

Electrical equipment evolution in civil aeronautics : Designer point of view

EXXELIA / SAFRAN

Magnetic components / Converters

July 03 2018

→ Introduction

Electrical energy in aircraft : history, how much and why
More electrical aircraft : what does it mean, consequences

→ Converter designer side and point of view

some information about soft switching
influence about transformer drawbacks on soft switching
contribution of digital technologies to soft switching

→ Magnetic component designer side and point of view

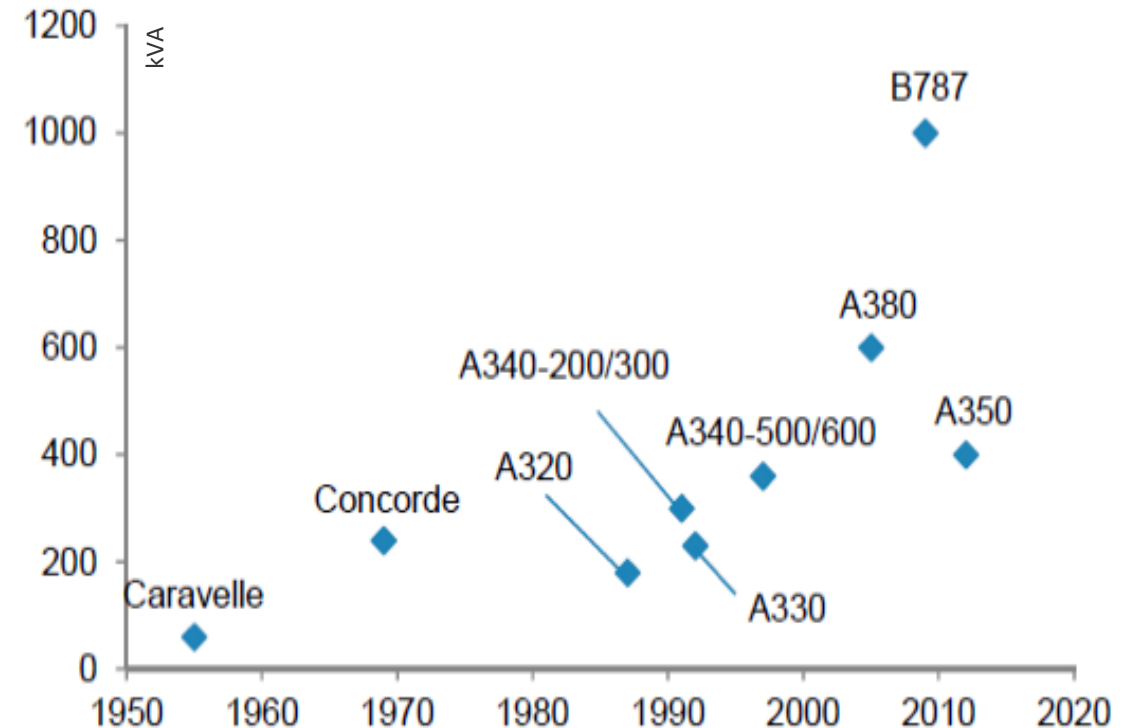
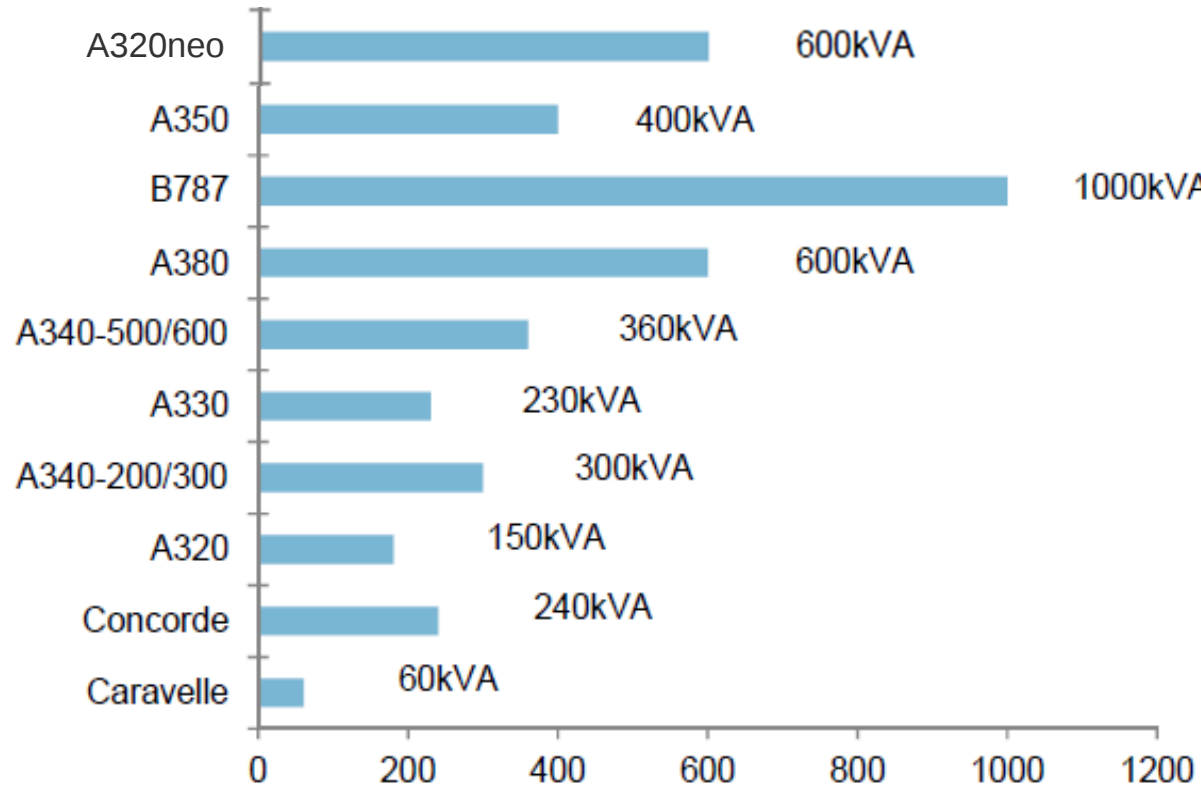
What is an « optimized » design?
3 examples of designs in detail : 12 pulse, disymmetric $\frac{1}{2}$ bridge, 2 bridges 180° phase shift
other examples

