on this under "Core Shapes".

The design formula for γ_{opt} is calculated from catalog quantities;

$$\gamma_{opt} = \frac{\hat{\phi}_{\sim}}{\bar{\phi}} = \frac{\hat{B}_{\sim} \cdot A}{\mathcal{L} \cdot N\bar{i}} = \frac{\hat{B}_{\sim} \cdot A}{k_{sat} \cdot \mathcal{L}_0 \cdot N\bar{i}}$$

where Φ is magnetic flux (Λ peak or — average where ~ is ripple), $\mathcal{L}$ is field inductance, A is core cross sectional area, N is number of turns, k_{sat} is a saturation factor, and $\mathcal{L}_0$ is field inductance at zero current.

For example, a Micrometals Fe-pwd toroid T80-26 has a magnetic cross-sectional area of A = 23.1 mm^2, the transfer power is ΔP = 20 W at f_s = 100 kHz and $\hat{B}_{\sim}$ = 28 mT, $\mathcal{L}_0$ = 46 nH and for a fractional saturation of k_{sat} = 0.6, $N\bar{i}$ = 157 A. Calculate $\mathcal{L} = k_{sat} \cdot \mathcal{L}_0$ = (0.6)·(46 nH) = 27.6 nH. Substitute into γ_{opt} and γ_{opt} = 0.15.

Iron-powder (Fe-pwd) cores typically have γ_{opt} in the range of $\gamma_{opt} \approx$ 0.05 to 0.25. Small Fe-pwd cores are at the high end of γ_{opt}. Fe-pwd cores are well-suited for inductors (Fig. 1), including coupled inductors, though in some power-transfer circuits such as Ćuk-derived current-steered circuits the magnetic component swerves in and out across the boundary between CCM and DCM at γ_{ckt} = 1.

During part of the cycle, a Ćuk power-transfer circuit behaves as a transformer and otherwise as a coupled inductor. (To give magnetics parts with multiple windings a *structural* name, I call them *transductors*. Whether they are transformers or coupled inductors depends on how they behave in the circuit.) In PWM-switch circuits such as the CP (buck), current ripple is usually low relative to average inductor current, and Fe-pwd is usually optimal. The appended Innovatia Fe-pwd list (Appendix 2) gives an example inventory for stocking a magnetics laboratory.

Fig. 1. Iron-powder Micrometals toroid cores shown in the stack and on the left are made of materials 26 (the yellow and white cores) and 52 (the lone green core), which are often optimum for inductor applications when the highest performance is not critical. Higher magnetic performance at higher cost is achieved by the wound gray NiFeMo Magnetics Inc. core in front of the Fe-pwd core tower. The dark gray EE cores with bobbins to the left of the tower are also Micrometals Fe-pwd cores on the Innovatia list.

Ferrites and Fe-pwd span the range at the extremes of γ_{opt}. In between them are other materials in powder form in a plastic resin binder. They are FeSiAl, NiFeMo, NiFe, and FeSi, to use their chemical alloy designations. (Each supplier has its own trade name for them. Pronounce the alloy names, as we commonly do for AlNiCo magnets, and they are easier to remember.)

These differ not only in cost but also in maximum transfer-power density. Each material is available in a range of γ_{opt} choices that vary over the range of field inductances $\mathcal{L}$. For ferrites, this range corresponds to the variation in air gaps and in powder cores by the density of the powder in the plastic resin. For any material, transfer power is maximized by choosing a γ_{opt} that best fits γ_{ckt} to γ_{opt}. Appended is the Innovatia list of such parts (Appendix 3). Most of them are available in the form of toroids though Fe-pwd core shapes have expanded into EE cores as Fig. 1 shows.

Core Shapes

Which core shapes are best for power magnetics? You might expect an "it depends" answer, but from the research of Charles Sullivan's group at Dartmouth,[1] a more definitive response might be given. His grad students ran hundreds, if not thousands, of FEA simulations focusing on thermal properties and found that PQ and RM cores have geometries with the lowest power loss. The Innovatia core lists (mainly Appendix 1) show instead a preference for ETD cores—an example *not* to follow!

At this point, the Dartmouth research suggests an emphasis on PQ cores for optimal performance. This is the choice, for instance, of some commercial inverter designs such as the Statpower 500, as shown in Fig. 2. It has a long row of 8 PQ-core transformers (right 2 removed) in its converter stage.

Yet the final choice depends on the overall criteria for the particular converter design. Maximum power density or minimum loss is not always the driving parameter of a design. You might, for instance, want to rid your stock of a large inventory of some less optimal EE or ETD cores.

Or your manufacturing people might be more accustomed to build with ETD, EER, or ER cores and to change would add a significant expenditure to your operation. Your winding jigs might need to be changed or a new winding machine acquired. Sometimes criteria not directly associated with optimized transfer-circuit or loss performance dominate a design decision.

