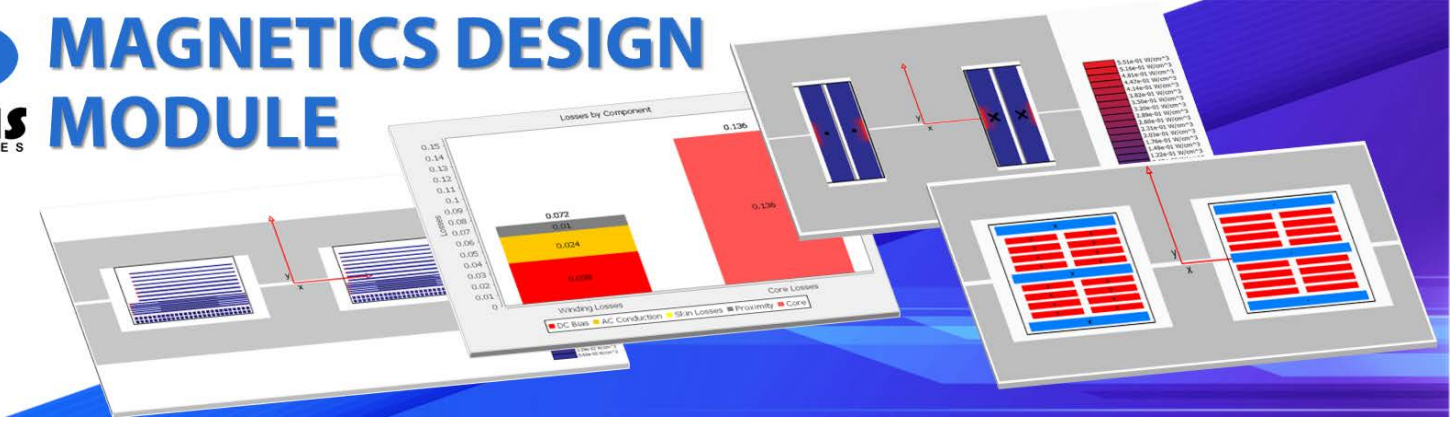
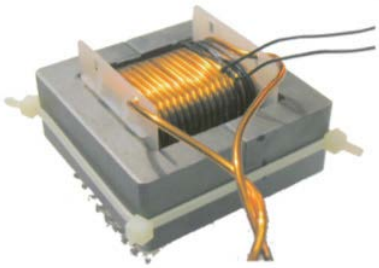
MAGNETICS DESIGN MODULE



SIMPLIS MAGNETICS DESIGN MODULE (MDM) – Simulation vs Measurement Results

A number of inductors and transformers were constructed for the purpose of confirming the accuracy of the simulation results obtained using SIMPLIS MDM. A non-exhaustive list of measurements is given in this document. Measurements were completed at different times using varying measurement setups. In some cases, both losses and temperatures were measured, in some only losses. Where possible, core and winding losses were measured separately. Photographs of the measured devices are provided where available.

E-Core Inductor, Nominal *L* = 190.75 µH

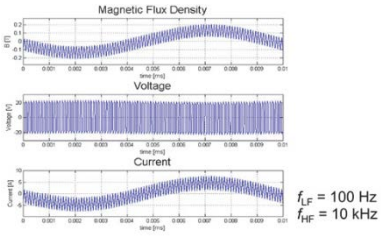


Core Material	EPCOS N27 Ferrite
Core	E55/28/21
Air gap type	Center leg only
Air gap size	1 mm
Turns	18
Wire type	Round Copper
Wire diameter	1.7 mm

Measurements with symmetrical triangular flux waveforms, zero DC bias

***ΔB* (T)**	***f* (kHz)**	**MDM Calculated Losses (W)**	**Measured Losses (W)**	**Relative Error (%)**
0.25	5	0.63	0.61	3.28
0.5	5	2.96	2.70	9.63
0.1	10	0.19	0.20	-3.06
0.2	10	0.89	0.88	1.14
0.2	10	2.10	2.01	4.48