→ Conclusions

converter side
magnetic side

Intro 1 : Historical evolution of electrical power in civil aircrafts

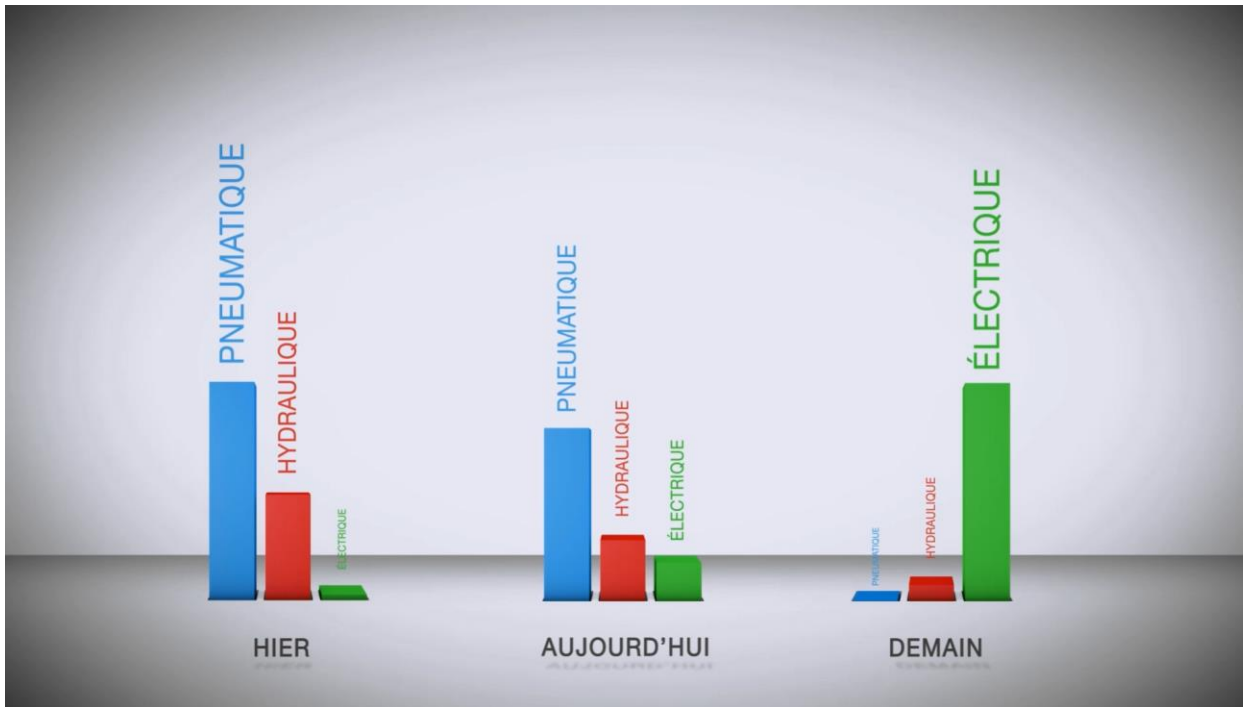
Intro 1 : Historical evolution of electrical power in civil aircrafts



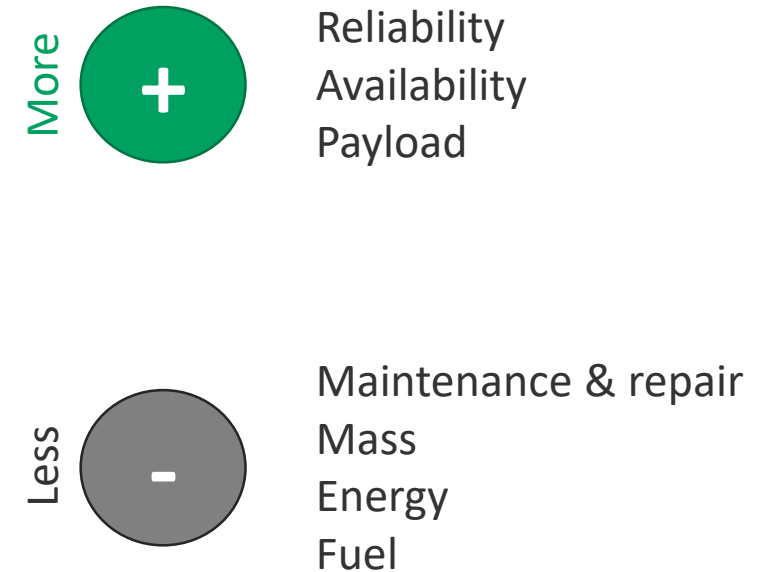
BOEING 787 is the most advanced electrical aircraft today

Intro 2 : Electrical power, how much and why

Distribution evolution : Pneumatics / Hydraulics / Electrics



Why « More Electrical » ?



Nowadays, on average, only 15% of energy in an aircraft is electrical --> **potential increase is huge!**

Intro 3 : More electrical aircraft? (1/2)

More electric aircraft. What does it mean?

- more electric functions and power ==> more equipments and converters
- ==> electrical network become more complicated

The weight cannot increase as much as the electrical power :

- ==> 1 : Power on volume/weight ratios have to increase
- ==> 2 : Equipements are used differently at different moments of the flight/mission :
(sharing of equipments)

Consequences for electric equipments (1/2) :

- Customer needs become more and more specifics
- More and more design constraints

Intro 4 : More electrical aircraft? (2/2)

Consequences for electrical equipments (2/2)

- converter efficiency has to increase (> 95% typical)
- functioning with innovative modes : new converter topologies
- increase of operating frequencies (also with SiC and GaN technologies)
- increase of operating temperatures : environment and internal heatings

Challenges to take for (magnetic) component designers :

Thermal : heating / warm up control,

Power Electronics : converter functioning understanding

Magnetism : better control of component drawbacks and limits
new design methods. Ex : leakage inductance

Magnetic component functioning is more and more connected with and dependent of Power Electronics



Converter designer side and point of view

Convert : Wide BandGap switches – hard-switching converters

- For the same die (puce) size, conduction losses and some of switching losses decrease significantly
=> possible gain on efficiency
- Opportunity to save volume/weight by increasing the switching frequency for equivalent losses
=> possible savings on the input filter
- Limits of this approach
 - 1 EMI common-mode emissions may increase, due to higher dv/dt applied
 - 2 Sensitivity of some WBG components to spikes due to the switching transients (e.g. gate spikes)
=> layout between Driver and Transistor is critical in this case
 - 3 Losses linked to the layout and to magnetic components drawbacks increase
 - 4 AC winding losses increase in magnetic components :
may be the biggest challenge
 - Knowledge + experience on **high frequency magnetic design** needed
 - Calculation/Simulation/Measurement of losses and **internal temperature** needed