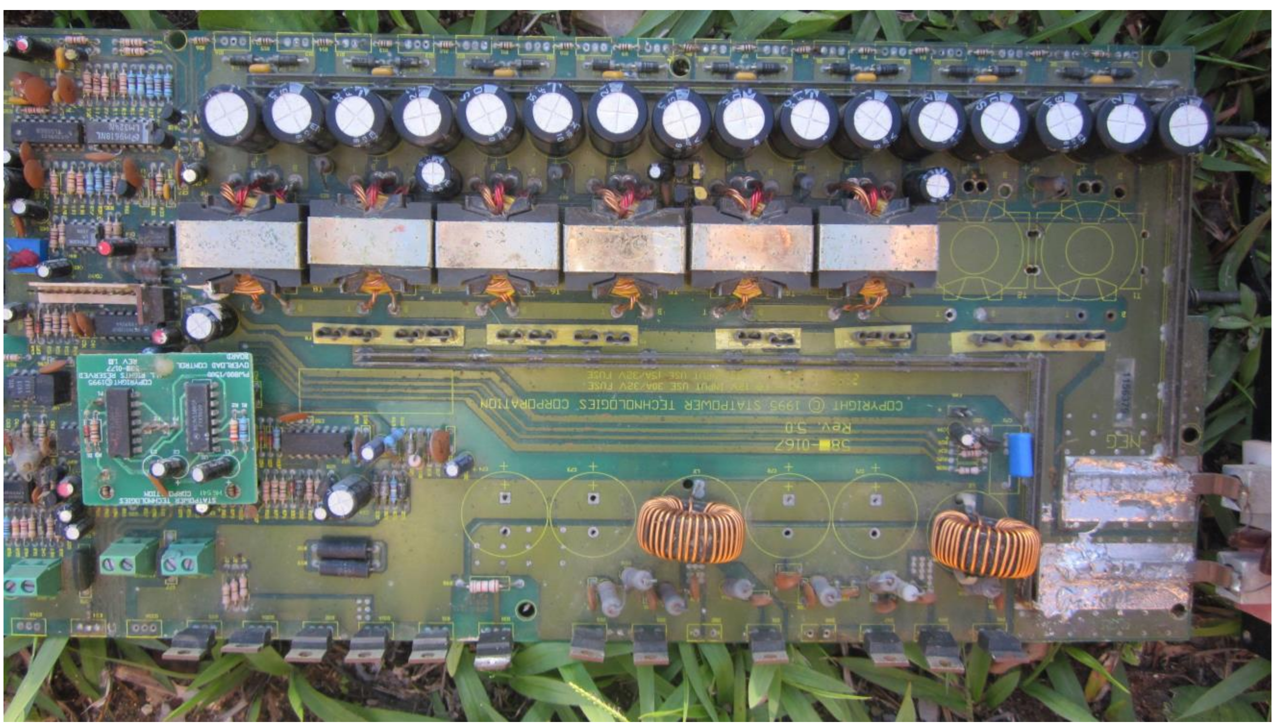

Fig. 2. Photo of a scrapped Statpower 500 inverter with eight parallel converter circuits having PQ transformers.

The oldest and least desirable core shapes are EE cores, though for some applications they are a reasonable choice. They have square center legs that are harder to wind around, and turns are longer with more resistance around a square than a circle. The attempt to optimize core shape has resulted in cores with a round center leg and a more uniform distribution of field within the core. In this generation of shapes are ER, EER, ETD, and EFD cores.

At the same time, other shapes have had their own history. Toroids have the most winding exposure to air and are the best thermally. They also confine the magnetic field well but are hardest to wind.

A quite different shape development is that of pot core evolution. The totally enclosed windings require all winding heat to traverse the core, plus core loss itself, placing twice the thermal load on the core. The largest advantage of pot cores is their near-total enclosure of the magnetic field, rendering them optimum when low noise is the driving factor and not transfer-power density.

Pot cores evolved into slabbed pot cores where parallel slices open the core for better cooling. These then evolved further into RM and PQ shapes which, according to the Dartmouth study, are better than the refined EE cores for minimizing total power loss including winding loss. Toroids, however, are still superior for heat transfer but are usually much harder to wind.

Consequently, the answer to the question of which shape is optimal is the predictable "it depends," but for many—probably most applications—the optimization criteria would favor the PQ and RM cores and also toroids if *buildability* is not a limiting factor.

Core Accessories

What can be an overlooked factor in design with cores are the accessories. Ferrite cores are fragile; drop one on a tile floor and it will likely splinter into two or three pieces or else (if you're tall) shatter to where it cannot be glued back together with cyanoacrylate glue and (now with gaps and a slightly lower $\mathcal{L}$) relegated to a research project.

Cores shipped in styrofoam protective enclosures have shapes that conform to and capture them. It is a good practice to store them in these same cartons and not put them in drawers or on shelves to achieve a higher storage density.

To assemble a core pair, clamps snap over them and hold the halves tightly together for a minimal magnetic air gap. The alternative is to glue the adjoining surface of the pairs with cyanoacrylate glue to minimize the air gap. The clamps are more versatile for disassembly, especially in research projects, though they add somewhat to the cost.

