High-Frequency LLC Converter with Narrow Frequency Variations for Aircraft Applications

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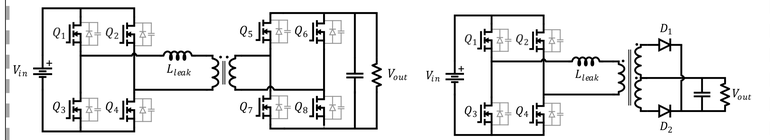
Problem Statement

For the last decades, there has been a great tendency for More Electric Aircraft (MEA), which leads to the necessity of high efficient and high power-density power converters. This paper describes the design and implementation of a compact and high-frequency LLC converter with a wide input voltage range, output power range, high efficiency, high power density (32kW/dm³) and narrow frequency variations. A summary of the specifications for this project is presented in the table below.

		Nominal	Normal range	Abnormal range
Input Voltage [V]	V_{in}	270	[235 – 285]	[220 – 320]
Output Voltage [V]	V_{out}	28	28	28
Output Power [W]	P_{out}	1000	[250 – 1000]	[1000 – 1500]
Switching frequency variation [%]	$\lvert 1 - f_{sw}/f_N \rvert$	±5	±15	
Efficiency [%]	η	96		
Power dissipation density [W/m²]		1.4	1.4	1.4
Mechanical dimensions [cm]			5.79 x 6.1 x 1.3	
Baseplate temperature [ºC]			90	

State of the art

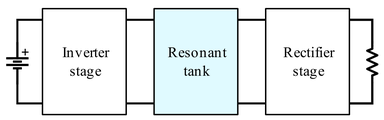
Soft switching PWM topologies

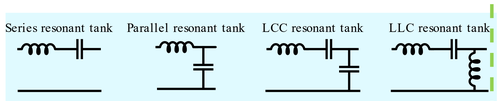


- Cannot guarantee ZVS in the entire range of operation.
- **Highly difficult modulation schemes for some of them.**

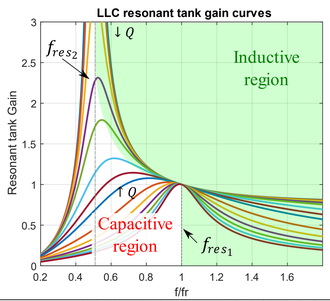
Resonant converter topologies → Series-parallel resonant converter or LLC converter

- Achievement of voltage regulation without load
- Achievement of ZVS throughout the entire operating range
- Input current decreases as load decreases → high efficiency





Theoretical Analysis



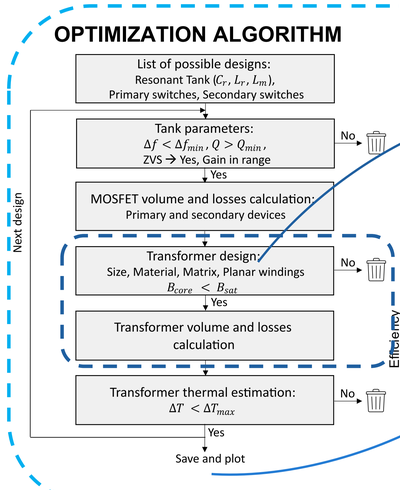
$$m = \frac{L_r + L_m}{L_r} \qquad Q = \frac{\sqrt{L_r/C_r}}{R_{ac}} \qquad F_x = \frac{f}{f_{res}}$$

$$K = \frac{F_x^2(m-1)}{\sqrt{(mF_x^2 - 1)^2 + F_x^2(F_x^2 - 1)^2(F_x - 1)^2 Q^2}}$$

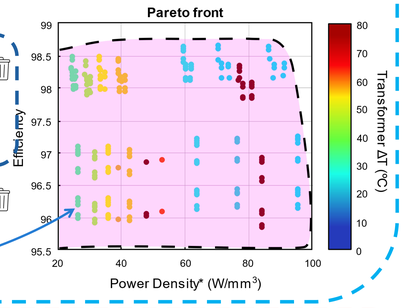
- n → in which **part of the gain curves** to operate
- **Low m** → f_{res_1} and f_{res_2} are closer → **smaller frequency variation range**
- Q → should be **kept over** 0,3 so that the resonant **tank is restrictive enough**