Convert : Wide Bandgap switches – soft-switching topologies(1/2)

→ Main interests of the soft-switching topologies :

- 1 minimization of the switching losses
optimum if soft-switching for all primary and secondary devices
- 2 limitation of the dv/dt (for ZVS converters) :
 - Good for EMI (especially common-mode emissions)
 - Minimization of spikes due to the switching transients
- 3 Potential limitation of the di/dt (e.g. LLC converter)
=> rectifier recovery losses lowered

→ Limitations

- 1 Soft-switching conditions can limit indirectly the optimum working range of the converter
- 2 RMS currents often increase compared to hard-switching at the same operating point
- 3 Some of the soft-switching topologies need to be controlled using variable frequency

Convert : Wide Bandgap switches – soft-switching topologies (2/2)

The association of a WBG device in a soft-switching topology is an efficient way to increase significantly the switching frequency of the converter

- smaller gate charge + smaller parasitic capacitance (compared to Si MOSFETs) of WBG switches leads to :
 - 1 easier to fulfill soft-switching conditions (less circulating energy + dead times reduced)
 - 2 allows indirectly to widen the operating range of the converter
- BUT : Design of the magnetic components becomes critical :
 - 1 When conduction and switching losses of active components have been reduced significantly the main losses of the converter may be in its inductive elements
 - 2 Applied dv/dt and di/dt reduction due to soft-switching helps to limit the AC winding losses in the inductive elements ...
 - 3 ... but the switching frequency is higher than previously
- As for hard-switched topologies :
same need of **knowledge and experience in the design of high-frequency magnetics**

Convert : WideBand GaP, a new way to design power converters

WBG makes it possible to increase 10 times the switching frequency for the same losses with SiC/GaN.

→ Easy to implement on one specific operating point
with appropriate existing topologies (LLC, DAB, Forward active-clamp)

BUT

Most of industrial applications need to cover a wide range of operating points

(variables : input voltage, output power, frequency, etc)

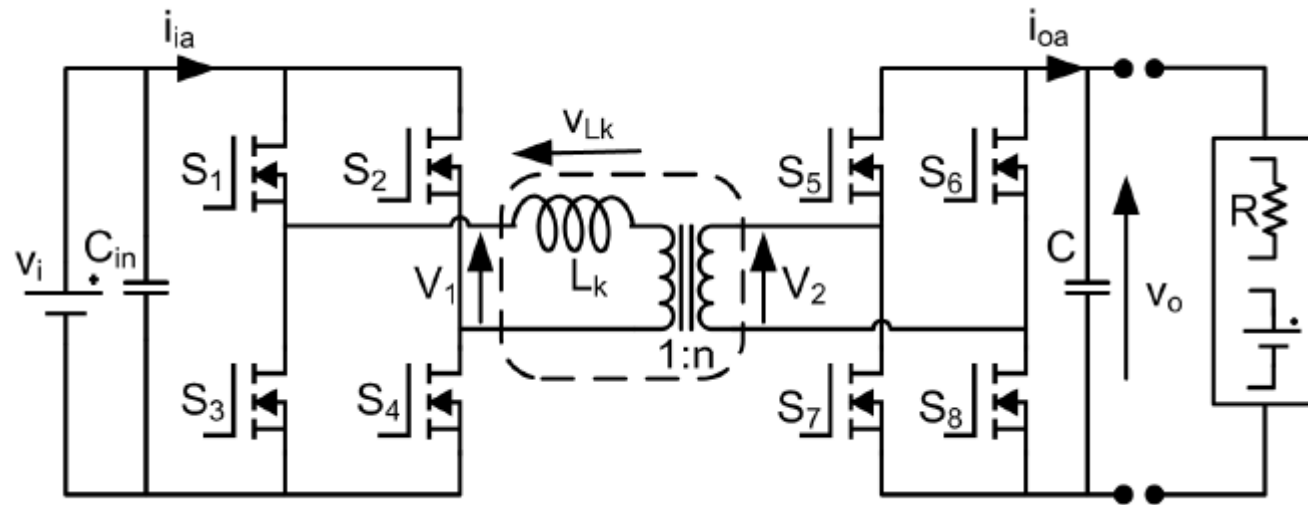
→ So the true challenge is :

How to keep soft switching over the whole operating range?

Convert : Transformer plays a key part, ReX on DAB converter

- In more and more isolated DC/DC topologies (DAB, PSB) , the problem :
« raising switching frequency + soft-switching (ZVS) over a wide range of operation points »

has a solution only with defining a complex transformer with many constraints



Typical requirements:

