Inductor design example

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Introduction

SmartNetics is a software for the design and analysis of magnetic devices: inductors and transformers. Although these devices can be designed to comply with any specification, SmartNetics is specially suited for magnetics to be used in medium power (15 kW - 100 kW), high frequency (15 kHz - 100 kHz) power converters.

Our approach is not to offer a single one-fits-all solution but to provide every possible design to have all the available information and, at the same time, an intuitive graphical interface that allows the user to easily assess the impact of every value.

In every part of the software, the user can select whether to input only the minimum amount of data and use the predefined configuration, or to manually adjust every little design parameter. With this approach, whether it is your first time designing a magnetic device or you are a seasoned expert, you can design the device that best suits your needs.

This tutorial aims to illustrate the complete design procedure for a magnetic device, in this particular case an inductor for a 3-phase 50 Hz, 50 kW inverter with a switching frequency of 30 kHz and refrigerated by natural convection.

Total power	Phases	Inductance	Main frequency	Switching frequency
50 kW	3	300 μH	50 Hz	30 kHz

Table 1: Main design parameters

Design

In SmartNetics, the design procedure is divided in 5 steps:

1. **Input data:** enter the minimum required data for the design (inductance and current for inductors; turns ratio, primary voltage and current for transformers).
2. **Configuration:** use the default configuration or modify any little aspect of the design procedure.
3. **Design:** find every possible combination of parameters that, complying with the restrictions, provide a suitable device. From those devices, select any number that are potential candidates.
4. **Selection:** analyze in detail the selected subset and select the best device.
5. **Device:** graphically access every property of the selected device, generate a report or export it to third-party software.

The aim of this tutorial is to guide the user in the 5 steps, from the definition of input signals to the simulation and validation of the desired device in third-party software. By default, SmartNetics opens with the first step active. The user can navigate through steps using the 5 buttons at the left side, as shown in Figure 1. Notice how some steps are not available until some previous requirement is met, for example, the user can not select a design until they have generated some.

Figure 1: Lateral menus

1 Input data

The first step is to define the target magnetic device, there are two options:

- Inductor: Defined by its inductance and current.
- Transformer: Defined by its turns ratio (n=N1/N2), current and voltage (both referred to primary side).

The device to design can be selected with the top switch. For this example, we are going to design an inductor; once it is selected, only the inductance and current waveform are needed and their default values are displayed, as shown in Figure 2.

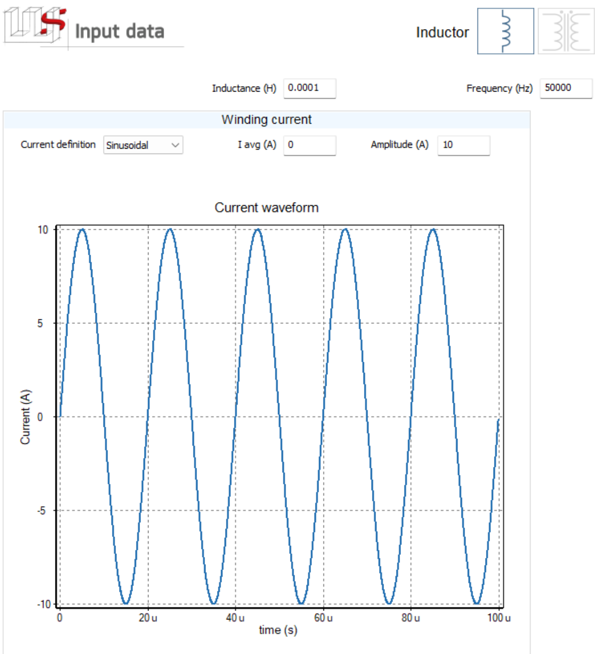


Figure 2: Default inductor

Inductance is defined in its own field. In this case, since we are going to design a 300 µH inductor, we can input 0.0003 (or 300e-6) in the dialog box, as shown in Figure 3:

Figure 3: Inductance value definition

The user can define the current waveform using one of the predefined shapes: sinusoidal, triangle, or rectangular; or use a generic waveform, that can be taken from a previous measurement or simulation loading a .csv file. In this case, we are going to design one of the inductors of a three-phase inverter, which handles a main 50 Hz sinusoidal current with an RMS value of 72.5 A, to which a high frequency ripple (from the 30 kHz inverter) is superimposed.

Since the high frequency ripple varies along the sinusoidal period, the easiest way to reproduce it is to get the waveform from a simulation. That is done by selecting "File" in the "Current definition" drop-down and clicking on "Load file" to select a previously saved signal (as .csv). Once loaded, the values are displayed and the main frequency is automatically extracted, as shown in Figure 4.

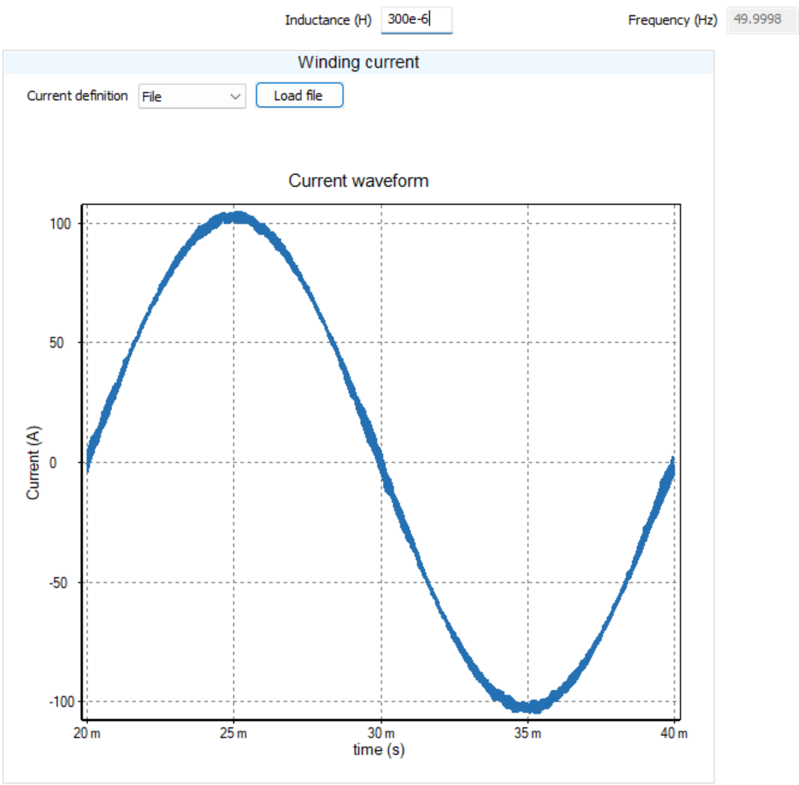


Figure 4: Loaded current waveform

Notice how, for a waveform defined in a file, the frequency field can not be modified (edit box turns gray), since it is extracted from the values of said file.

Once the desired inductance and current have been defined, the user can configure the design procedure in the next step, "Configuration".

2 Configuration

This step is accessible by the second button of the lateral menus ("Configuration") and is divided in 4 parts:

- Databases
- Device parts
- Models
- General

By default, "Databases" is selected, but the user can navigate them using the tabs on top, as shown in the next figure:

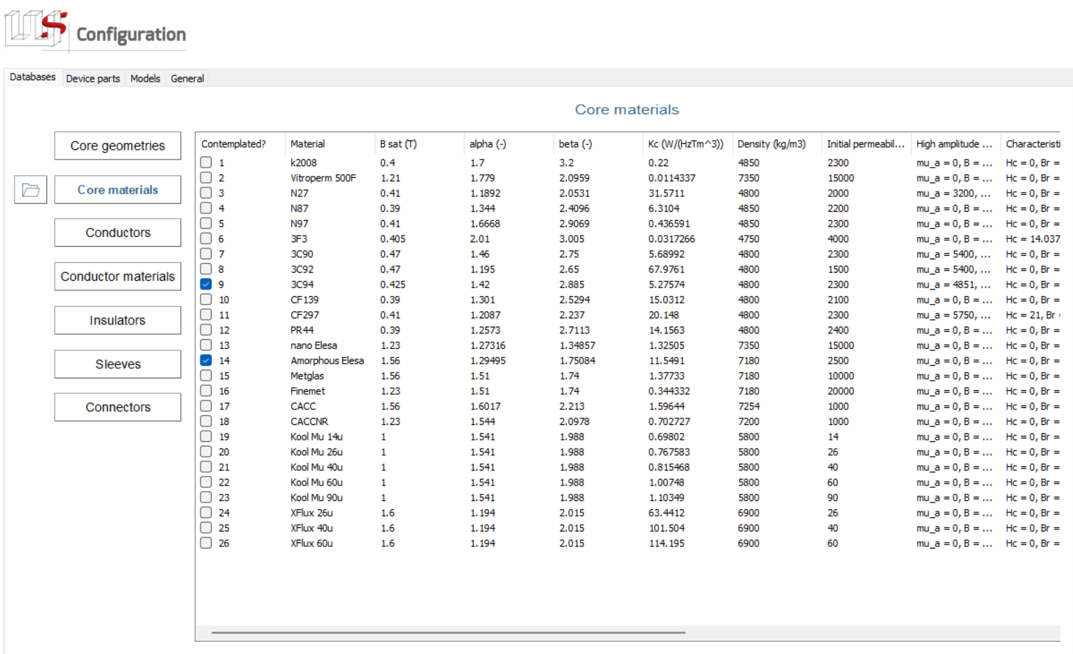
Figure 5: Configuration tabs

In general, the default configuration can produce good results for many applications, but the user is free to use any prior knowledge to achieve an even better result. In this particular case we are going to modify a few aspects as part of the example.