There is a small choice in bobbins. Some have separators to keep primary and secondary windings isolated. The tradeoff is reduced window area. Perhaps the design can make use of more area for conductors in a single-section bobbin by isolating windings with polyester tape. It is a design decision. Bobbin vertical or horizontal configurations offer a choice in circuit-board footprint and mechanical design.

Pot-based cores can be fitted with a "clamp" cover with pins that solder into the circuit-board, as shown in Fig. 2. (Note the board hole patterns of the removed parts to the right. Four holes are for mounting the cover.) Some pot cores have a center-hole that accommodates a bolt and screw to hold the part to the circuit-board.

The magnetic field in the center hole will cause loss in a steel bolt, consisting mostly of iron with high eddy-current loss. A fringe field in the core center can heat it to a high temperature. Plastic bolts eliminate that problem but are not as strong, weaken with temperature, and can shear under acceleration in violently vibrating vehicular venues.

Wire Type

The dominant wire for windings is round "magnet wire". This is enamel-coated wire with a thin layer of high-temperature nylon or other plastic insulation and is optimum for most applications. Square magnet wire is theoretically better in that squares pack with a packing factor of $k_p = 1$, leaving no gaps between turns of conductor except the insulation. (Part of the winding packing factor is *porosity* k_{pw}—nonconductor area in the spacing between conductors.)

A few turns of large square wire can be laid down in the bobbin or coil-former and approach this ideal, but when more than a few turns with multiple layers are wound, maintaining square packing is not feasible. Square wires twist and skew, and the result is no better than round wire; thus, square wire is uncommon in use. It might be worthwhile to keep some larger-size square wire in stock to optimize the windings of high-current low-inductance parts, but otherwise round is better because its symmetry makes it independent of its orientation and does not affect its packing. The Innovatia wire table appended to this article includes eddy-current parameters for both copper and aluminum conductors.

Copper (Cu) is the dominant conductive material for windings, but in some cases, aluminum (Al) is superior. Cu has higher static (0 Hz) conductivity than Al which has higher losses for static current. Because of its lower conductivity, Al also has a deeper skin depth δ for the dynamic component of current, the current ripple. The approximated view of skin depth is that the eddy-current skin effect causes current to crowd to the periphery—the OD—of a conductor so that the equivalent conductive area is that of a ring at the circumference with a thickness of δ. Because Al has a larger δ than Cu, it has more conductive area and hence lower resistivity under some conditions.

Charles Sullivan of Dartmouth has a paper comparing the two as does my magnetics book in a section that was independently developed before finding Sullivan's paper and hence gone about in a different way. The conclusion is that if a winding has two layers, there is a narrow range of wire sizes that have lower resistance in Al, and this range widens as the number of layers increase.

For two layers the advantage of Al is shown by the graph in Fig. 3. Al has less resistance than Cu at wire sizes from 29 to 32 AWG. The range for Al of three layers broadens, from 29.5 to 33.5 AWG, with a maximum advantage in resistance of 14% around 31.5 AWG. For four layers, the advantage is largest at 32 AWG, having a Cu f_δ of 519 kHz; f_δ is the frequency at which δ = 1. The resistance ratio is lowest, favoring Al by 21%, and is below one in the range from 28 to 36 AWG.