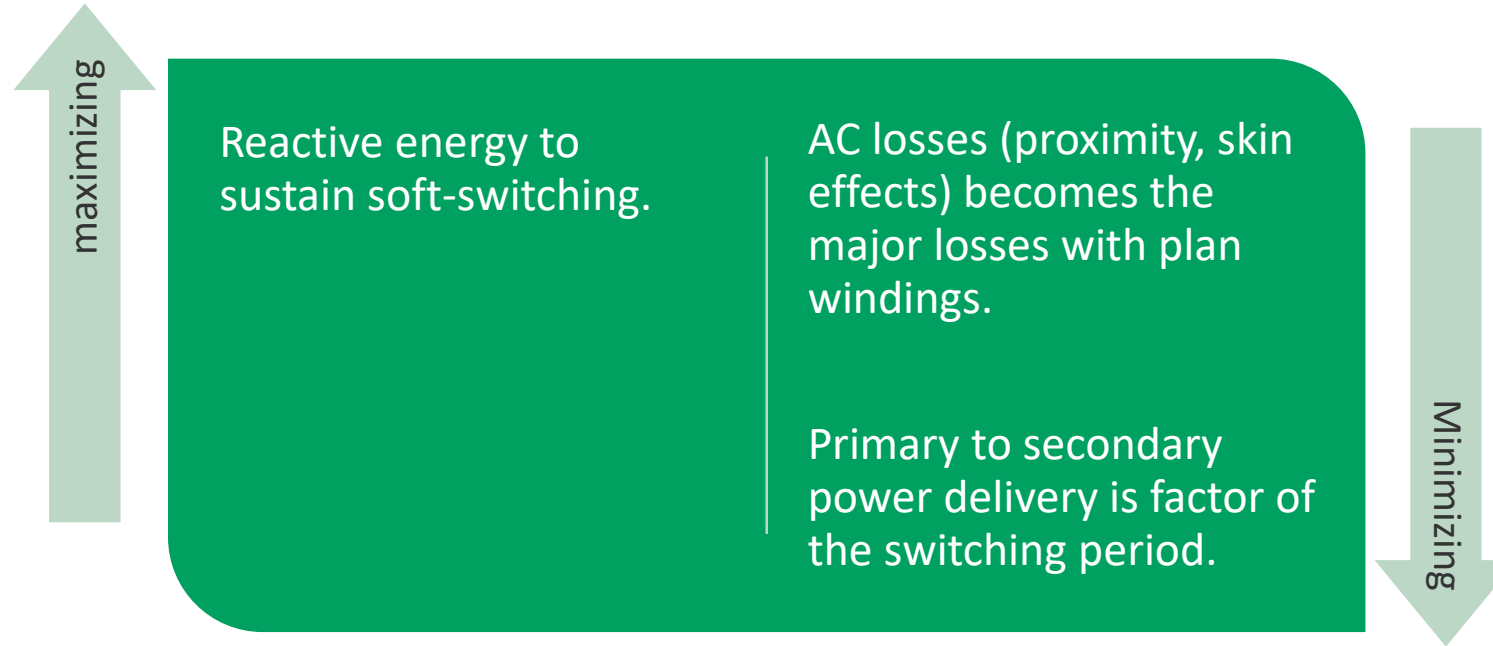
Power dynamic of [1 to 3]

Regulated output dynamic of [1 to 3]

At each operating point, the conditions to stay in soft-switching will lead to different constraints on transformer (L_k , C_p)

Convert : Design of leakage inductance is a key point

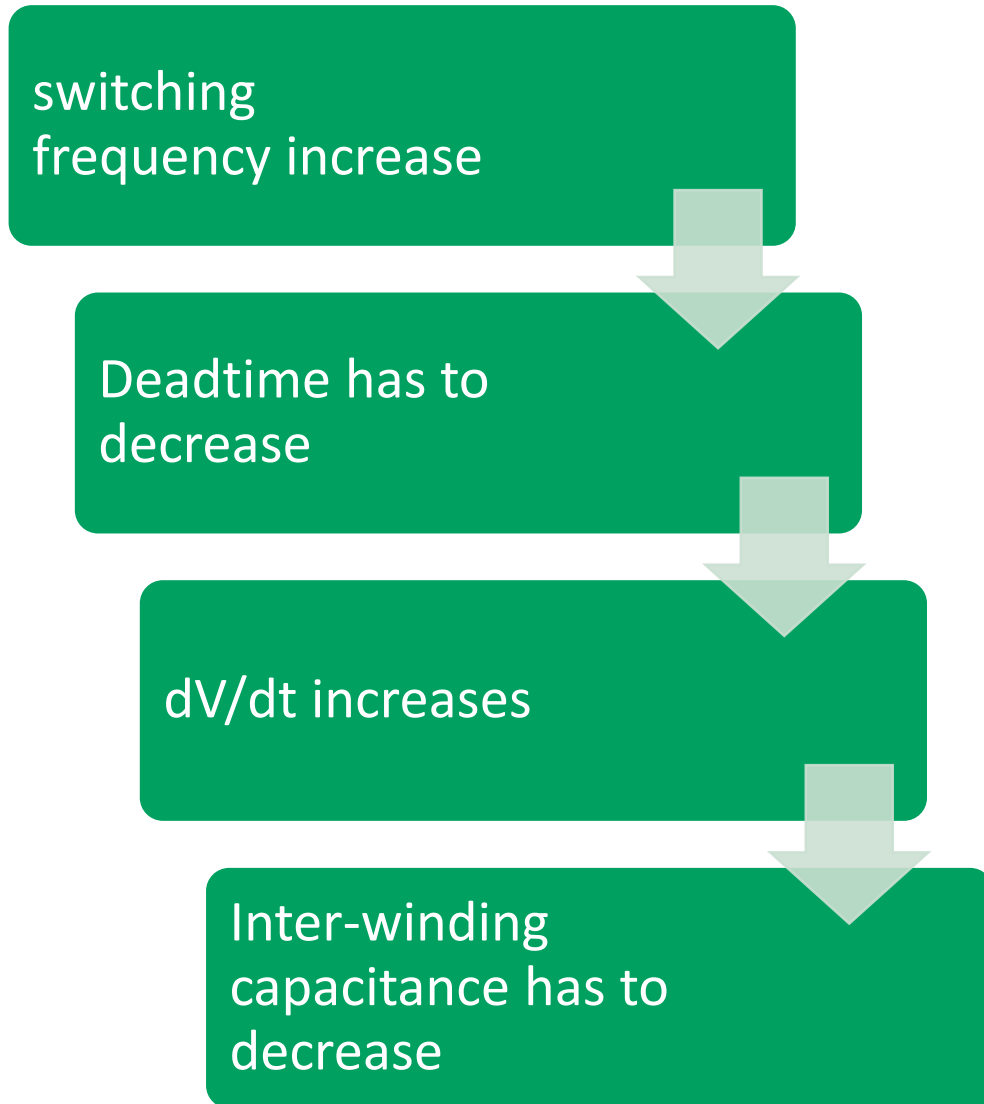
- Leakage inductance has to meet antagonist purposes:



**Leakage inductance value has to be more accurate by design
and its tolerance tighten : target < 5% (down to 2%?!)**

→ it leads to use multi layer PCB/sheet technology

Convert : The key role of inter-winding capacitance



- This capacitance decrease is not compliant with the minimization of AC losses with standard planar transformer interleaving technics.
- Capacitance can have an influence on dead time
- ➔ **Energy stored in the inter-windings capacitance has to be taken into account in the soft-switching!**