2.1 Databases

We are designing an inductor where, although there is a high frequency ripple, the low frequency (50 Hz) component dominates. Since the peak value of the current used in this design is 102.5 A, saturation may become a big problem, even bigger than losses. To cover every possible scenario, instead of only using ferrite (with a saturation around 0.4 T), we are also going to consider an amorphous material (with a saturation around 1.5 T).

In this design, on top of the ferrite 3C94 by Ferroxcube, we are considering an amorphous material manufactured by ELESA; both materials are selected by activating their "Contemplated?" fields in the database, as shown in Figure 6.



Contemplated?	Material	B sat (T)	alpha (-)	beta (-)	Kc (W/(HzTm^3))	Density (kg/m3)	Initial permeabil...	High amplitude ...	Characteristi
1	k2008	0.4	1.7	3.2	0.22	4850	2300	mu_a = 0, B = ...	Hc = 0, Br =
2	Vitroperm 500F	1.21	1.779	2.0959	0.0114337	7350	15000	mu_a = 0, B = ...	Hc = 0, Br =
3	N27	0.41	1.1892	2.0531	31.5711	4800	2000	mu_a = 3200, ...	Hc = 0, Br =
4	N87	0.39	1.344	2.4096	6.3104	4850	2200	mu_a = 0, B = ...	Hc = 0, Br =
5	N97	0.41	1.6668	2.9069	0.436591	4850	2300	mu_a = 0, B = ...	Hc = 0, Br =
6	3F3	0.405	2.01	3.005	0.0317266	4750	4000	mu_a = 0, B = ...	Hc = 14.037
7	3C90	0.47	1.46	2.75	5.68992	4800	2300	mu_a = 5400, ...	Hc = 0, Br =
8	3C92	0.47	1.195	2.65	67.9761	4800	1500	mu_a = 5400, ...	Hc = 0, Br =
✓ 9	3C94	0.425	1.42	2.885	5.27574	4800	2300	mu_a = 4851, ...	Hc = 0, Br =
10	CF139	0.39	1.301	2.5294	15.0312	4800	2100	mu_a = 0, B = ...	Hc = 0, Br =
11	CF297	0.41	1.2087	2.237	20.148	4800	2300	mu_a = 5750, ...	Hc = 21, Br
12	PR44	0.39	1.2573	2.7113	14.1563	4800	2400	mu_a = 0, B = ...	Hc = 0, Br =
13	nano Elesa	1.23	1.27316	1.34857	1.32505	7350	15000	mu_a = 0, B = ...	Hc = 0, Br =
✓ 14	Amorphous Elesa	1.56	1.29495	1.75084	11.5491	7180	2500	mu_a = 0, B = ...	Hc = 0, Br =
15	Metglas	1.56	1.51	1.74	1.37733	7180	10000	mu_a = 0, B = ...	Hc = 0, Br =
16	Finemet	1.23	1.51	1.74	0.344332	7180	20000	mu_a = 0, B = ...	Hc = 0, Br =
17	CACC	1.56	1.6017	2.213	1.59644	7254	1000	mu_a = 0, B = ...	Hc = 0, Br =
18	CACCNR	1.23	1.544	2.0978	0.702727	7200	1000	mu_a = 0, B = ...	Hc = 0, Br =
19	Kool Mu 14u	1	1.541	1.988	0.69802	5800	14	mu_a = 0, B = ...	Hc = 0, Br =
20	Kool Mu 26u	1	1.541	1.988	0.767583	5800	26	mu_a = 0, B = ...	Hc = 0, Br =
21	Kool Mu 40u	1	1.541	1.988	0.815468	5800	40	mu_a = 0, B = ...	Hc = 0, Br =
22	Kool Mu 60u	1	1.541	1.988	1.00748	5800	60	mu_a = 0, B = ...	Hc = 0, Br =
23	Kool Mu 90u	1	1.541	1.988	1.10349	5800	90	mu_a = 0, B = ...	Hc = 0, Br =
24	XFlux 26u	1.6	1.194	2.015	63.4412	6900	26	mu_a = 0, B = ...	Hc = 0, Br =
25	XFlux 40u	1.6	1.194	2.015	101.504	6900	40	mu_a = 0, B = ...	Hc = 0, Br =
26	XFlux 60u	1.6	1.194	2.015	114.195	6900	60	mu_a = 0, B = ...	Hc = 0, Br =

Figure 6: Core materials selected for the design

In a 50 kW three-phase converter, every inductor handles one third of that power, around 16.7 kW. For such a high power, we are only going to select the biggest E geometry available in the database: E/100/60/28. Many ferrites area available in that geometry but, since we are also considering an amorphous material for the design, which is only available in C/U shapes, we are going to also add them for this design.

In the current version, only EE shapes are considered for the design, but two U/C cores can be used side-to-side to generate an E shape, as shown in Figure 7. That is done by checking the “Generate E cores from Us”.

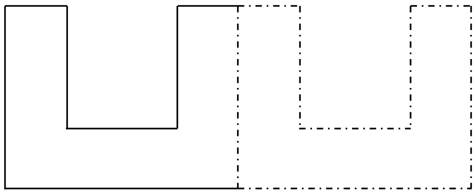
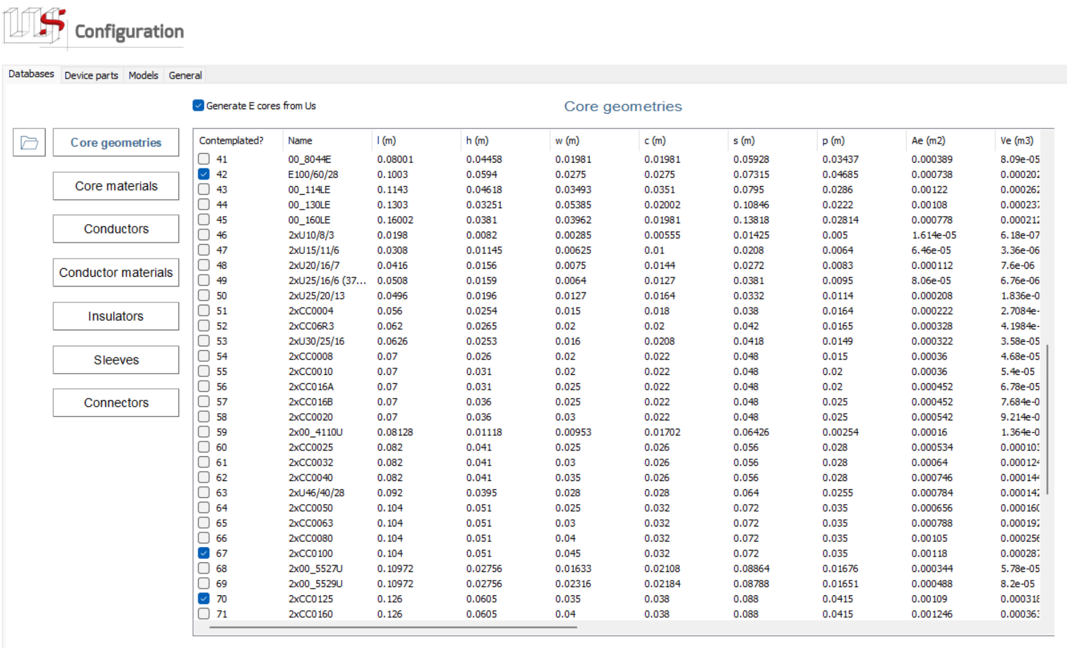


Figure 7: E cores generated from U/C shapes

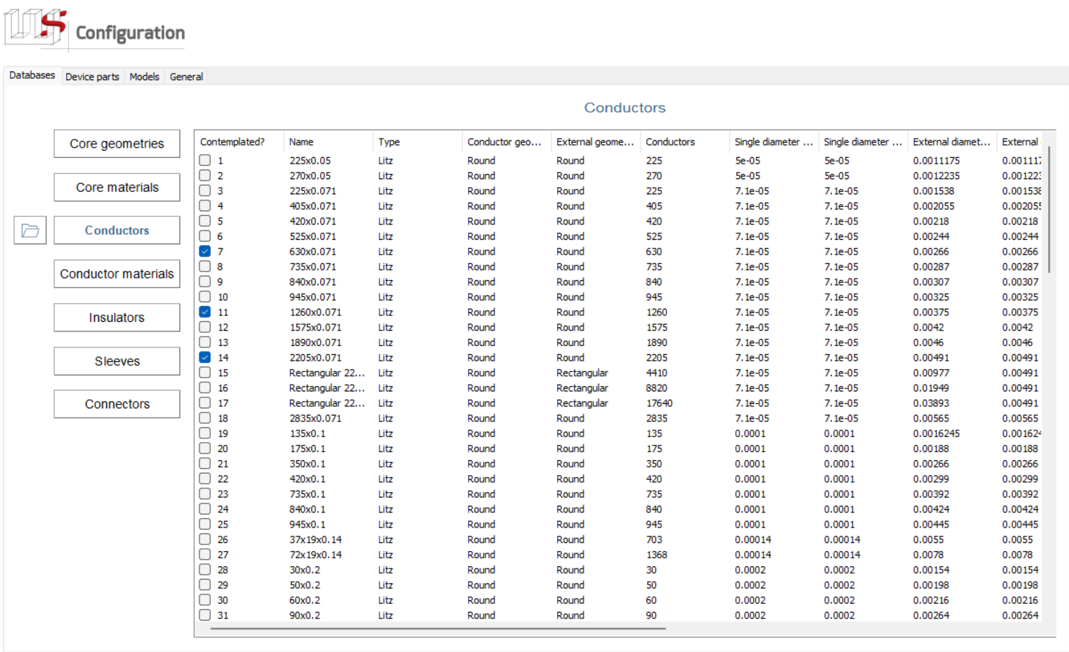
Since the inductor is intended for a 50 kW inverter, only some big cores are active in this example. Once selected, the database items to be used are shown in the next figure:



Contemplated?	Name	l (m)	h (m)	w (m)	c (m)	s (m)	p (m)	Ae (m2)	Ve (m3)
☐ 41	00_8044E	0.08001	0.04458	0.01981	0.01981	0.05928	0.03437	0.000389	8.09e-05
☑ 42	E100/60/28	0.1003	0.0594	0.0275	0.0275	0.07315	0.04685	0.000738	0.00020
☐ 43	00_114LE	0.1143	0.04618	0.03493	0.0351	0.0795	0.0286	0.00122	0.00026
☐ 44	00_130LE	0.1303	0.03251	0.05385	0.02002	0.10846	0.0222	0.00108	0.00023
☐ 45	00_160LE	0.16002	0.0381	0.03962	0.01981	0.13818	0.02814	0.000778	0.00021
☐ 46	2xU10/8/3	0.0198	0.0082	0.00285	0.00555	0.01425	0.005	1.614e-05	6.18e-07
☐ 47	2xU15/11/6	0.0308	0.01145	0.00625	0.01	0.0208	0.0064	6.46e-05	3.36e-06
☐ 48	2xU20/16/7	0.0416	0.0156	0.0075	0.0144	0.0272	0.0083	0.000112	7.6e-06
☐ 49	2xU25/16/6 (37...	0.0508	0.0159	0.0064	0.0127	0.0381	0.0095	8.06e-05	6.76e-06
☐ 50	2xU25/20/13	0.0496	0.0196	0.0127	0.0164	0.0332	0.0114	0.000208	1.836e-0
☐ 51	2xCC0004	0.056	0.0254	0.015	0.018	0.038	0.0164	0.000222	2.7084e-
☐ 52	2xCC06R3	0.062	0.0265	0.02	0.02	0.042	0.0165	0.000328	4.1984e-
☐ 53	2xU30/25/16	0.0626	0.0253	0.016	0.0208	0.0418	0.0149	0.000322	3.58e-05
☐ 54	2xCC0008	0.07	0.026	0.02	0.022	0.048	0.015	0.00036	4.68e-05
☐ 55	2xCC0010	0.07	0.031	0.02	0.022	0.048	0.02	0.00036	5.4e-05
☐ 56	2xCC016A	0.07	0.031	0.025	0.022	0.048	0.02	0.000452	6.78e-05
☐ 57	2xCC016B	0.07	0.036	0.025	0.022	0.048	0.025	0.000452	7.684e-0
☐ 58	2xCC0020	0.07	0.036	0.03	0.022	0.048	0.025	0.000542	9.214e-0
☐ 59	2x00_4110U	0.08128	0.01118	0.00953	0.01702	0.06426	0.00254	0.00016	1.364e-0
☐ 60	2xCC0025	0.082	0.041	0.025	0.026	0.056	0.028	0.000534	0.00010
☐ 61	2xCC0032	0.082	0.041	0.03	0.026	0.056	0.028	0.00064	0.00012
☐ 62	2xCC0040	0.082	0.041	0.035	0.026	0.056	0.028	0.000746	0.00014
☐ 63	2xU46/40/28	0.092	0.0395	0.028	0.028	0.064	0.0255	0.000784	0.00014
☐ 64	2xCC0050	0.104	0.051	0.025	0.032	0.072	0.035	0.000656	0.00016
☐ 65	2xCC0063	0.104	0.051	0.03	0.032	0.072	0.035	0.000788	0.00019
☐ 66	2xCC0080	0.104	0.051	0.04	0.032	0.072	0.035	0.00105	0.00025
☑ 67	2xCC0100	0.104	0.051	0.045	0.032	0.072	0.035	0.00118	0.00028
☐ 68	2x00_5527U	0.10972	0.02756	0.01633	0.02108	0.08864	0.01676	0.000344	5.78e-05
☐ 69	2x00_5529U	0.10972	0.02756	0.02316	0.02184	0.08788	0.01651	0.000488	8.2e-05
☑ 70	2xCC0125	0.126	0.0605	0.035	0.038	0.088	0.0415	0.00109	0.00031
☐ 71	2xCC0160	0.126	0.0605	0.04	0.038	0.088	0.0415	0.001246	0.00036

Figure 8: Core geometries selected for the design

With the aim to reduce high frequency conductor losses and to ease manufacture in case several wires need to be used in parallel (since the selected cores are very big), only some Litz wires have been selected (items 7, 11, and 14 in Figure 9).



Contemplated?	Name	Type	Conductor geo...	External geome...	Conductors	Single diameter ...	Single diameter ...	External diamet...	External
☐ 1	225x0.05	Litz	Round	Round	225	5e-05	5e-05	0.0011175	0.00111
☐ 2	270x0.05	Litz	Round	Round	270	5e-05	5e-05	0.0012235	0.00122
☐ 3	225x0.071	Litz	Round	Round	225	7.1e-05	7.1e-05	0.001538	0.00153
☐ 4	405x0.071	Litz	Round	Round	405	7.1e-05	7.1e-05	0.002055	0.00205
☐ 5	420x0.071	Litz	Round	Round	420	7.1e-05	7.1e-05	0.00218	0.00218
☐ 6	525x0.071	Litz	Round	Round	525	7.1e-05	7.1e-05	0.00244	0.00244
☑ 7	630x0.071	Litz	Round	Round	630	7.1e-05	7.1e-05	0.00266	0.00266
☐ 8	735x0.071	Litz	Round	Round	735	7.1e-05	7.1e-05	0.00287	0.00287
☐ 9	840x0.071	Litz	Round	Round	840	7.1e-05	7.1e-05	0.00307	0.00307
☐ 10	945x0.071	Litz	Round	Round	945	7.1e-05	7.1e-05	0.00325	0.00325
☑ 11	1260x0.071	Litz	Round	Round	1260	7.1e-05	7.1e-05	0.00375	0.00375
☐ 12	1575x0.071	Litz	Round	Round	1575	7.1e-05	7.1e-05	0.0042	0.0042
☐ 13	1890x0.071	Litz	Round	Round	1890	7.1e-05	7.1e-05	0.0046	0.0046
☑ 14	2205x0.071	Litz	Round	Round	2205	7.1e-05	7.1e-05	0.00491	0.00491
☐ 15	Rectangular 22...	Litz	Round	Rectangular	4410	7.1e-05	7.1e-05	0.00977	0.00491
☐ 16	Rectangular 22...	Litz	Round	Rectangular	8820	7.1e-05	7.1e-05	0.01949	0.00491
☐ 17	Rectangular 22...	Litz	Round	Rectangular	17640	7.1e-05	7.1e-05	0.03893	0.00491
☐ 18	2835x0.071	Litz	Round	Round	2835	7.1e-05	7.1e-05	0.00565	0.00565
☐ 19	135x0.1	Litz	Round	Round	135	0.0001	0.0001	0.0016245	0.00162
☐ 20	175x0.1	Litz	Round	Round	175	0.0001	0.0001	0.00188	0.00188
☐ 21	350x0.1	Litz	Round	Round	350	0.0001	0.0001	0.00266	0.00266
☐ 22	420x0.1	Litz	Round	Round	420	0.0001	0.0001	0.00299	0.00299
☐ 23	735x0.1	Litz	Round	Round	735	0.0001	0.0001	0.00392	0.00392
☐ 24	840x0.1	Litz	Round	Round	840	0.0001	0.0001	0.00424	0.00424
☐ 25	945x0.1	Litz	Round	Round	945	0.0001	0.0001	0.00445	0.00445
☐ 26	37x19x0.14	Litz	Round	Round	703	0.00014	0.00014	0.0055	0.0055
☐ 27	72x19x0.14	Litz	Round	Round	1368	0.00014	0.00014	0.0078	0.0078
☐ 28	30x0.2	Litz	Round	Round	30	0.0002	0.0002	0.00154	0.00154
☐ 29	50x0.2	Litz	Round	Round	50	0.0002	0.0002	0.00198	0.00198
☐ 30	60x0.2	Litz	Round	Round	60	0.0002	0.0002	0.00216	0.00216
☐ 31	90x0.2	Litz	Round	Round	90	0.0002	0.0002	0.00264	0.00264

Figure 9: Conductor geometries selected for the design

The remaining databases are left as default for this example, but the user is free to configure what entries to use referring Conductor materials, Insulators, Wire sleeves and Connectors.

2.2 Device parts

The next step is to configure the rules that apply to every part of the device. Here, the user can leave everything as it is, which will be enough for many designs, or can fine tune every parameter. There are 4 parts to be configured:

- Core
- Conductors
- Insulators
- Bobbin

Every configuration parameter is accessible (and a comprehensive definition is provided in the help installed along SmartNetics, accessible by pressing *'f1'* in any part of the tool). If the designer has some particular requirements or some previous knowledge about the design output, they can use this configuration to reduce simulation time, by only allowing designs that they know are going to match the desired result. As an example, we have modified 4 fields for this particular design:

- Since the selected cores are already pretty big, "Maximum stacked cores" has been reduced from 4 to 3.