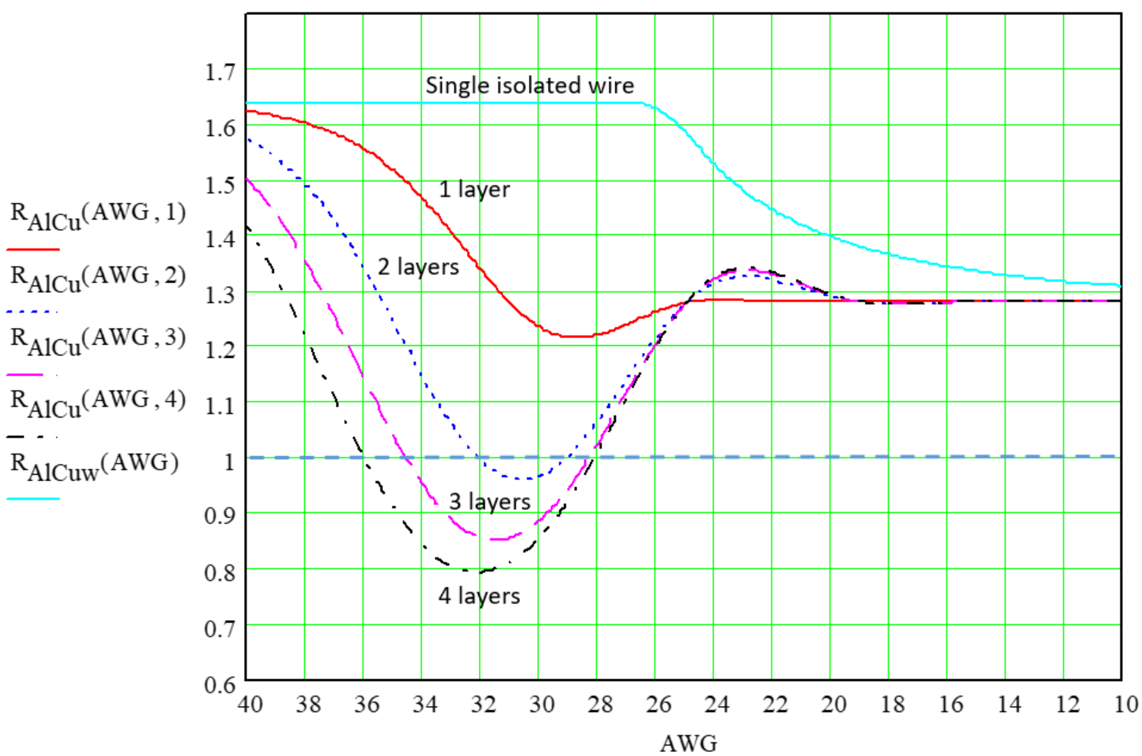

Fig. 3. Ratios of Al to Cu resistance over wire size in AWG and number of layers, at 150 kHz. The R_{AlCuw}(AWG) plot is of a single isolated wire. Plots dipping under 1 show an Al advantage.

Besides round and square, another conductor shape is that of foil. It is rectangular with a thin height dimension. High-current windings are often foil-wound because of the large conductive cross-sectional area of foil. Typical widths are 1/8 inch (3.175 mm) to ¼ inch (6.35 mm) with thicknesses of 50.8 µm (2 mil) to 127 µm (5 mil). Common ampacities range from 0.73 A to 3.6 A and are comparable to 10.5 AWG round wire. Foil has eddy-current advantages because it shows a geometric length limit in only the height dimension for wide foil.[2]

Foil for windings is not easy to find. I stocked Innovatia through an order to Bridgeport Magnetics Group with Alpha-Core Cu foil in the widths and thicknesses cited above. Copper wire or foil has a thermally-limited current density of 4.5 A/mm^2 and for Al it is 2.75 A/mm^2. Aluminum foil is sold at grocery stores in two thicknesses: 15 µm and 22.5 µm with ampacities per width of 0.4125 A/cm and 0.619 A/cm. Kitchen foil is not thick enough for high ampacity and multiple layers of it are required for high-power applications.

Connectivity is more problematic with Al than with Cu wires or foils. Al can be soldered to Cu but requires a higher soldering temperature than Cu. An intermediate Cu connecting wire reduces the temperature applied to bobbin pins.

In high-voltage applications involving offline supplies, safety considerations require sufficient isolation of primary and secondary windings. This is often accomplished with layers of 25-µm (1-mil) thick polyester tape that is (for reasons unknown to me) predominantly of yellow color.

Multiple windings can cause these tape layers to occupy significant window area. An alternative is for the wire itself to be sufficiently insulated to meet safety requirements. Insulative sleeves are one alternative, but a more integrated alternative is Rubadue insulated wire from Rubadue Wire. It is a niche market with few major competitors. Yet another way to insulate is to use bobbins with multiple sections.

A high-performance winding option is *Litz wire* which is not really a wire but a bundle of wires as *strands* configured geometrically to reduce eddy-current resistance. These can be made in-house with a variable-speed drill and a hook some distance away, to loop the wire around. The two wire ends in the drill chuck twist into a two-strand bundle, but more loops back and forth from the hook add strands.

Multiple bundles can be twisted into a bundle of bundles. By flipping the spool end to end every so often as wire is expended from it, wire torsion is reduced along with wire knotting and kinking. Twisted strands of wire are the simplest form of Litz wire that can reduce eddy-current losses in windings. For greatest optimization, commercially available braided Litz wire has lower eddy-current loss.

Wire Accessories

Wire is sold on spools and best stored as it is delivered, to avoid the horrors of "Gordian knots" of tangled heaps of wire. Spools can be placed on a holder that is easily constructed of PVC tube cut to length and fitted in a fixture contrived of styrofoam packing material. Two holders—one simple and the other more deluxe—are shown in Fig. 4 along with the plan for the wood holder.

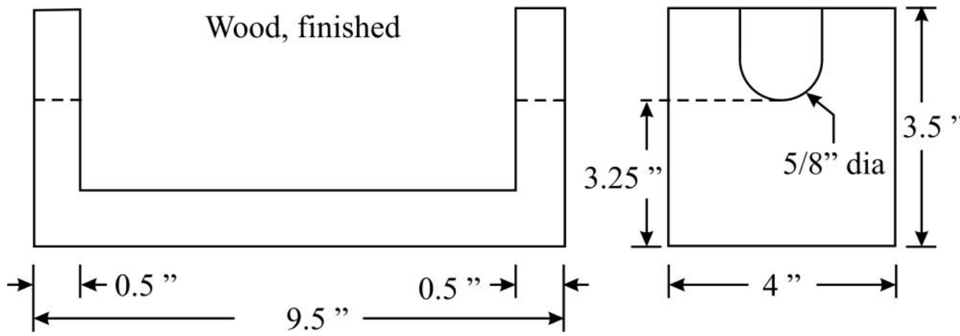

Fig. 4. Wire spool holders for letting out wire on the prototyping bench or for forming bundles: styrofoam holder (top); wood holder (middle); and the plan for the wood holder (bottom).