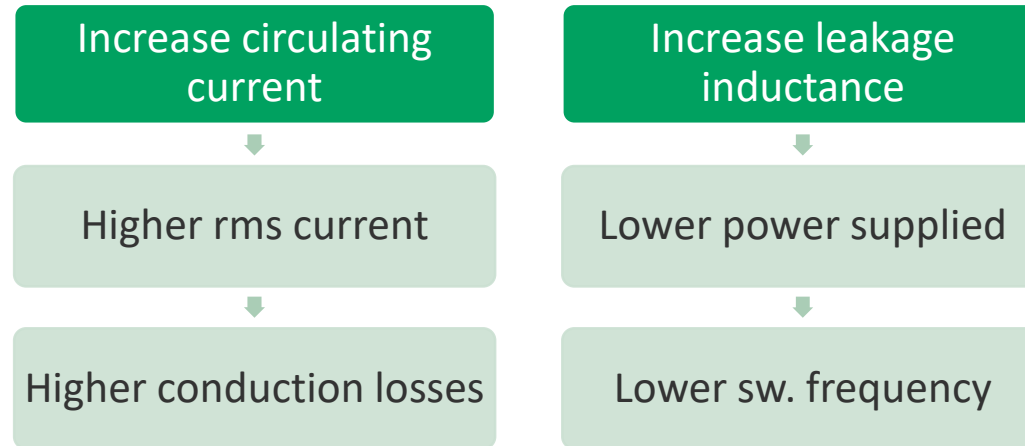
Convert : What about transformer turn ratio?

- Eddy currents & skin effect force to cut plan layer into a matrix of inter-connected thin tracks that lead to:
 1. Additional constraints on the PCB of the planar transformer that can't be met except with advanced PCB assembly technologies
 1. Number of vias increases and can't be ignored in the Finite Element modelling to get a correct evaluation of the leakage inductance.
 2. Window factor is less optimized for a given current density.
- Increase the number of tracks doesn't help to decrease the inter-winding capacitance.
- Therefore a good practical rule is :

**Soft switching at high frequency is only achievable
with low turn (ratio) for the transformer**

Convert : How wide voltage range give a headache!

- Sustain soft-switching for higher voltage means higher LI^2 to manage higher CV^2 .
- 2 paths are given :



- Possible mitigations:
 - Adapt the reactive energy and the switching frequency on each operating point
 - Use variable permeability material to shape leakage inductance

Consequences for the converter :

1 needs a non-linear parameter variant system : magnetic material of magnetics?

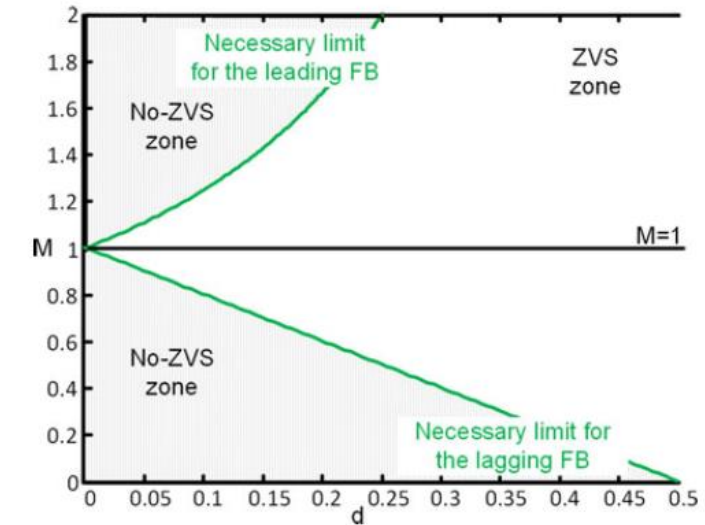
2 requires more robust control/command/regulation (pb of dynamic behaviour)

Convert : Move from one single variable to multi-variable control

- Most of popular topologies are driven with one single control variable:

Popular topologies	Control variable
Buck, boost, Flyback, forward, cuk, sepic...	Duty-cycle
LLC, LCL, TotemPole PFC	Frequency
PSB, DAB	Phase

(with usually fixed deadtime)



DAB soft-switching boudaries (M , d are normalized voltage and power)

**Multi-variable control is able to drive all these variables together
to extend the range of soft-switching.**

Convert : How digital control can decrease transformer constraints

- Multi-variable control is easily implementable in an FPGA or MCU:
 - One command variable to regulate output voltage
 - One command variable to perform soft-switching and minimize reactive energy.
 - Command on duty cycle to cancel DC current.
 - Switching Frequency to perform soft-switching and supply minimum power required.
 - Deadtime to perform soft-switching
- Management of trajectories between operating points to avoid magnetic saturation.
- Leakage inductance value is estimated with non-linear parameter observer.
- Digital robust controller can provide good stability margin of the closed-loop system with large parameter variations of the converter.

Trade-off for the transformer is extended to the control part

Convert : Transformer of the future for high frequency purpose

- Current density increased in the conductors thanks to innovative integration and layer cooling
- Magnetic material improved with variable « non-linear » permeability
- New geometries of cores to ease PCB constraints (exp : Matrix transformer)
- End of opposition between decreasing leakage inductance and parasitic capacitance
- Repeatability of drawbacks improved



Magnetic component designer side and point of view

Mag comp : What is an « optimised » design? (1/2)

Identify **the smallest size** (weight / volume) able to transfer power → trade-off between :

Too small → excessive internal heating	} Why? Because in aviation, 1g = 1€ → big security margins, IT'S OVER
Too big → too heavy and/or too large	

It is mandatory to be able to identify **configurations of use** which lead to the **highest constraints**
They **vary** from one converter to **the other** : I/Vmin/max? Pmin/max? Fmin/max? Tmin/max?
Is it possible to identify them without understanding how the converter functions? → **NO**

It is **mandatory** to know **wave forms I/V** inside the component

Could the magnetic designer *know* them without *calculating* them? → **VERY DIFFICULT**

Conclusion

Magnetic components designers have to understand (at least partially) how the converter works.
They must be able to calculate wave forms in all configuration of use

Power Electronics

Mag comp : What is an « optimised » design? (2/2)

Taking into account **3** types of **variations** :

1 : Excitation (I and/or V) 2 : Frequency 3 : Temperature

4 (+1) design criteria :

Saturation, copper losses, iron losses, heating ... **+ manufacturing** (raw materials and process)

Need of behaviour models reliable and accurate (!?) for :

Induction : nonlinearities, main and secondary hysteresis loop

Copper losses : DC resistances and Eddy currents

Iron losses : Are circuit/material manufacturer formulas sufficient?