Measurements with low frequency (LF) sinusoidal flux (100 Hz) with superimposed high frequency (HF) triangular switching ripple (100 kHz)



LF *ΔB* (T)	**HF *ΔB* (T)**	**Calc. Losses (W)**	**Measured Losses (W)**	**Relative Error (%)**
0.25	0.15	0.79	0.76	3.95
0.5	0.3	3.35	3.60	-6.94

Thermal Measurements of E-Core Inductors

Inductors A, B, C

Core Material	EPCOS N87 Ferrite
Air gap type	Center leg only
Wire type	Round Copper

Inductor A

Nominal L	85.66 µH
Core	E25/13/7
Air gap size	1.05 mm
Turns	27
Wire diameter	0.8 mm

Inductor B

Nominal L	88.77 µH
Core	E32/16/9
Air gap size	0.55 mm
Turns	18
Wire diameter	0.8 mm

Inductor C

Nominal L	526.94 µH
Core	E20/10/6
Air gap size	1 mm
Turns	80
Wire diameter	0.45 mm

Measurements with symmetrical triangular flux waveforms, zero DC bias

Unless noted otherwise, losses presented in this document were measured using a Yokogawa WT3000 Precision Power Analyzer. The thermal measurements in this section are of surface temperatures and were made with a FLIR ThermaCAM infrared camera. The inductors were cooled by natural convection (no forced cooling system of any kind) at room temperature.

Inductor A

	Operating Point	
	ΔB = 0.3 T, f = 10 kHz	**ΔB = 0.3 T, f = 20 kHz**
MDM Calculated Losses (W)	0.47	0.73
Calculated Core Temperature (°C)	36	41
Calculated Winding Temperature (°C)	44	53
Measured Losses (W)	0.50	0.74
Measured Core Temperature (°C)	40	43
Measured Winding Temperature (°C)	49	58
Relative Error – Losses (%)	-6.00	-1.35
Relative Error – Core Temp. (%)	-10.00	-4.65
Relative Error – Winding Temp. (%)	-10.20	-8.62

Inductor B

	Operating Point	
	ΔB = 0.3 T, f = 10 kHz	**ΔB = 0.3 T, f = 20 kHz**
MDM Calculated Losses (W)	0.45	0.65
Calculated Core Temperature (°C)	33	37
Calculated Winding Temperature (°C)	38	41
Measured Losses (W)	0.45	0.60
Measured Core Temperature (°C)	35	37
Measured Winding Temperature (°C)	43	45
Relative Error – Losses (%)	0.00	8.33
Relative Error – Core Temp. (%)	-5.71	0.00
Relative Error – Winding Temp. (%)	-11.63	-8.89

Inductor C

	Operating Point	
	***ΔB* = 0.3 T, *f* = 20 kHz**	***ΔB* = 0.4 T, *f* = 50 kHz**
MDM Calculated Losses (W)	0.40	1.66
Calculated Core Temperature (°C)	38	64
Calculated Winding Temperature (°C)	46	97
Measured Losses (W)	0.38	1.60
Measured Core Temperature (°C)	39	60
Measured Winding Temperature (°C)	46	91
Relative Error – Losses (%)	5.26	3.75
Relative Error – Core Temp. (%)	-2.56	6.67
Relative Error – Winding Temp. (%)	0.00	6.59

P-Core Inductor, Nominal *L* = 48 µH

Core Material	EPCOS N87 Ferrite
Core	P30x19
Air gap type	All three legs
Air gap size	0.24 mm
Turns	10
Wire type	Round Copper
Wire diameter	1.0 mm

Measurements with symmetrical triangular flux, zero DC bias

***ΔB* (T)**	***f* (kHz)**	**MDM Calculated Losses (W)**	**Measured Losses (W)**	**Relative Error (%)**
0.2	20	0.29	0.29	0.00
0.1	50	0.17	0.18	-5.56
0.2	50	0.62	0.77	-19.48