Bundles can be constructed from a stationary spool to avoid wire torsion by pulling the wire out of the spool to a far hook and back. This is not as feasible for small wire.

An essential accessory for designing with wire is a wire table. These are commonly available in wire catalogs and power electronics books. The Innovatia wire table is appended (Appendix 4).

In closing, magnetics design is not only about design formulas and their derivations but also includes a familiarity with what the variables in the equations represent physically—the portrayal of their characteristics in tables, their accessories, and some of the additional tools for working with them.

References

1. “Aluminum Windings and Other Strategies for High-Frequency Magnetics Design in an Era of High Copper and Energy Costs” by C. R. Sullivan, *IEEE Transactions on Power Electronics*, vol. 23, no. 4, pp. 2044–2051, 2008.

2. “Foil Vs. Wire Windings - How Do They Differ?” How2Power Today, October 2020 issue.

About The Author

Dennis Feucht has been involved in power electronics for 40 years, designing motor-drives and power converters. He has an instrument background from Tektronix, where he designed test and measurement equipment and did research in Tek Labs. He has lately been working on projects in theoretical magnetics and power converter research.

For more on magnetics design, see these How2Power Design Guide search results.

Appendix 1: Innovatia MnZn Ferrite Core List

Core Type	V, cm^3	A, mm^2	l, mm	A_w, mm^2	B_{sat}, mT 100°C	f_μ, MHz	f_{MAX}, MHz	$\hat{B}_\sim$, mT @ $\overline{p}_c$; f_s, kHz		$\mathcal{L}_0$, μH	$\overline{p}_c$, mW/cm^3
								100	200		
P1408-3C8	0.495	25.1	19.8	8.8	325	0.6		150	100	2.8	496
P1408-3B7 P1408-3B7A250 RS1408-3B7	0.495	25.1	19.8	8.8	300	0.8				2.0 0.25	496
PQ2020 NC-2H	3.03	64.3	47.2	65.8	375	1.5		160	95	3.15	246
RM8 NC-2H	2.43	64	38	63.5	375	1.5		170	100	3.7	283
EI187 EE19.3 NC-2H	0.918	22.9	40.2	55.5	375	1`.5		190	115	1.26	365
EF20-N27	1.50	33.5	44.9	34	375	1.3		100	80	1.30	316
E24-25-3C80 E25/10/6	1.93	39.5	49.0	58.1	375	1.5		125	85	> 1.58	280
EF25-N30	3.02	52.5	57.5	56	240	0.6				3.10	246
EER28 NC-2H	5.8	88.3	65.7	109	375	1.5		150	90	3.05	206
EC35 B-50	6.53										198
EER28L NC-2H	6.76	87.7	77.1	141.6	375	1.5		140	88	2.80	190
EFD20 EET20C NC-2H	1.45	31.4	46.1	50.1	375	1.5		190	110	1.20	340
EFD25-3F3	3.30	58.0	57.0	40.2	350	3.5	0.6	140	95	2.0	253
EFD30-3C94	4.70	69.0	68.0	52.3	350	1.2	0.3	170	110	1.9	223
ETD34-3C90	7.64	97.1	78.6	123	350	1.2		168	105	2.7	186
EER35L NC-2H	10.4	112.8	92.2	210.2	375	1.5		135	85	3.05	157
EI21 B-50 EI21 H-5A	11.8	152	77.5	126						2.5	145
ETD39-3F3	11.5	125	92.2	177		3.5	0.6	150	90	2.8	160
ETD44-3C90	17.8	173	103	214	350	1.2		125	80	3.8	136
ETD49-3C90	24.0	211	114	273	350	1.2		120	70	4.20	121
EC70 N27	40.1	279	144	469	375	1.3		70	50	3.6	99
TOR-23 41306-TCK	0.457	14.6	31. 2	49.3				170	115	0.850	541
TOR-53	8.22	103	80	287				170, 75 kHz		7.94	192

Total power dissipation of core + winding is split equally between core and winding and half assigned to core as $\overline{p}_c$, Δ40 °C; $\overline{p}_c = \frac{1}{2} \cdot \Xi_\theta \cdot \overline{p}_c(\text{sphere})$ Ξ_θ (EE) = 1.55; Ξ_θ(square toroid) = 1.63; Ξ_θ(round toroid) = 1.47; Ξ_θ(ETD) = 1.8