- Even though Litz wire is easier to handle than solid wire, the maximum number of parallel wires, set by “Paralleled wires limit” has been reduced from 6 to 5 to ensure an easy winding.
- At the same time “Allow a reduction of n parallel wires” has been increased from 1 to 2, to allow designs with 5, 4 (4=5-1) or only 3 (3=5-2) wires in parallel.
- Since the window of these cores is very big, a high amount of different values for the number of turns can be possible. To reduce the imposed restriction to this value, “Maximum N combinations” has been increased from 10 to 20.

The full configuration, once those fields have been modified, is shown in Figure 10.

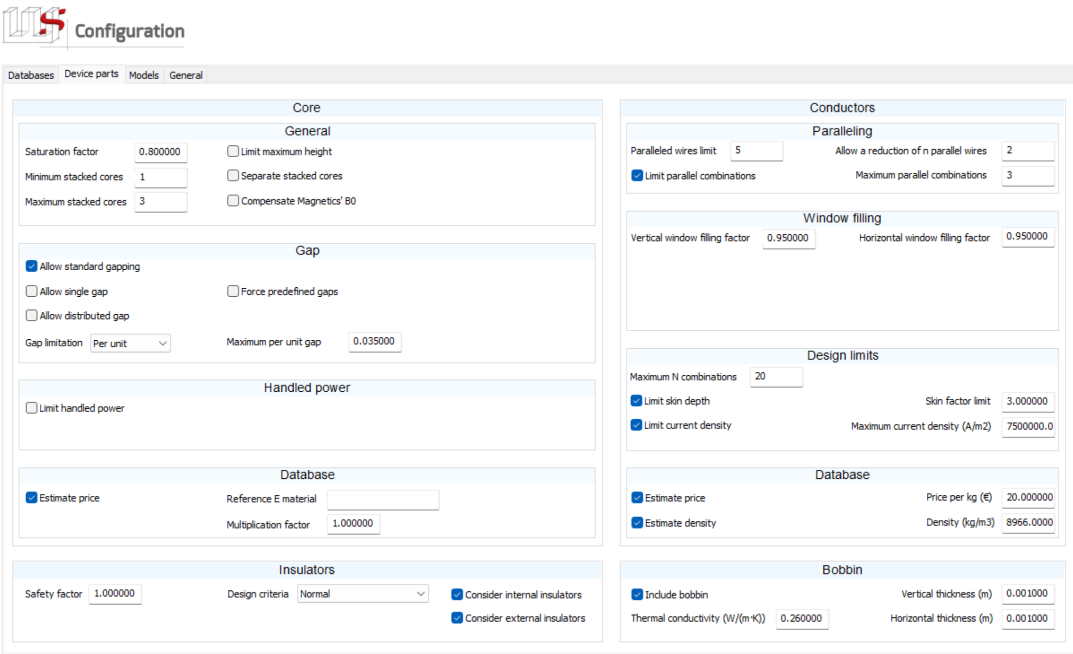


Figure 10: Device parts configuration

The remaining options have been left as in the default configuration but, as in every part of the tool, the user is free to use any prior knowledge or any information coming from the future manufacturer to adapt the design to the particular needs of a given project.

2.3 Models

In the next tab, “Models”, the user can select the model to be used for the calculation of every parameter of the device, including losses, inductance and temperature. By default the most precise models are used for the design, so we will not modify them. The only change in the fields shown in Figure 11 is the ambient temperature, that has been increased to 35º, knowing that the inductors are going to operate inside an enclosure.

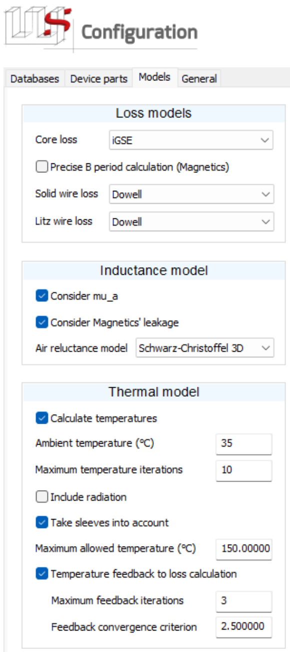


Figure 11: Models configuration

By using the most precise models the user can achieve the most accurate results but at the cost of an increased design time. To reduce simulation time, a simpler model can be used; for example, if the user knows that core losses are not relevant for the design or that the regular Steinmetz approximation is enough, they can select that model for “Core loss”; or if a rough estimation is enough, the “Maximum temperature iterations” can be reduced. For this example, assuming no prior knowledge of the desired results, high precision models are used.

2.4 General

In this last step the user can set any (or every) parameter of the design. Since we don’t have any restriction in that regard, let’s leave everything as is, including a maximum difference between wanted and achieved inductance of 5% (“Maximum design deviation” = 0.05).

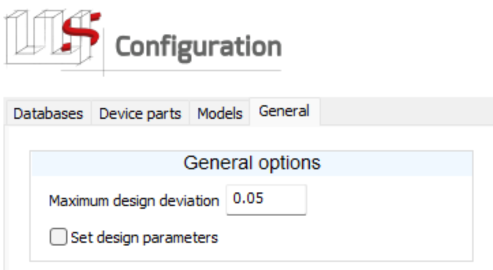


Figure 12: General configuration

Having set every configuration parameter, the user can proceed to the next available step, “Design”, using the lateral menu.

3 Design

Once everything has been configured, the design process can begin, and every parameter combination that produces a valid result is displayed. Any numeric variable that has any impact in the design can be selected at the right-side selectors to be used for comparison. The default variables are selected considering the values that usually impact the most in the design decision, so we are going to use them for this section, as shown in the next figure.

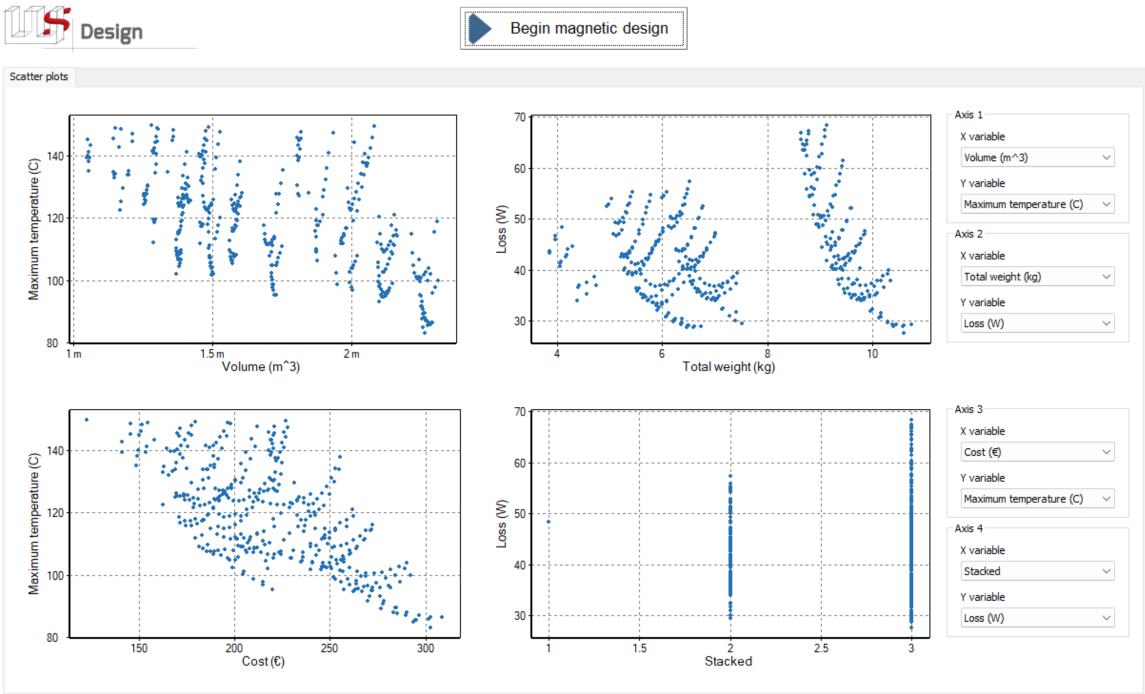


Figure 13: Design results

Once every valid solution is known, we can star filtering out the ones that are considered most convenient for this particular project. To do so, simply click and drag the cursor to select the desired devices in any graph, those designs will become highlighted in every other graph, enabling an easy comparison of up to 8 different variables at the same time.