Internal heating : - thermal model of magnetic component?
 - Rth variations depending on losses and environment temperature
 - taking account of cooling : conduction, convection, radiation

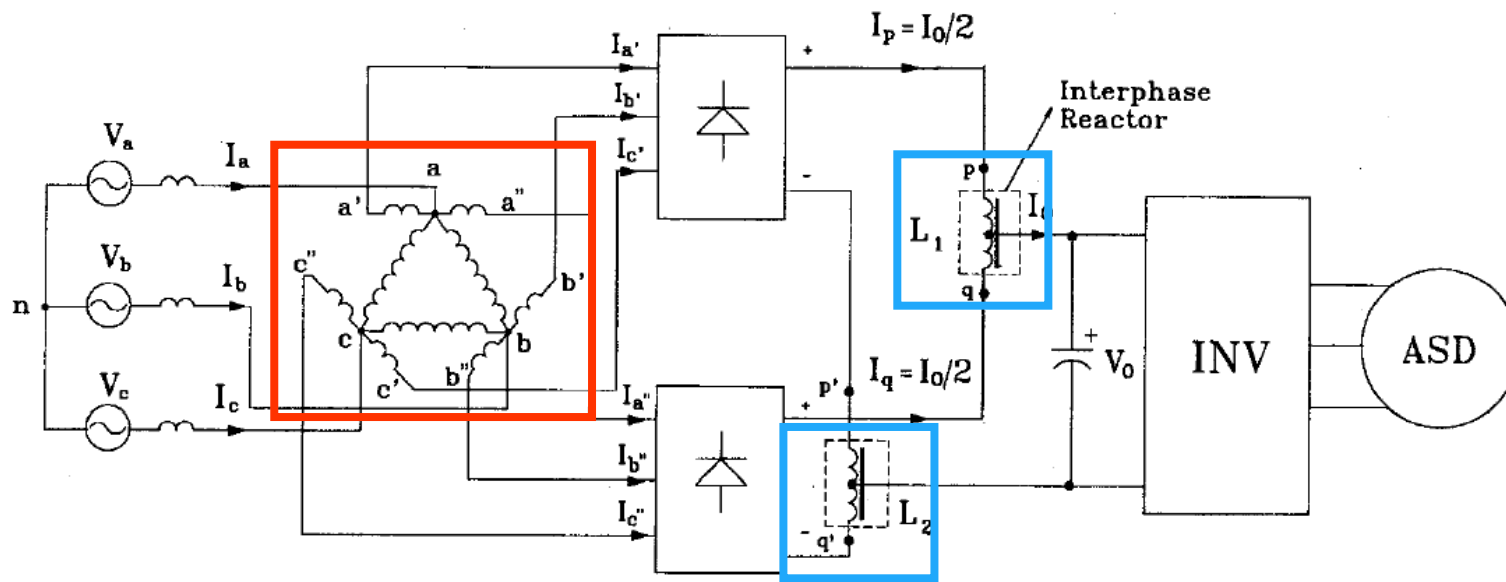
Challenge : to know limits of our (these) behaviour models!!

Electromagnetism + Thermics

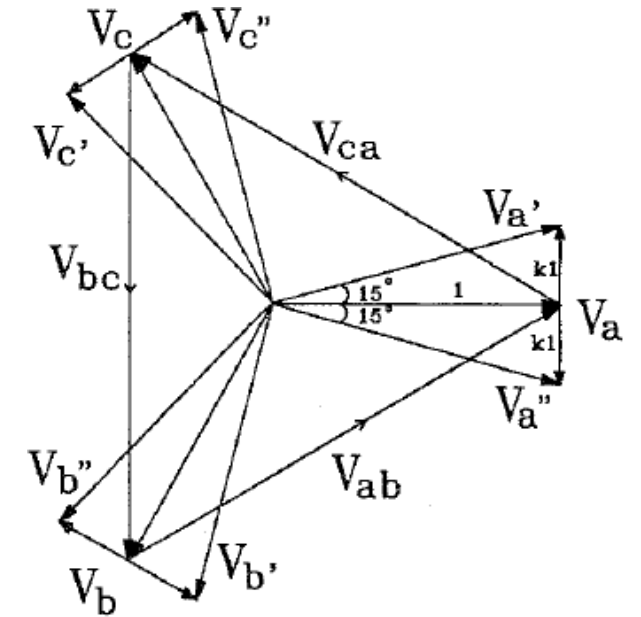
Mag comp Ex 1 : 12 pulse auto-transfo + interphase reactor (Safran)

Application : rectifier 115/230Vrms 3ph / 270/540Vdc low harmonics

3 stage converter : **auto transformer** + 12 diode bridge rectifiers + **2 interphase reactors**



schematics



operating principle :
To respect the vectorial diagram

hard to analyze and understand analytic calculations!

Mag comp Ex 1 : 12 pulse auto-transfo + interphase reactor (Safran)

4 steps to design the 2 magnetic components :

- Step 1 :
- understanding the scientific (IEEE) publications ...
 - ... including partial recalculations (to correct errors!)
 - understanding the 2 component functioning + all interactions between all components
for ex : unbalance current between interphase reactor coils
- Step 2 : derive a design method for the 2 components including the 4 (+1) aspects
- magnetic : define saturation level after excitation wave forms analysis
 - electrical to be able to evaluate copper and iron losses
 - thermal : which behaviour model?
 - mechanical after evaluating volume and weight (shocks, vibrations)
 - and industrial with raw materials and manufacturing process

Mag comp Ex 1 : 12 pulse auto-transfo + interphase reactor (Safran)