Solution

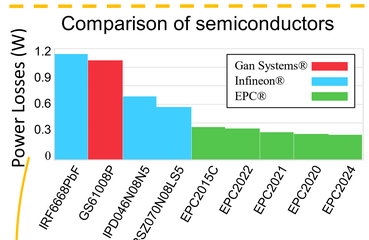
OPTIMIZATION ALGORITHM



- High-frequency magnetic materials: 3F46, 67, M3…
- Winding losses → Ferreira equations → skin and proximity effect
- Core losses → Steinmetz



Final topology



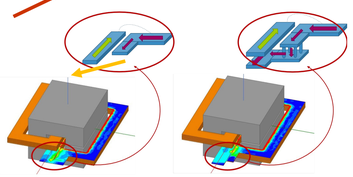
- Primary side devices: **GS66516B**
- Secondary side devices: **BSZ070N08LS5**

Losses calculated on the secondary side @$P_{out_{max}}$

Additional design of **Resonant Litz inductor** to improve efficiency and reduce switching frequency variation range

Matrix Transformer

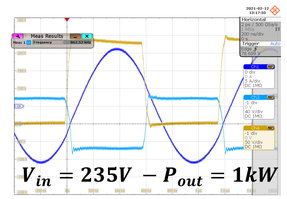
- Four 1:1 Transformers integrated in just two magnetic devices
- Current balancing and current-sharing

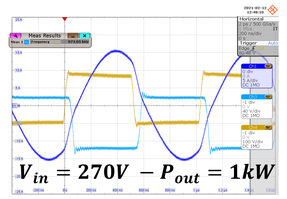


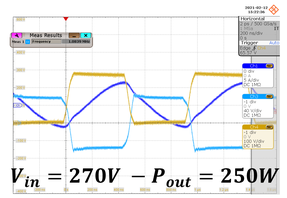
Analysis of the **termination effect of the tranformer** to optimize its implementation

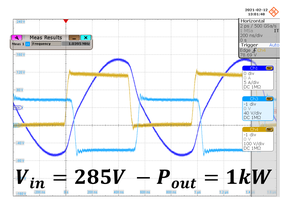
Results

	P_{out} (W)	V_{in} (V)	$Efficiency$	F (kHz)	T_{trafo} $(ºC)$	T_{ind} $(ºC)$
	905,45	270,35	96,83	945,00	42,70	54,30
	906,60	285,50	96,55	992,50	46,50	56,00
NORMAL	905,48	235,01	96,73	836,00	40,80	56,90
OPERATION	241,31	235,46	93,08	873,60	46,70	29,30
	240,82	270,65	94,06	1028,60	42,00	28,30
	240,81	284,64	94,21	1132,00	36,80	28,00
ABNORMAL	903,51	220,8	96,21	792	60	49,8
OPERATION	904,08	320,8	96,28	1117	69	61

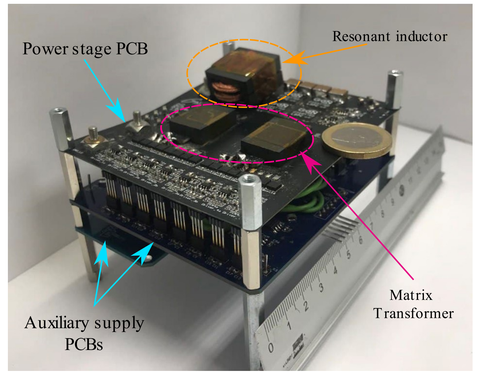


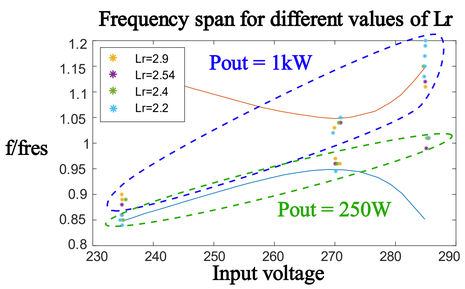






FINAL PROTOTYPE





Conclusion

- An LLC for aircraft applications with a wide input voltage range, output power range, high efficiency and high power-density has been developed.
- A **Matrix Transformer** is implemented to share the current between different secondaries and achieve a balanced current-sharing.
- An **optimization algorithm** has been developed to find the best combination of resonant tank, semiconductors and magnetic components for the exposed specifications.
- An additional **resonant litz inductor** is designed to achieve a reduced frequency variation range for regulating the output voltage.
- The **prototype operates properly** in the entire **range of input voltage** and **power** specified, achieving **high efficiency** at nominal conditions.