In the first place, to ensure a correct working of the converter, taking into account that only natural convection is considered, let's filter out the designs with a maximum temperature higher than 100^{o}, as shown in the next figure:

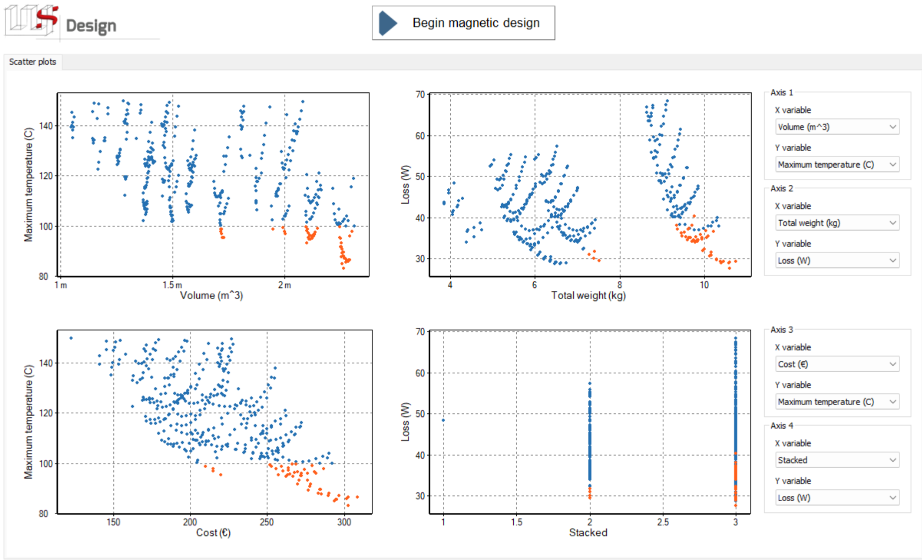


Figure 14: Design results after filtering by Temperature

Figure 14 highlights the advantages of the SmartNetics approach. As can be seen, a device with approximately the same value in a given parameter can be built in many different ways, and sometimes allowing a slightly increase in a parameter can allow for a much better design in every other aspect.

At the bottom-right graph we can see that the device can be constructed by using two or three stacked cores and at the bottom-left that it can have a very different cost depending on the selection. Even though the device with the lowest losses (the one that would be provided by a direct method that just gives the most efficient device) uses 3 stacked cores, in exchange for a little increase in losses, devices that are much more convenient can be found To reduce cost and ease manufacturability, from the previous subset, let's take only the designs that use only 2 stacked cores, as shown in the next figure.

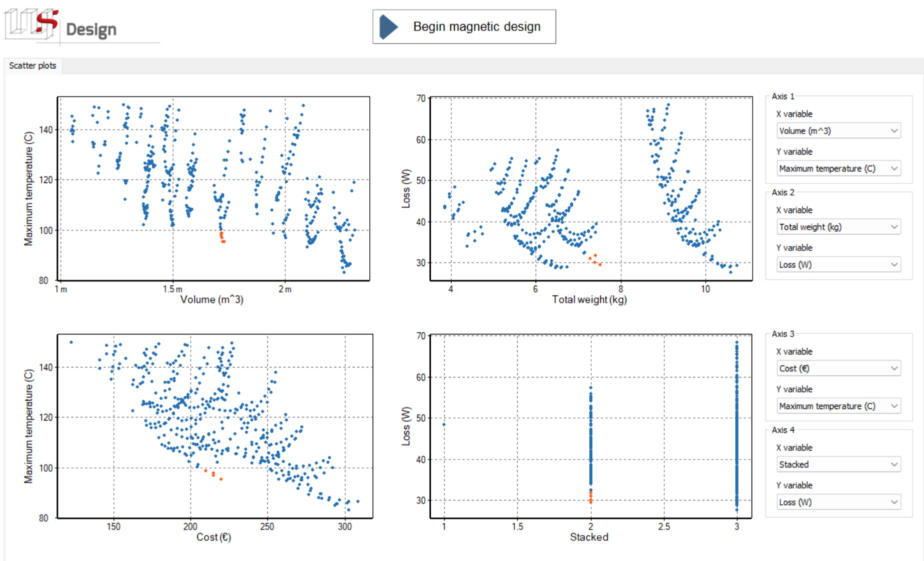


Figure 15: Design results after filtering by Stack

Once a subset of all the possible combinations has been selected, using up to 8 variables, a detailed description of the remaining designs can be used for a fine selection of the design to build. That can be done in the next dialog: "Selection", which is now available in the lateral menu.

4 Selection

In this dialog, the details of the remaining devices can be inspected in detail to select the one that best fits the need of the current project. The definition of every parameter can be consulted in the provided help (accessed bu pressing *'f1'* or clicking in the corresponding button, always available at the bottom-left corner). The user can change the width of every field or even hide the ones not considered important, as shown in Figure 16.

Selection

	Cores	Material	Stacked	l_g (m)	Insulator	N	Window filling	Winding conductor	Vertical wires	Horizontal wires	R_{DC}	P_{w} (W)	P_{c} (W)	Available windo...	Delta Bpp	Total weight (kg)	Volume (m^3)	Area (m^2)	Loss (W)	L_{PT} (H)
1	2xCC0125	Amorphous Elesa	2	0.00170328	NOMEX	12	0.8336	2205x0.071	5	1	0.00187621	9.86532	21.7552	0.0777591	2.42085	7.40155	0.00171466	0.0140717	31.6205	0.00029994
2	2xCC0125	Amorphous Elesa	2	0.00250536	NOMEX	14	0.8276	2205x0.071	1	4	0.0027367	14.3896	16.6171	0.07814	2.07557	7.27409	0.00171568	0.0140339	31.0067	0.000300021
3	2xCC0125	Amorphous Elesa	2	0.00250536	NOMEX	14	0.8296	2205x0.071	2	2	0.00273878	14.4005	16.6171	0.07814	2.07557	7.27611	0.00171722	0.0140465	31.0176	0.000300021
4	2xCC0125	Amorphous Elesa	2	0.00298352	NOMEX	15	0.8276	2205x0.071	1	4	0.0029152	15.3284	14.7442	0.0783672	1.93854	7.39528	0.00171903	0.0140339	30.0726	0.000300229
5	2xCC0125	Amorphous Elesa	2	0.00352604	NOMEX	16	0.8276	2205x0.071	1	4	0.00309613	16.2801	13.1604	0.0786249	1.81672	7.51646	0.00172284	0.0140339	29.4405	0.000300118
6	2xCC0125	Amorphous Elesa	2	0.00352604	NOMEX	16	0.8296	2205x0.071	2	2	0.00309851	16.2926	13.1604	0.0786249	1.81672	7.51864	0.00172439	0.0140465	29.4529	0.000300118
7	2xCC0125	Amorphous Elesa	2	0.00352604	NOMEX	16	0.8336	2205x0.071	4	1	0.00310326	16.3176	13.1604	0.0786249	1.81672	7.52301	0.00172748	0.0140717	29.4779	0.000300118

Figure 16: Selection. Available devices

The devices shown in the figure are the ones selected in the previous step, so all of them comply with the imposed restrictions. As can be seen, every design selected uses the same core geometry (2 stacked 2xCC0125), the same core material (an amorphous core manufactured by ELESA) and the same wire (a 2205 strands Litz wire with a 0.071 mm diameter).

They even have very similar losses (28.05 to 31.7 W in a 50 kW converter), similar maximum temperatures (93.1° to 98.9°), similar weights (7.0 to 7.5 kg), etc. In a different approach, only one of these devices would be available, for example the one with the lowest losses. This remarks the disadvantages of that approach, where designs that are very similar in a given parameter could be discarded by a small difference that wouldn't even have any impact on the converter, without considering the big improvement they could provide in other metrics.

The biggest differences are the length of the magnetic flux thorough air ("l_g (m)", which is twice the distance between top and bottom core for a device with gaps in every leg), the number of turns ("N") and how the wires of each turn are paralleled ("Vertical wires" and "Horizontal wires").

Even though we have established a limit for the maximum B field ("Saturation factor" in Figure 10), for this particular project we know that there are situations when the current can be even higher than the nominal one. To account for that, we are going to select the devices with a reduced maximum B ("B_max (T)"), that correspond to the ones with the highest turns. The three last options shown in Figure 17 match that criteria.

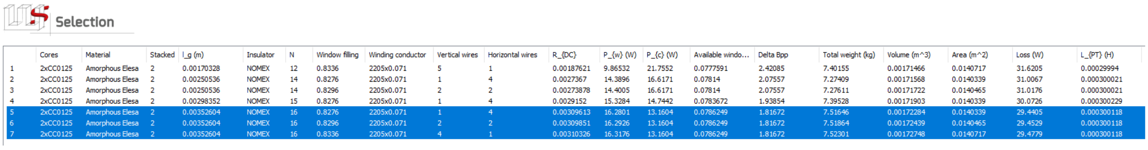


Figure 17: Selection. Subset of available devices

Every selected design uses 4 wires in parallel for each turn. The difference between the remaining devices is how those 4 wires area paralleled: 4x1, 2x2 and 1x4 ("Vertical wires" x "Horizontal wires"). With the aim to ease manufacturability, let's select the one with a wire paralleling strategy that produces a stack closer to a square: 2x2.