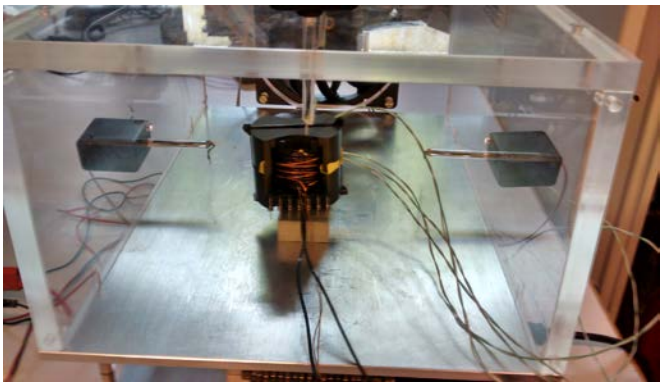
PM-Core Inductor, Nominal *L* = 981.53 µH

Core Material	EPCOS N87 Ferrite
Core	PM50/39
Air gap type	All three legs
Air gap size	0.37 mm
Turns	38
Wire type	Round Copper
Wire diameter	1.0 mm

Measurements with symmetrical triangular flux, zero DC bias

***ΔB* (T)**	***f* (kHz)**	**MDM Calculated Losses (W)**	**Measured Losses (W)**	**Relative Error (%)**
0.2	10	0.40	0.34	17.65
0.1	20	0.18	0.18	0.00
0.2	20	0.87	0.76	14.47

Thermal Measurements of PM-Core Inductor, Nominal *L* = 1.036 mH



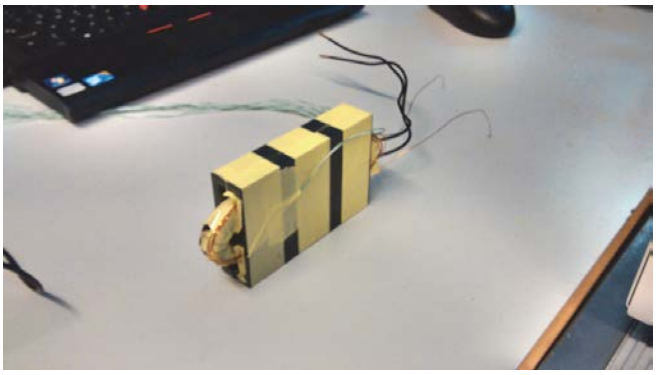
Core Material	EPCOS N87 Ferrite
Core	PM50/39
Air gap type	All three legs
Air gap size	0.6 mm
Turns	48
Wire type	Round Copper
Wire diameter	1.5 mm

Thermal measurements in this and the following section were made using thermocouple sensors inserted into the windings and placed on the core surface, and in a chamber allowing for measurement of forced air flow from the cooling fan.

Measurements with symmetrical triangular flux waveforms, zero DC bias

	Operating Point	
	***ΔB* = 0.2 T, *f* = 10 kHz**	***ΔB* = 0.3 T, *f* = 10 kHz**
Cooling Type	Natural convection	Forced convec., 3.5 m/s
MDM Calculated Losses (W)	0.96	2.17
Calculated Core Temperature (°C)	29	29
Calculated Winding Temperature (°C)	38	45
Measured Losses (W)	1.01	2.38
Measured Core Temperature (°C)	35	31
Measured Winding Temperature (°C)	39	41
Relative Error – Losses (%)	-4.95	-8.82
Relative Error – Core Temp. (%)	-17.14	-6.45
Relative Error – Winding Temp. (%)	-2.56	9.76

Thermal Measurements of ELP-Core Inductor, Nominal *L* = 421.6 µH



Core Material	EPCOS N87 Ferrite
Core	2xELP64
Air gap type	All three legs
Air gap size	0.9 mm
Turns	21
Wire type	Round Copper
Wire diameter	2 mm