Appendix 2: Innovatia Fe-Pwd Cores

Core Type	V, cm^3	A, mm^2	l, mm	A_w, mm^2	$N\bar{i}$, A @ k_{sat}			$\hat{B}_{\sim}$, mT; $\overline{P}_{xfr}$, k_{sat} = 0.6, 26		L$_0$, nH	γ_{opt}	$\overline{p}_c$, mW/cm^3 Δ40 °C, $p_w = p_c$
					0.5	0.6	0.7	100 kHz	250 kHz			
T20-26	0.026	2. 3	11.5	3.94	46	35	27	63; 1.00	34; 1.35	18.5	0.224	1446
T26-26	0.133	9.0	14.7	5.60	59	45	35	43; 3.5	23; 4.7	57	0.252	829
T37-26	0.147	6.4	23.1	21.3	92	71	54	48; 4.3	26; 5.9	28.5	0.253	801
T37-52	0.147	6.4	23.1	21.3	105	88	66	58; 6.5	32; 9.0	26	0.270	801
T44-26	0.266	9.9	26.8	26.6	107	82	63	42; 6.8	23; 9.4	37	0.228	652
T50-26	0.358	11.2	31.9	46.6	127	98	75	41; 9.0	23; 12.6	33	0.237	589
T50B-26	0.471	14.8	31.9	46.6	127	98	75	39; 11.3	21; 15.2	43.5	0.225	535
T50D-26	0.711	22.3	31.9	46.6	127	98	75	35; 15.3	19; 21	72	0.185	463
T68-26	0.759	17.9	42.3	69.4	168	130	99	36; 16.7	19; 22	43.5	0.190	453
T80-26	1.19	23.1	51.4	125	205	157	121	28; 20	15; 27	46	0.150	386
T106-26	4.28	65.9	64.9	165	258	199	153	26; 68	14; 92	93	0.115	244
T130-26	5.78	69.8	82.8	308	330	254	195	26; 92	14; 124	81	0.147	219
T131-26	6.84	88.5	77.2	209	307	237	181	24; 101	13; 136	116	0.128	206
T150-26	8.31	88.7	93.8	363	373	287	220	24; 122	13; 166	96	0.128	191
T157-26	10.7	106	101	456	402	309	237	23; 151	13; 213	100	0.133	174
T184-26	21.0	188	112	456	446	343	263	20; 257	11; 354	169	0.108	135
T201-26	33.2	281	118	456	470	362	277	18; 366	9.5; 483	242	0.097	113
T250-26	57.4	384	150	794	597	460	353	16; 563	9.0; 791	242	0.092	91
T300D-26	67.0	338	198	1886	788	607	465	18; 739	9.5; 975	160	0.105	86
E49-26	0.288	10.1	28.6	17.23	114	88	67	40; 7.1	22; 9.7	38	0.202	547
E100-26	2.05	40.3	50.8	57.03 EE2425 PB100E	202	156	119	28; 35	15; 47	92	0.132	274
E137-26	6.72	90.7	74.0	83.86	295	227	174	23; 95	12; 124	134	0.115	178
E162-26	13.6	161	84.1	123.5	335	258	198	19; 158	10; 208	210	0.093	137
E187-26	23.3	248	95.3	143.4	379	292	224	16; 229	9.0; 321	297	0.077	112
E220-26	47.7	283.6	132	283.6	525	404	310	15; 439	8.0; 585	286	0.078	85
E305A-26	139	597	185	597	736	567	435	12.5; 1065	6.6; 1405	382	0.072	55
E450-26	280	1270 no bobbin	229	1270 no bobbin	911	702	538	11.5; 1973	6.2; 2660	550	0.060	41

Total power dissipation of core + winding is split equally between core and winding and half assigned to core as $\overline{p}_c$.

$\overline{p}_c = \frac{1}{2} \cdot \Xi_\theta \cdot \overline{p}_c(\text{sphere})$ Ξ_θ (EE) = 1.55 ; Ξ_θ(square toroid) = 1.63 ; Ξ_θ(round toroid) = 1.47 ; Ξ_θ(ETD) = 1.8

$\hat{B}_{\sim}$ based on given $\overline{p}_c$ $\Delta B = 2 \cdot \hat{B}_{\sim}$ $\gamma_{opt} = \dfrac{\hat{B}_{\sim} \cdot A}{\mathcal{L} \cdot N\bar{i}}$, f_s = 100 kHz, k_{sat} = 0.6, L = k_{sat}· L$_0$, L$_0$ = L (0 A)

$$\overline{P}_{xfr} = (V_p \cdot (D \cdot I_p)) = V_p \cdot \bar{i}_p = [\overline{H} \cdot \Delta B] \cdot V \cdot f_s = \Delta\phi \cdot N\bar{i} \cdot f_s$$

Micrometals Inc. 26 and 52 material μ_r = 75
Fe-pwd 26, 1 cm^3, 100 kHz ⇒ power-loss density = p = 16 W/cm^3 ; Fe-pwd 52, 1 cm^3, 100 kHz ⇒ p = 25 W/cm^3