Once the desired design is found, it can be selected by clicking in the "Select design" button below. Once done, the data of the device is replicated at the bottom, as shown in the next figure:

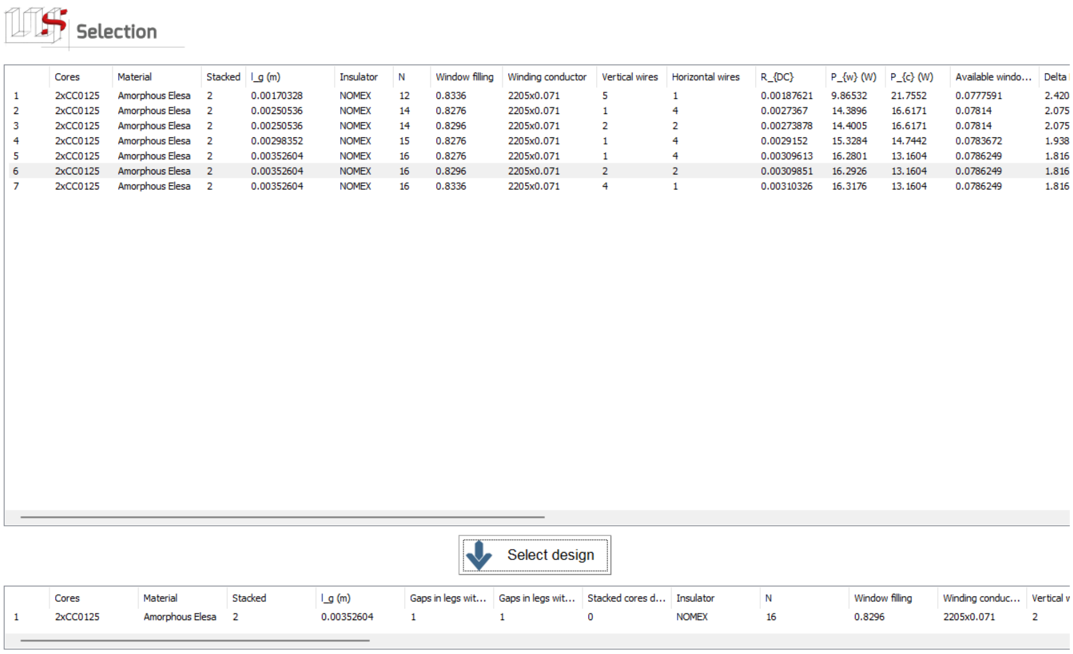


Figure 18: Selection. Single device

Please, keep in mind that, for devices with a single gap, the total length of the magnetic flux thorough air ("l_g (m)") is the same as the gap distance. For this particular example we have selected standard gapping, which means we have gaps in every leg. This means the "l_g (m)" value corresponds to twice the gap, since it is traversed twice by the magnetic flux (this also applies for distributed gaps).

Once a design is selected, the last button on the lateral menu, "Device", is enabled and the user can proceed with the last step of the process.

5 Device

In this last dialog, the user can see the details of the selected device and export it to third-party tools for validation.

The user can navigate through the 5 available tabs:

- Geometry
- Performance
- Report
- Ansys
- Altair

5.1 Geometry

In this first tab, a graphical representation of the device is shown, along with a drawing of a single core and wire with their main dimensions.

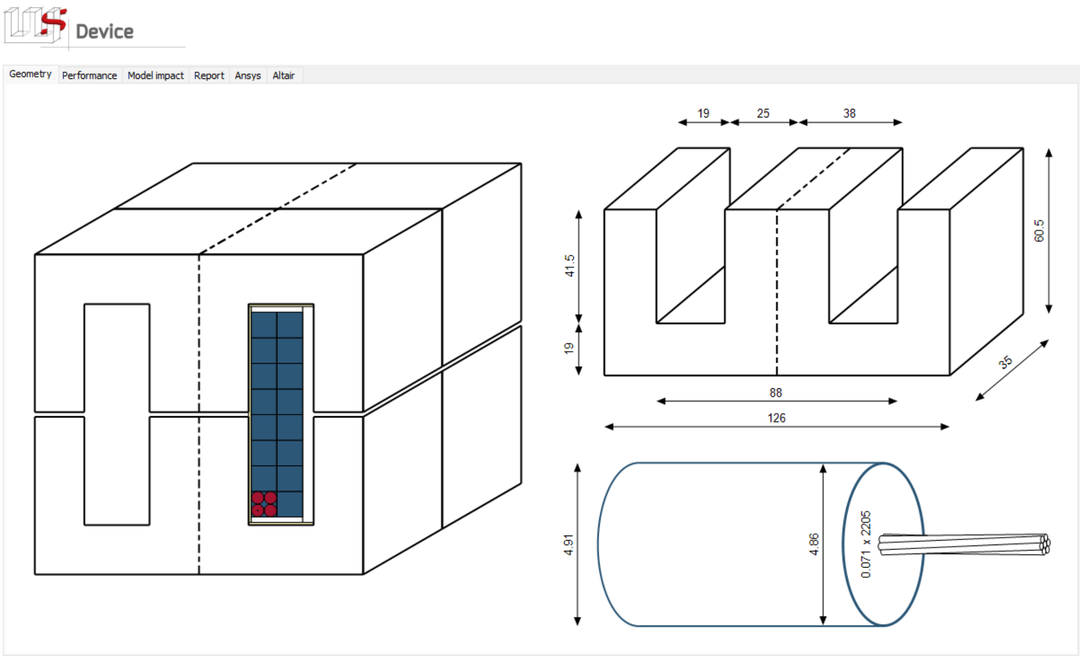


Figure 19: Geometry visualization

5.2 Performance

In the second tab, the user can see the distribution of temperatures in the different parts of the device, depicted in Figure 20. The temperatures shown are calculated for the center of the device and divided in: center of the central column, center of the lateral columns, center of the top and bottom yokes and center of the windings (one winding for inductors and two for transformers).

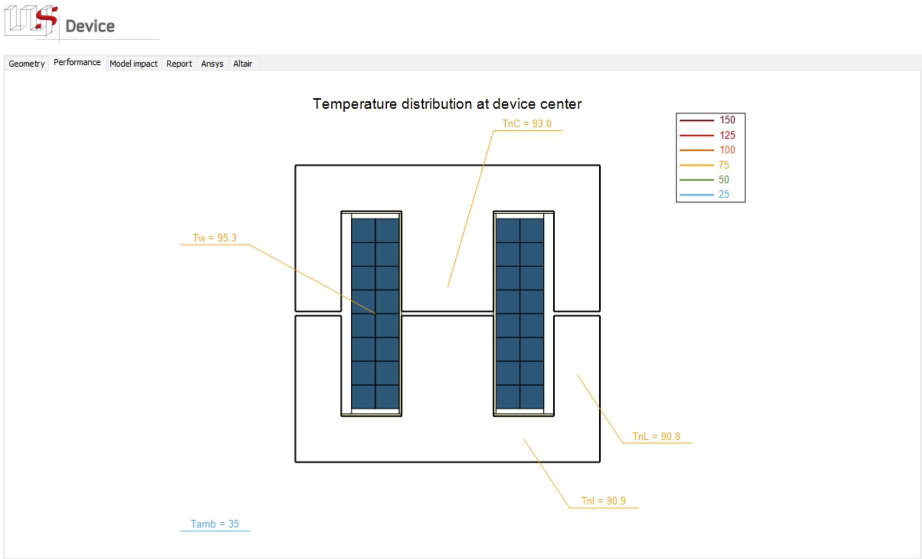


Figure 20: Temperature distribution

5.3 Model impact

Although the model to be used for every calculation was selected in the second step ("Configuration"), the user can see in this tab the results that would have been provided by the other available models. This way, the user can get important information that can help them in the current design and in future ones. The impact of the models selected for the calculation of core loss, conductor loss and inductance are shown in Figure 21.

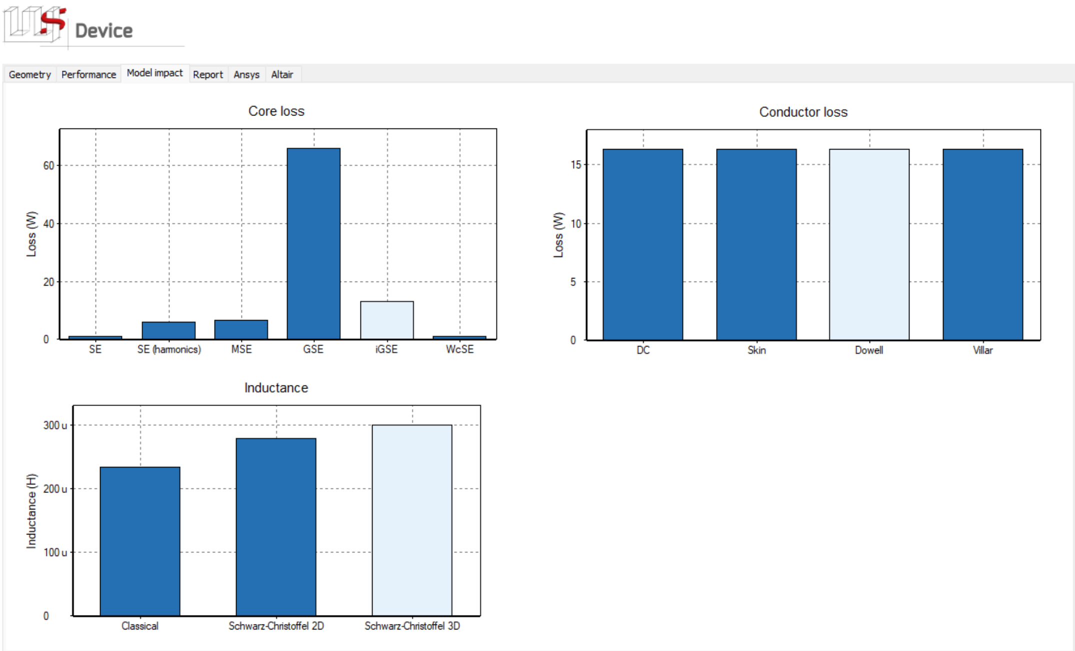


Figure 21: Model impact

In the case of core loss (displayed at the top left corner), by selecting the most precise model ("iGSE") the underestimation given by the use of the regular Steinmetz model ("SE") or the overestimation provided for this particular waveform by its generalization ("GSE") can be avoided. For the conductor loss (top right corner), the fact that the selection of the Litz wire was the correct choice is highlighted by assessing that skin and proximity losses have a very small impact in total loss (Skin, Dowell and Villar models very similar to DC model). Lastly, at the bottom left corner, the inductance model comparison demonstrates that, once the gap starts having a high value (1.75 mm in this particular case), the fringing effects can not be omitted, and using a model like Schwarz-Christofel 3D is compulsory.