Step 3 : validation of the design method and the 2 designs

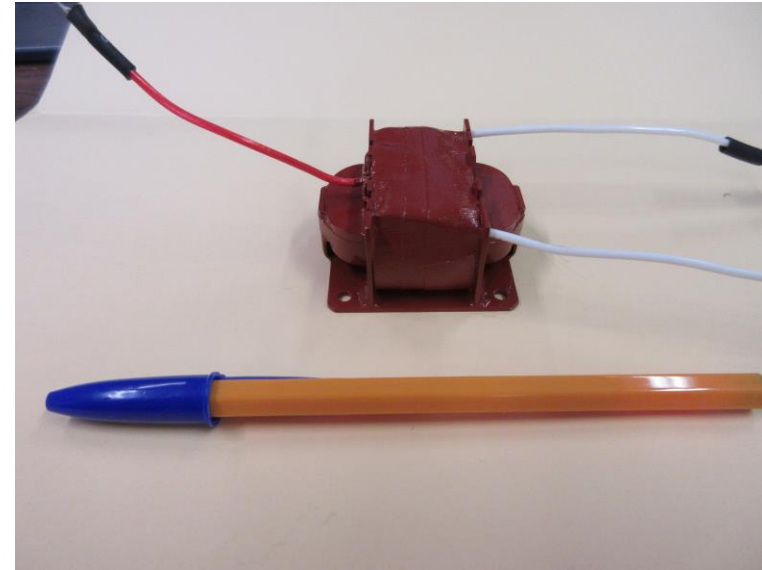
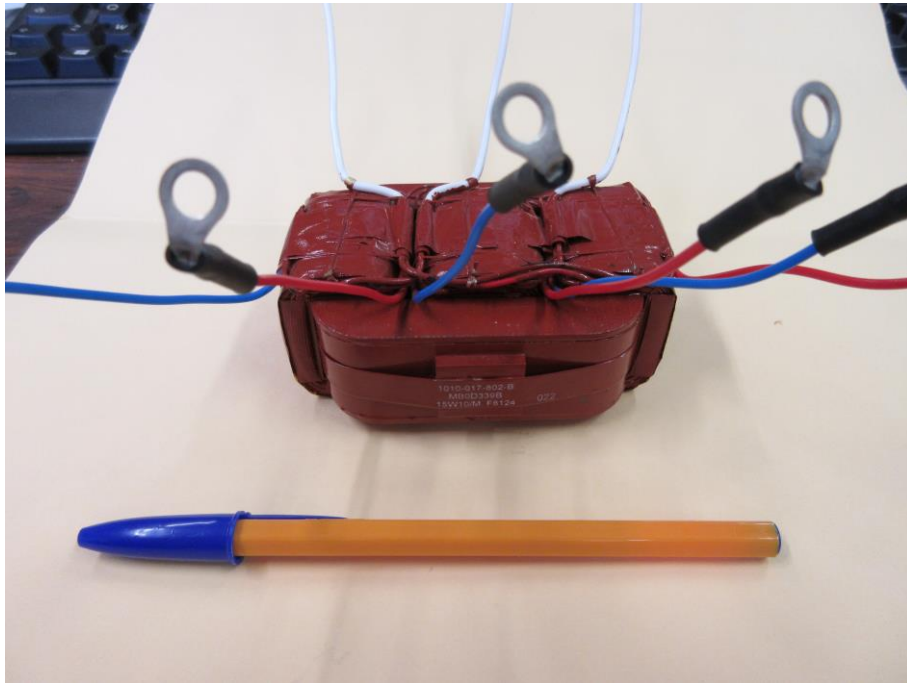
- manufacturing prototypes
- test measurements by Exxelia
- functional tests by customer

The 1st prototypes functionned correctly ... but

Step 4 : question : why the 4 harmonics are present?

(partial?) answer : because the vectorial diagram is not respected
the magnetics component drawbacks have a part of responsibility
which drawback(s)? How to modify the design to decrease the impact?
after analysis, a modified design was made for auto trfo
partially validated by customer simulations

Mag comp Ex 1 : 12 pulse auto-transfo + interphase reactor (Safran)



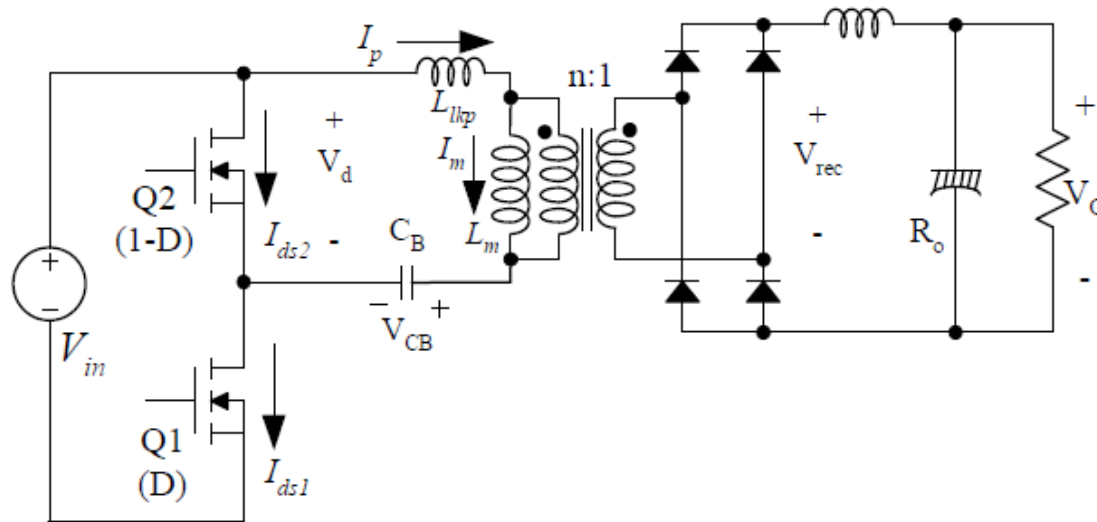
Conclusion : without understanding the whole equipment functioning, magnetic component designs were not optimized or **not even suitable**

Mag comp Ex 2 : disymmetric capacitor half bridge (Airbus)

Application : DC/DC converter 400/900V 150W 250kHz 12V

1 transformer + 1 output filtering choke

Topology developped by Fairchild 10 years ago



Advantages

(viewed from customer and Fairchild side) :

- few components
- simple to control
- low Mosfet constraints
- well adapted for ZVS mode
- small output filter

first step consists in analyzing and understanding Fairchild documents

Mag comp Ex 2 : disymmetric capacitor half bridge (Airbus)

After understanding the converter operation and creating a design software module, it leads to the conclusions below :

Key point 1 :- viewed from primary side, transformer works as a continuous Flyback

- mean current component depends on Duty Cycle, so input voltage V_e
- reasoning is identical for induction
- continuous B_{dc} component can be greater than ripple ΔB_{ac}
- the more important is V_e variation, bigger is the air-gap of the transformer

Key point 2 :- ZVS mode depends on leakage inductance value of transformer

- ZVS mode leads to a dead time for power transfer
- Dead time depends on L_k , F_s , D , V_e , N_2/N_1
- ➔ leak induc value must be neither too small nor too large and with small tolerance!