Appendix 3: Innovatia FeSiAl, NiFe, NiFeMo List

Core Type	V, cm^3	A, mm^2	l, mm	A_w, mm^2	$N\bar{i}$, A @ k_{sat}			$\hat{B}_\sim$, mT			L_0, nH	μ_r	$\overline{p}_c$, mW /cm^3	γ_{opt}
					0.5	0.6	0.7	100 kHz	200 kHz	300 kHz				
FeSiAl (Kool-µ)														
0077050A7	0.356	11.4	31.2	38.3	117	92	69.6	90	54	40	56	125	659	0.199
0077120A7	0.789	19.2	41.1	71.3	203	164	124	78	47	34	72	90	489	0.127
0077206A7	1.15	22.6	50.9	114	190	150	114	73	44	33	68	125	441	0.162
0077310A7	1.88	33.1	56.7	141	212	167	126	65	39	28	90	125	350	0.143
0077930A7	4.15	65.4	63.5	156	313	253	192	55	34	25	157	90	249	0.093
0077254A7	10.5	107.2	98.4	427	368	290	219	49	30	22	168	125	193	0.110
0077259A7	10.5	107.2	98.4	427	626	498	376	49	30	22	101	75	193	0.106
K2510-E090	1.87	38.5	48.5	77.75	239	193	147	70	42	31	100	90	394	0.140
K4022-E090	23.3	23.7	98.4	278	485	392	297	31	18	14	281	90	78	0.065
NiFeMo (MPP)														
C055175A2	0.0302	2.85	10.6	11.7	17.7	15.2	10.1	120	80	58	99	300	1526	0.126
C055266A2	0.1254	9.20	13.6	3.84	5.96	4.60	3.79	81	50	40	466	550	802	0.172
C055286A2	0.206	9.45	21.8	14.3	9.53	7.37	6.06	72	54	46	290	550	712	0.169
C0550504 (gray)	0.356	11.4	31.2	38.4	104	112	89	43	65	105	56	125	660	0.151
C055045A2	0.356	11.4	31.2	38.4	52.1	44.6	29.8	90	55	39	134	300	660	0.086
C055046A2	0.356	11.4	31.2	38.4	13.6	10.6	8.67	73	50	35	255	550	660	0.155
C055116A2	0.789	19.2	41.1	71.3	18	13.9	11.4	65	43	31	317	550	489	0.172
C055202A2	1.15	22.6	50.9	114.4	22.2	17.2	14.2	61	40	30	320	550	441	0.123
C055306A2	1.88	33.1	56.7	141	24.8	19.2	15.8	53	36	25	396	550	351	0.123
C055928A2	4.15	65.4	63.5	156	205	187	142	60	35	24	201	160	249	0.049
C055925A2	4.15	65.4	63.5	156	106	90.8	60.6	60	35	24	377	300	249	0.054
C055926A2	4.15	65.4	63.5	156	27.8	21.5	17.7	46	31	22	740	550	249	0.096
C055543A2	5.48	67.2	81.5	293	136	117	77.8	59	34	23	305	300	241	0.053
C055544A2	5.48	67.2	81.5	293	35.6	27.6	22.7	45	30	22	559	550	241	0.109
C055320A2	6.09	67.8	89.8	363	39.2	30.4	25	45	30	22	515	550	237	0.108
C055250A2	10.55	107.2	98.4	413	43	33.3	27.4	41	25	20	740	550	192	0.094
C055433A2	21.37	199	107.4	427	179	154	103	49	28	19	674	300	136	0.045
NiFe (Hi-Flux)														
C058928	4.15	65.4	63.5	156	253	202	152	45	70, 50 kHz		201	160	249	0.107

Total power dissipation of core + winding is split equally between core and winding and half assigned to core as $\overline{p}_c$, Δ40 °C; $\overline{p}_c = \frac{1}{2} \cdot \Xi_\theta \cdot \overline{p}_c(\text{sphere})$ Ξ_θ(EE) = 1.55; Ξ_θ(square toroid) = 1.63; Ξ_θ(round toroid) = 1.47; Ξ_θ(ETD) = 1.8

$\hat{B}_\sim$ based on given $\overline{p}_c$ $\Delta B = 2 \cdot \hat{B}_\sim$ $\gamma_{opt} = \dfrac{\hat{B}_\sim \cdot A}{\mathcal{L} \cdot N\bar{i}}$; k_{sat} = 0.6 ; f_s = 200 kHz, FeSiAl; 300 kHz, NiFeMo, NiFe

$\mathcal{L} = k_{sat} \cdot \mathcal{L}_0$, $\mathcal{L}_0 = \mathcal{L}$(0 A) $\overline{P}_{xfr} = (V_p \cdot (D \cdot I_p)) = V_p \cdot \bar{i}_p = [\overline{H} \cdot \Delta B] \cdot V \cdot f_s = \Delta\phi \cdot N\bar{i} \cdot f_s$, 26 and 52 material μ_r = 75

Supplier: Magnetics Inc.
Toroids except for Kxxxx

Appendix 4: Innovatia Wire Table. Conditions: heavy (double) insulation, r_c is 20 AWG/dec ≈ 6 AWG/oct, Ac is 10 AWG/dec ≈ 3 AWG/oct and f_δ at 80°C.