5.4 Report

In the fourth tab, the user can generate a high-resolution report that includes the desired information. The user can select what fields to include in said report:

- Include geometry: includes the graphs displayed in the "Geometry" tab.
- Include performance: includes the graph displayed in the "Performance" tab.
- Include model impact: includes the graphs displayed in the "Model impact" tab.
- Include component list: generates a list of the components needed to build the device.
- Include input signals: replicates the signals (current for inductors; current and voltage for transformers) used as input for the design in the first dialog.
- Include design configuration: generates a list of every configuration option.

Once the desired options are selected, the user can press on "Generate report" to generate the PDF file in the path selected below.

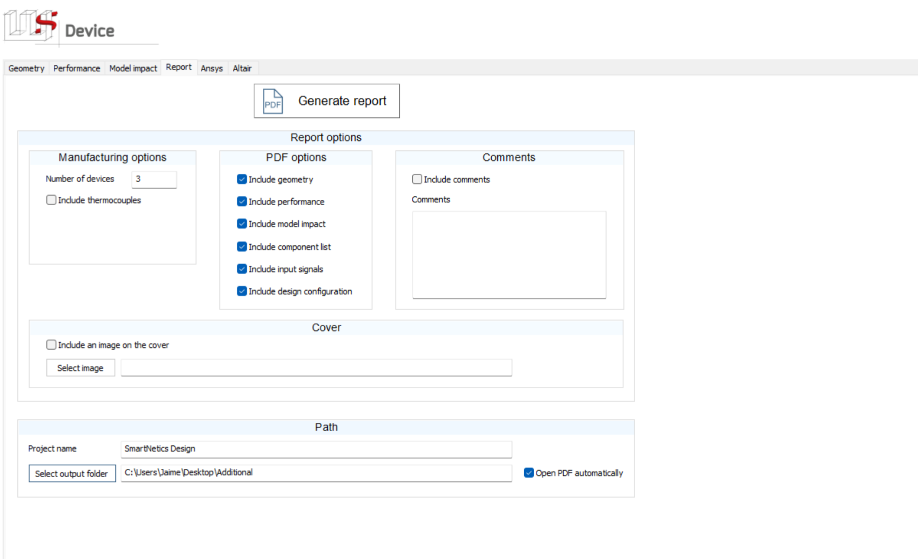


Figure 22: Report configuration

Please, keep in mind that the PDF is generated by a LaTeX file that need MikTex to compile. If it is not installed, the user will be asked to do so (and guided thorough its corresponding Help section).

5.5 Ansys

Every design in SmartNetics is based on analytical models. This way, thousands of possible combinations can be tried in a short time. Once a particular design is selected, a deeper analysis can be carried out by means of Finite Elements tools.

In this regard, SmartNetics allows the direct exportation to Ansys-Maxwell and Ansys-IcePack, where the device can be simulated. To do so, the first step is to generate the model, which is defined in a python script. This is done when clicking on "Generate Ansys model" and no Ansys installation is required.

Once the model is created, the user can launch Ansys themselves and run it, in the same computer SmartNetics is installed or any other with a valid Ansys license. Ansys can also be launched from this same screen, by clicking on "Launch Ansys" (Ansys is a third-party software and has to be installed beforehand).

In the case of Ansys, the user can carry electromagnetic simulations by means of Ansys-Maxwell or Temperature simulation by means of Ansys-IcePack. For this example we will run a temperature simulation, taking into account insulators, wire sleeves and bobbin for an increased precision. To reduce simulation time, the X and Y region percentages have been reduced to 25% and, taking advantage of its symmetry, only one quarter of the device is going to be simulated (2.25D under "Generate symmetry simplifications"). The full simulation configuration is shown in Figure 23.

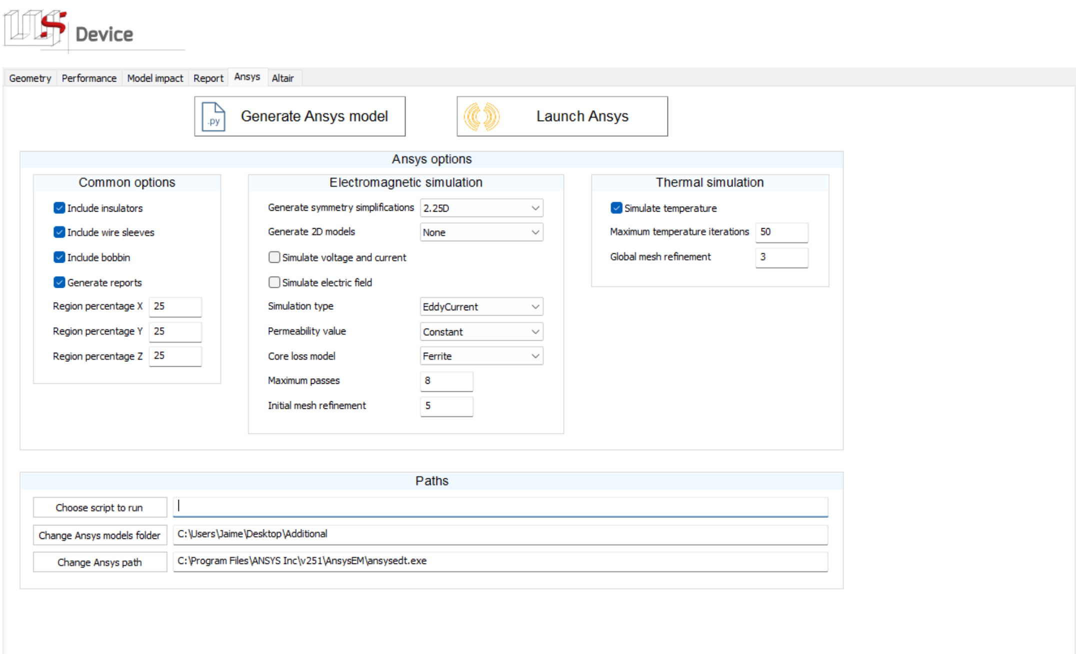


Figure 23: Ansys simulation configuration

Once the user clicks on “Generate Ansys model” and then on “Launch Ansys”, the simulator automatically opens and build the geometry, assigning the required materials, boundaries and perturbations, as shown in the next figure.

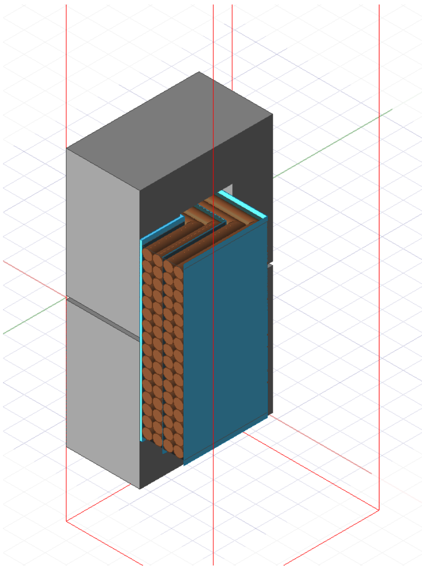


Figure 24: Ansys 2.25 geometry

Once the model is generated, the user can click on “Analyze all” to start the simulation, as shown in Figure 25.

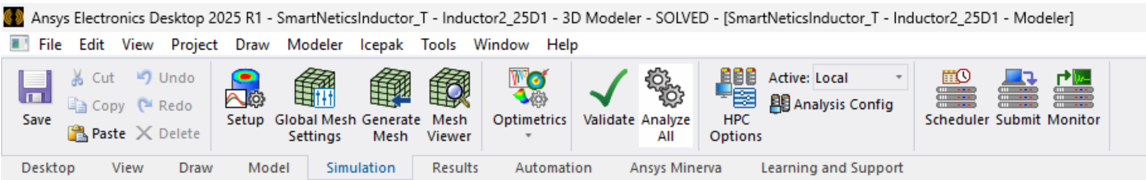


Figure 25: Ansys “Analyze all” button

*Since this is a very complex model, inside Ansys-IcePack the negative Z boundary was edited to be a 25% and the Mesh region was edited to achieve a good convergence, as shown in the next figure:

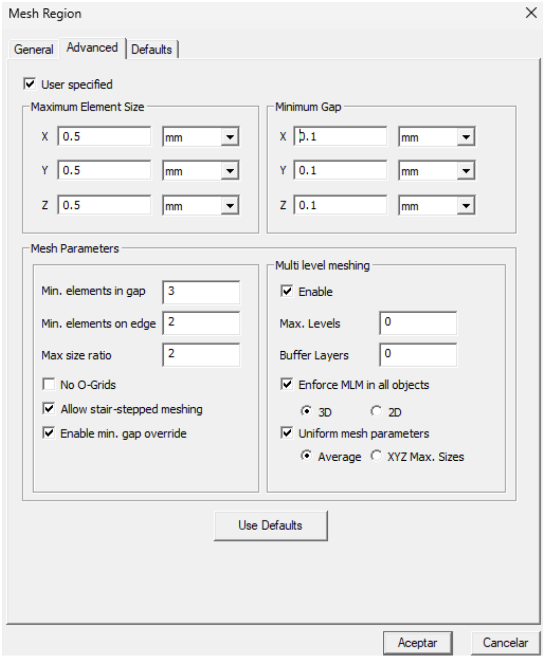


Figure 26: Ansys-IcePack mesh configuration

The simulation results are shown in the next figure for the YZ plane.