Mag comp Ex 2 : disymmetric capacitor half bridge (Airbus)

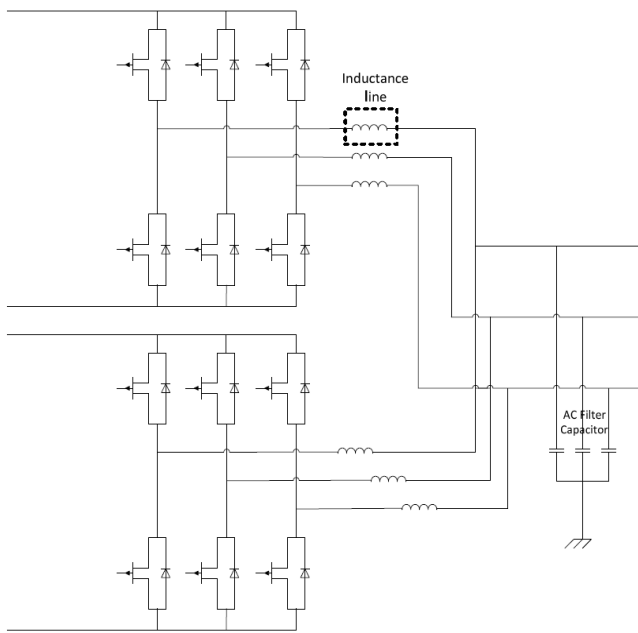


Conclusions :

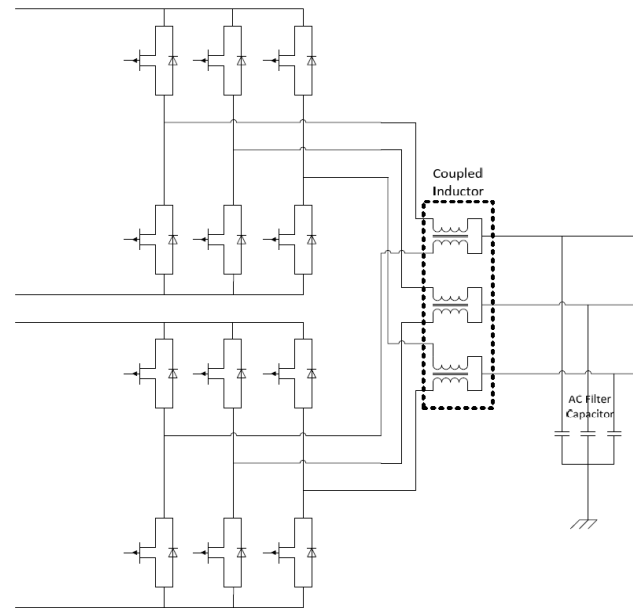
- 1 designing the transformer requires understanding **how does the converter work**
- 2 topology **shows** advantages, but transformer inside has got (big) drawbacks
- 3 big interest to exchange about advantages/drawbacks with customer partnership?

Mag comp Ex 3 : 2 full bridges / 180° phase shift / 3 phases (Safran)

Application : 3 phases 45kVA 20/40kHz 400Hz inverter



mode 1 :
6 separated chokes



mode 2 :
3 coupled chokes

Why 3 coupled inductors?

some parameters offset each other
=> volume and/or weight reduction

Questions :

- designing 1 (separated) choke → OK
- designing 2 coupled chokes →
How calculating accurately
leakage inductance?
- better thermal behaviour
with coupled chokes?

Mag comp Ex 3 : 2 full bridges / 180° phase shift / 3 phases (Safran)

How to calculate a leakage inductance with reasonable accuracy/tolerance?

With analytic calculations : - formulae exist in university books (J.P. Ferrieux / F. Forest, D. Sadarnac, G. Segulier)
- but with simplifying hypotheses : H field unidirectional
- most of time, coupling is low and/or H field is really bidirectional
- insufficient to reach the desired accuracy

With finite element simulations (Flux) : - most of time, need to use 3D simulations
- low coupling => formulation and meshing are tricky
- low coupling + air-gap(s) => be careful to definition of infinite boundaries
- leakage inductor + frequency + air-gap
=> magnetodynamics/harmonics with Eddy currents
- off set problem inherent in / related to finite element simulation
- extrapolation of results from one geometry to another difficult

Conclusion : designing a coupled choke is complex
requires a good level of knowledge of electromagnetism
thermal behaviour not better than simple inductor every time

Multicellular Parallel Converters

- coupled chokes 2 by 2 or all around the same magnetic circuit
- works with leakage inductances of coupled chokes
- average power distribution depends on choke impedances
- control/command/regulation complex and sensitive to coupled chokes drawbacks

Resonant converters :

- I/V waveforms (harmonics) inside components very variable
- strongest constraints can be at another frequency than that of resonance
 - => at a lower power level than nom/max power

X Active Bridges family :

- (1 of) advantages : multiple possibilities of control/command/regulation
 - example of aim : constant efficiency according to power or input voltage
- drawback : (magnetic) component wave form analysis (very) complicated

Conclusion from Converter side view

- GaN and SiC technologies allow to increase (a lot) switching frequencies and/or reduce inverter/rectifier cell losses
 - New topologies create new interactions between inverter/rectifier cells and magnetic component(s)
 - New digital technologies allow to do multi variable control/command/regulation
 - Main losses and challenges are now on magnetic components :
 - understanding interactions between component and its environment
 - magnetic drawback control
- Safran ① is aware of importance of magnetics to succeed in increasing converter switching frequencies and so ② wants to acquire a better knowledge of magnetics behavior and design**

Conclusion from Magnetic Component side view

The era of design with some simple rules of electromagnetism is :
over

Design compliant with future needs in aeronautics results from
a system approach

understanding magnetic component environment

taking into account multi-domain physical phenomena

need to communicate and interact with customers

=> relationship between supplier (sub contractor) / customer becomes **partnership**

It is neither more nor less than a cultural revolution

it has already started for several years – **our customers are ahead of us**

will we be able to take up this challenge in time?

Thank you for your attention
Questions?



Louis GRIMAUD – Bertrand LACOMBE

Responsable R&T – Expert Conversion • Safran

Louis.grimaud@safrangroup.com

bertrand.lacombe@safrangroup.com

Bruno COGITORE

Senior R&D Engineer • Exxelia Magnetics

Phone: +33 (0)4 76 35 05 92

Cell: +33 (0)6 99 36 16 47