Measurements with symmetrical triangular flux waveforms, zero DC bias

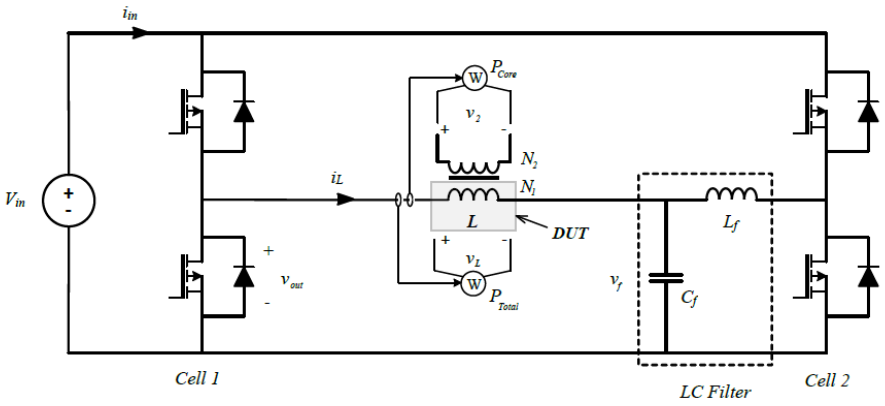
	Operating Point	
	***ΔB* = 0.1 T, *f* = 10 kHz**	***ΔB* = 0.3 T, *f* = 10 kHz**
Cooling Type	Natural convection	Forced convec., 2.5 m/s
MDM Calculated Losses (W)	1.23	11.1
Calculated Core Temperature (°C)	31	43
Calculated Winding Temperature (°C)	33	59
Measured Losses (W)	1.01	8.8
Measured Core Temperature (°C)	28	38
Measured Winding Temperature (°C)	32	63
Relative Error – Losses (%)	21.78	26.13
Relative Error – Core Temp. (%)	10.71	13.16
Relative Error – Winding Temp. (%)	3.13	6.35

The error above 20% in the above measurements is due to relatively large proximity loss. Proximity losses are highly sensitive to the position of the windings relative to each other, the core, and especially the air gap. The experimental inductor with the ELP64 cores was built without a bobbin. Therefore, it was not possible to exactly match the winding position in the simulation and the measurement. To confirm this was the source of the error, losses were also measured at a much lower frequency where proximity losses were very low:

***ΔB* (T)**	***f* (kHz)**	**MDM Calculated Losses (W)**	**Measured Losses (W)**	**Relative Error (%)**
0.1	2	1.69	1.69	0.00
0.3	2	0.19	0.18	5.56

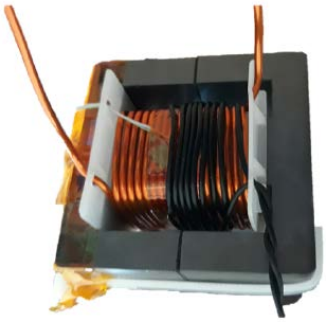
Core and Winding Loss Measurements of E-Core Inductors

A small secondary winding was used to measure core losses separately for two inductors. This measurement was subtracted from the total loss measurement to get winding losses.



Measurements with symmetrical triangular flux waveforms, zero DC bias

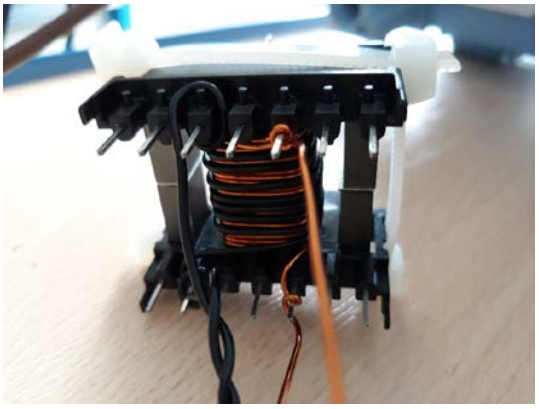
Inductor 1



Nominal L	344.62 µH
Core Material	EPCOS N27 Ferrite
Core	E55/28/21
Air gap type	All three legs
Air gap size	0.5 mm
Turns	18
Wire type	Round Copper
Wire diameter	1.7 mm