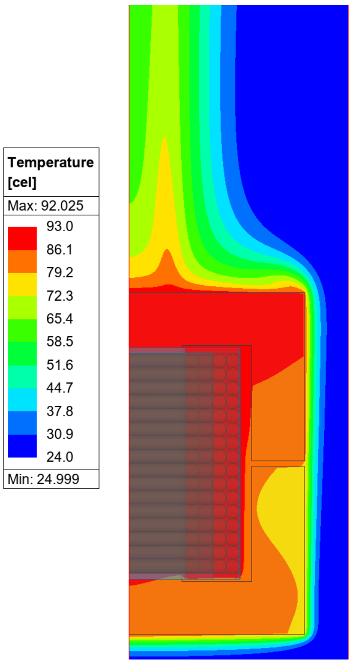


Figure 27: Ansys-IcePack temperature results

As can be seen, there is a very good match between the simulation and the estimation shown in Figure 20, taking into account that only the highest temperature of every part is calculated, instead of an accurate distribution. This highlights one of the advantages of proposed approach: first use analytical equations, that allow the design of thousands of magnetics in a very short amount of time; and then validate the decision with a Finite Elements software, that can achieve a very high precision but at the cost of an increase in time and resources (for this particular example, a two hour simulation requiring 47 GB of RAM).

5.6 Altair

The remaining option for the validation of the design in a third-party software is the simulation in another Finite Elements tool: Altair-Flux. The configuration options are shown in Figure 28 and are similar to the ones in Ansys, with slight changes due to the differences in both programs.

As in the previous step, the user can click on "Generate Flux model" (no Flux installation is required) to generate a python file with the full description of the model, including geometry, materials, main waveform values, etc. Once generated, the user can run the simulation on a different machine or on the one SmartNetics is installed, by clicking on "Launch Flux" (for this step Flux must be previously installed in the path selected below).

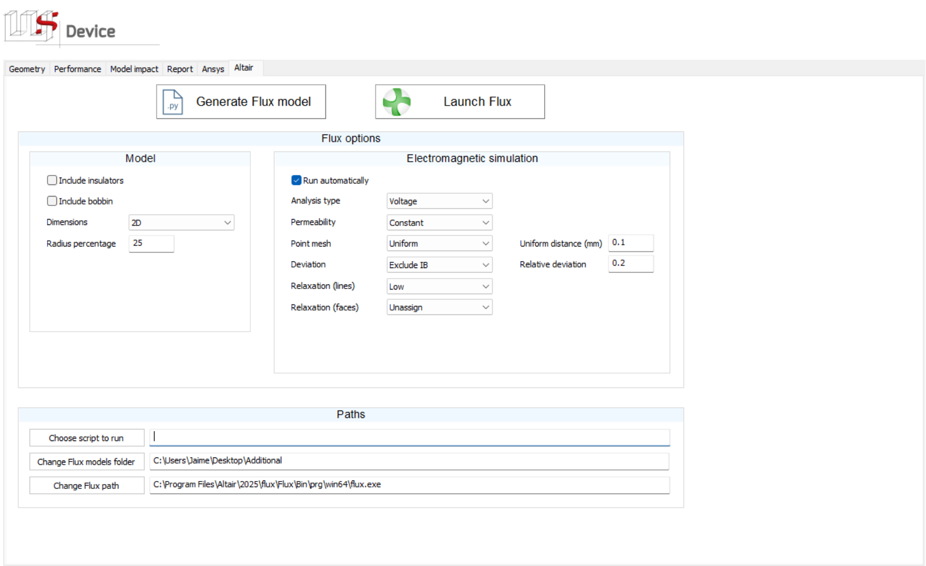


Figure 28: Flux simulation configuration

Since "Run automatically" is checked, once the model is built inside Flux, the simulation starts automatically. The results of the simulation are displayed in the next figure, where the B field is shown. As can be seen, the B field matches the one predicted on average for the whole core (shown in Figure 18 as "B_max (T)"), which is one of the estimated device parameters.

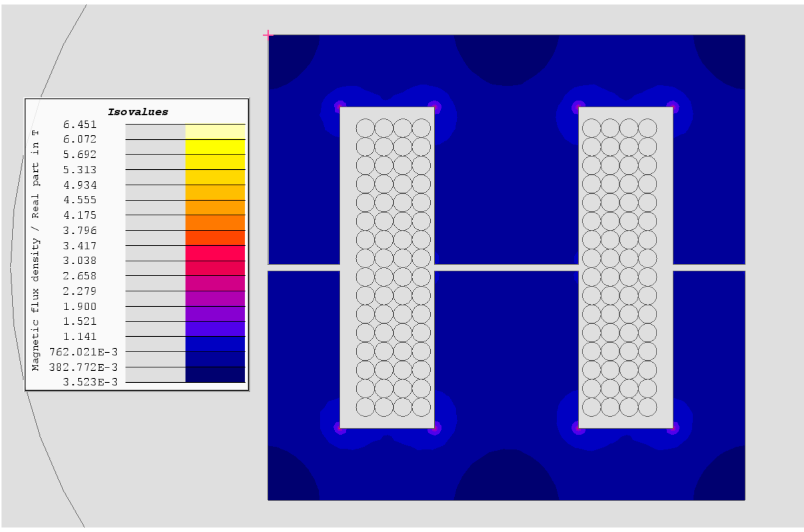


Figure 29: Flux simulation results. B field

The inductance and resistance calculated values are shown in the "Output" box inside Flux. As can be seen, the inductance value is a bit lower than expected (280 µH versus the expected 300 µH), as shown in the next figure.

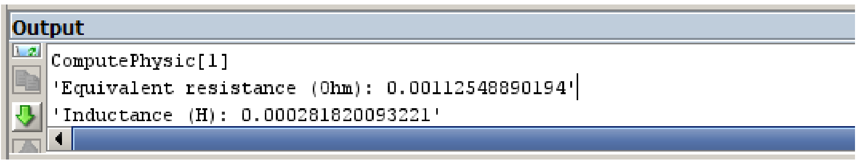


Figure 30: Flux simulation results. Output

That can be in part explained by the simplifications assumed when doing a 2D model of a 3D device but, on top of that, thanks to the accurate Finite Elements model, we can achieve a better insight into the device specifics. To do so, we can display the H field as well, as shown in Figure 31.

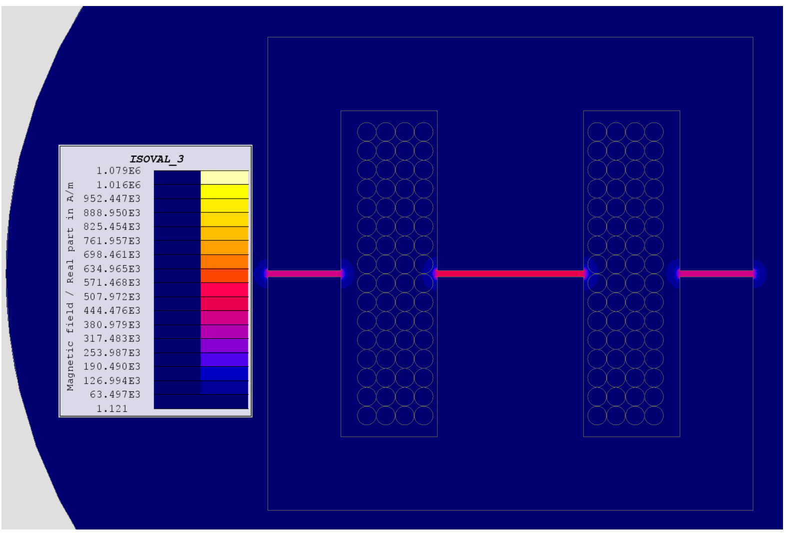


Figure 31: Flux simulation results. H field

As can be seen, the H filed around the gap enters the wires next to it, which can also explain some of the difference. Once again, this highlights the advantages of the combination of an analytical approach, that allows the selection of the best device, and the Finite Elements simulation, that allows a deep understanding of the details of the device, letting the user take measures before manufacturing, like increasing the gap-wires distance by increasing the bobbin thickness, for example.

Conclusion

In this tutorial, an example on how to fully design, export and simulate an inductor using SmartNetics has been carried out. Starting from a current and inductance definition, the user can control any aspect of the design process. Once every possible device is designed, the user can easily select the one that best suits their needs and, for the selected design, they can generate a report or export it for simulation in third-party Finite Elements Analysis software.

As has been shown, the advantage of the proposed approach over the classical one (where only the device that is the best in one or two properties is provided) is clear. Thanks to this strategy, a device that has only a slightly lower performance in one aspect (and so would be discarded in the classical approach) but much better in every other, can be identified, allowing the selection of the device that best suits the current project.

Once the device that is considered best for the project (regardless of the definition of "best") is selected, the user can export it to third-party software for its validation. In this tutorial, we have validated the result against two Finite Elements Analysis tools: Ansys-IcePack and Altair-Flux, with very good results in both of them, assessing the validity of the proposed approach.

This tutorial is intended as an example, so the user is encouraged to try different configurations to find the one that is best suited for their particular project.

Please, keep in mind that the images shown in this document may not exactly coincide with the options and distribution shown in the application, since different updates may incur in slight changes.