Gage, AWG	r_c, mm	r_{cw}, mm	A_c, mm^2	A_{cwp}, mm^2	k_p	I_{max}, A	$f_{\delta Cu}$, kHz	$f_{\delta Al}$, kHz
0	4.126	4.251	53.482	71.552	0.747	240.67	0.317	0.519
1	3.676	3.794	42.449	56.987	0.745	191.019	0.400	0.655
2	3.275	3.023	33.692	45.395	0.742	151.612	0.505	0.826
3	2.918	2.986	26.741	36.169	0.739	120.335	0.636	1.041
4	2.599	2.698	21.224	28.824	0.736	95.510	0.802	1.312
5	2.316	2.409	16.846	22.976	0.733	75.806	1.012	1.656
6	2.063	2.151	13.371	18.318	0.730	60.167	1.276	2.086
7	1.838	1.921	10.612	14.608	0.726	47.755	1.608	2.630
8	1.637	1.716	8.423	11.653	0.723	37.903	2.028	3.318
9	1.459	1.533	6.685	9.298	0.719	30.084	2.559	4.185
10	1.300	1.369	5.306	7.421	0.715	23.877	3.226	5.277
11	1.158	1.223	4.211	5.925	0.711	18.952	4.071	6.658
12	1.032	1.093	3.343	4.732	0.706	15.042	5.132	8.394
13	0.919	0.977	2.653	3.780	0.702	11.939	6.453	10.554
14	0.819	0.874	2.106	3.021	0.697	9.476	8.153	13.335
15	0.729	0.781	1.671	2.415	0.692	7.521	10.278	16.810
16	0.650	0.698	1.327	1.931	0.687	5.969	12.985	21.239
17	0.579	0.625	1.053	1.545	0.681	4.738	16.340	26.725
18	0.516	0.559	0.836	1.237	0.670	3.760	20.608	29.668
19	0.459	0.500	0.663	0.990	0.671	2.985	25.980	42.494
20	0.409	0.448	0.526	0.793	0.664	2.369	32.613	53.342
21	0.365	0.401	0.418	0.636	0.657	1.880	41.225	67.428
22	0.325	0.359	0.332	0.510	0.651	1.492	52.103	85.220
23	0.289	0.321	0.263	0.409	0.644	1.184	65.586	107.27
24	0.258	0.288	0.288	0.328	0.637	0.940	82.432	134.83
25	0.230	0.258	0.166	0.264	0.629	0.746	103.92	169.98
26	0.205	0.231	0.132	0.212	0.622	0.592	132.40	216.55
27	0.182	0.207	0.104	0.170	0.614	0.470	164.90	269.71
28	0.162	0.186	0.083	0.137	0.605	0.373	211.03	345.16
29	0.145	0.167	0.066	0.110	0.597	0.296	260.53	426.12
30	0.129	0.150	0.052	0.089	0.588	0.235	334.94	547.83
31	0.115	0.134	0.041	0.072	0.579	0.187	423.08	691.99
32	0.102	0.121	0.033	0.058	0.570	0.148	519.25	849.29
33	0.091	0.108	0.026	0.047	0.561	0.118	666.94	1091
34	0.081	0.097	0.021	0.038	0.551	0.093	844.10	1381
35	0.072	0.088	0.016	0.030	0.541	0.074	1072	1753
36	0.064	0.079	0.013	0.025	0.531	0.059	1148	2157
37	0.057	0.071	0.010	0.020	0.521	0.047	1663	2720
38	0.051	0.064	0.00823	0.016	0.511	0.037	2077	3397
39	0.046	0.057	0.00653	0.013	0.500	0.029	2668	4364
40	0.041	0.052	0.00518	0.011	0.489	0.023	3376	5523
41	0.036	0.047	0.00411	0.0086	0.479	0.019	4168	6818
42	0.032	0.042	0.00326	0.0070	0.467	0.015	5276	8629
	0.892		2.5	3-wire cable		11.25	6.79	
	1.128		4.0			18.0	4.24	
12.7 mm × 76.3 μm (0.5”, 3 mil) Cu foil			0.968			4.36	928	1518

$I(AWG) = 4.5\ \text{A/mm}^2 \cdot A_c(AWG)$ $A_{cw}(AWG) = \pi \cdot r_{cw}^2$ $k_p = k_{pf} \cdot k_{pw}$, k_{pf} = fill factor, k_{pw} = wire porosity = A_c/A_{cw}

$$k_{pf} = \frac{7}{8} \cdot \frac{\pi}{2 \cdot \sqrt{3}} \approx \frac{1}{1.260} \quad A_{cwp}(AWG) = \frac{A_{cw}(AWG)}{k_{pf}} = \frac{A_c}{k_p} \quad A_c(AWG) = (53.48\ \text{mm}^2) \cdot 10^{\frac{-AWG}{9.97}}$$