ΔB **(T)**	***f*** **(kHz)**	**MDM Calculated Losses (W)**			**Measured Losses (W)**			**Relative Error**
		Core	**Winding**	**Total**	**Core**	**Winding**	**Total**	**Total (%)**
0.2	10	0.483	0.336	0.818	0.45	0.28	0.73	12.05
0.3	10	1.071	0.751	1.822	1.14	0.65	1.79	1.79
0.5	5	1.271	0.961	2.232	1.56	1.11	2.67	-16.4

Inductor 2

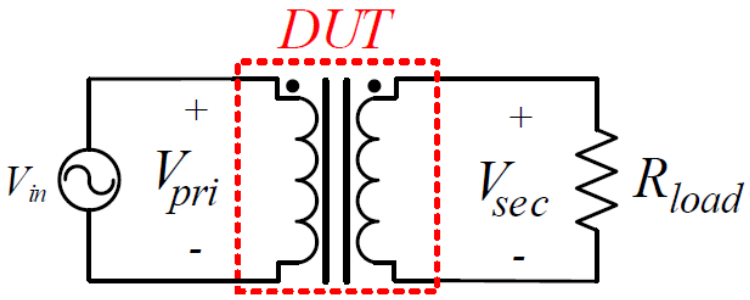


Nominal L	144.33 µH
Core Material	EPCOS N87 Ferrite
Core	E32/16/9
Air gap type	All three legs
Air gap size	0.3 mm
Turns	18
Wire type	Round Copper
Wire diameter	1.7 mm

ΔB **(T)**	***f*** **(kHz)**	**MDM Calculated Losses (W)**			**Measured Losses (W)**			**Relative Error**
		Core	**Winding**	**Total**	**Core**	**Winding**	**Total**	**Total (%)**
0.3	10	0.163	0.140	0.303	0.17	0.14	0.35	-13.43
0.3	20	0.358	0.197	0.555	0.36	0.24	0.60	-7.5
0.35	20	0.489	0.269	0.758	0.53	0.32	0.85	-10.8

Two-Winding E-Core Transformers

The primary side of each transformer was excited with a sinusoidal voltage waveform, while the secondary side was loaded with a resistance selected to produce a desired output current.



Transformer 1

Nominal L_{mag}	12.12 mH
Core Material	EPCOS N87 Ferrite
Core	E55/28/21
Air gap type	All three legs
Air gap size	0 mm
Turns Ratio	22:11
Wire type	Round Copper
Wire diameters	1 mm, 1.2 mm

Transformer 2

Nominal L_{mag}	6.41 mH
Core Material	EPCOS N87 Ferrite
Core	E55/28/21
Air gap type	All three legs
Air gap size	0 mm
Turns Ratio	16:2
Wire type	Round Copper
Wire diameters	1 mm, 1.4 mm

Transformer 3

Nominal L_{mag}	57.68 mH
Core Material	EPCOS N87 Ferrite
Core	E55/28/21
Air gap type	All three legs
Air gap size	0 mm
Turns Ratio	48:10
Wire type	Round Copper
Wire diameters	0.5 mm, 0.85 mm

Measurements with sinusoidal voltage excitation on the primary side, zero DC bias

	Transformer 1	***Transformer 2***	***Transformer 3***
***V_{in}* (V)**	10	48	24
***I_{out}* (A)**	5	6	1
***f* (kHz)**	1	25	50
Calculated Loss (W)	0.585	0.446	0.049
Measured Loss (W)	0.677	0.515	0.0435
Relative Error (%)	-13.59	-13.40	12.64