DC/DC Fixed Frequency Resonant LLC Full-Bridge Converter with Series-Parallel Transformers for 10kW High Efficiency Aircraft Application

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I. INTRODUCTION

This research topic is rooted under the More Electric Aircraft umbrella (MEA) [1] [2] [3] which is the tendency in modern aircraft design to substitute mechanical, hydraulic and pneumatic systems by their electrical equivalents, in order to increase the overall efficiency of aircraft and reduce the manufacturing cost and reducing fuel consumption. The power demand from aircraft generators is increasing, and also the need for higher power converters, with a focus not only on efficiency but also on weight and volume. Aircraft generators usually supplies power in AC at variable frequency from 360Hz to 800Hz, but loads in the airplane require 28Vdc REF. Current aircraft rectifiers are based on passive solutions that are robust but also bulky and without regulation and active solutions are being developed in the MEA philosophy. These active systems are composed usually of three stages: EMI filter, AC/DC rectifier and isolated DC/DC converter. This paper is focused on the design of the isolated DC/DC converter for this application; this converter is providing galvanic isolation and also stepping down the voltage to 28V from the high voltage DC bus, output of the upstream rectifier.

Fig. 1. Active isolated rectifier system specification.

II. COMPARISON HIGH POWER ISOLATED DC-DC TOPOLOGIES

In the field of high power isolated DC-DC conversion, there is no question that the optimized topologies are always Full-Bridge based [4]. With increasing output power, magnetic component design complexity is also increased. A high frequency transformer is chosen to add the required isolation and typically is the most complex and bulky component of the entire system. To optimize volume and weight of the transformer and other magnetic component, the frequency is usually increased. However, high frequency increases the stress in the switching devices so a trade off has to be met for an optimal converter design.

High currents in the transformer create additional copper losses in the windings because of proximity effect [5] even when skin effect is reduced with the correct thickness of copper foil or Litz wires. Full-Bridge topologies take advantage of the full magnetization of the core and therefore lead to optimized transformer, both in volume and losses. Additionally, the symmetry of the bridges is helping the switching devices to achieve soft switching (ZVS) in a big range of input and output voltages with correct use of the transformer magnetizing current. Zero current switching (ZCS) is also possible with the use of discontinuous conduction mode (DCM) or with the use of a resonant tank.

Three isolated DC/DC topologies are analyzed for this application: Full-Bridge Phase-Shifted (FBPS) [6], Triangular current Full-Bridge (TFB), which is a DCM modulation of the Dual Active Bridge converter (DAB) [7] [8], and Series

Capacitor Resonant Full-Bridge (SCRFB), [9] which can also be a specific case of LLC converter with active full-bridges both at input and output [10].

A brief overview of the analyzed topologies follows:

A. Full-Bridge Phase-Shifted (FBPS)

The standard Full-Bridge Phase-shifted topology has been the choice for converters with more than 500W of output power [4]. By this merit, this topology is the starting point of the comparison, however the topology has some drawbacks when compared with more advanced full-bridge based topologies. The center tapped secondary of the transformer is more complex and has more volume than a regular transformer of the same characteristics. Also, secondary devices have twice the voltage stress so they have worst characteristics. A DC inductor is present in the secondary of this converter, transformer integration is not possible and the DC bias of the inductor causes design problems when increasing the output power.

Fig. 2. Full-Bridge Phase-Shifted (FBPS).

Fig. 3. Full-Bridge Phase-Shifted Transformer Current (FBPS).

B. Discontinuous conduction mode Full-bridge (DCM-FB)

This topology consists of two full-bridges in primary and secondary sides. The transformer has then only two windings and the primary inductor is in series with the leakage inductance, magnetic integration is thus achievable. The discontinuous conduction mode current operation was chosen in order to avoid as many hard switchings as possible. This topology has only two hard switchings in the high side primary devices per switching cycle. Secondary diodes can be substituted with transistors in order to increase efficiency. Then the converter is similar to the Dual Active Bridge (DAB) but this application does not require bidirectional operation so it will not be used.

Fig. 4. Discontinuous Conduction Mode Full-Bridge (DCM-FB).

Fig. 5. DCM-FB Transformer Current.

C. LLC Full-Bridge (LLC-FB)

The addition of a series capacitor to the last configuration converts the topology to an Full-Bridge based LLC resonant converter. This converter achieves soft switching in all transitions. Zero voltage switching (ZVS) is achieved naturally with the help of the magnetizing current. Zero current switching (ZCS) is also naturally achieved when working at 50% duty cycle, however as explained before, the magnetizing current is needed so the current is never really zero in the transitions, we call this soft switching quasi zero current switching (q-ZCS) [12]. However, typically the values for the magnetizing current needed for the ZVS are small in comparison with the nominal current. As in the previous converter, transistors can substitute diodes in the secondary bridge. In that case the converter is similar to the series resonant capacitor DAB (SRC-DAB) but the bi-directionality is not used in this application.

Fig. 6. LLC resonant Full-Bridge (LLC-FB).

Fig. 7. LLC-FB Transformer Current.

Fig. 8. Comparison of Power Losses

D. Power Losses Comparison

The comparison was made at different input voltages, representing the different topologies for the upstream AC/DC rectifier [11]. 700V represents Boost type rectifiers, 400V Buck type rectifiers and 500V is for passive multi-pulse rectifiers. In the final submission of this paper, advantages and disadvantages of the topologies are going to be analyzed in detail. The input voltage value is affecting the selection of the switching devices in primary, 650V devices and higher can be used for 400V input voltage; 800V devices can be used for 500V input and finally only 1200V devices can be used for 700V of input voltage. Low breakdown voltage devices have lower on resistance, however at lower input voltage the primary current has to be higher to achieve the same power.

It can be seen in figure 8 that the resonant topologies are around a point over the non-resonant topologies. The traditional full-bridge phase-shifted has the worst behavior with increasing switching frequency. In the case of the DCM-FB topologies, the best option is 700V of input voltage. This is because the higher currents at 400V are not only affecting the conduction losses but are also increasing the switching current value. In the case of the resonant topologies where the switching transitions are always soft the two input voltages have a similar value of efficiency. For the prototype the LLC resonant topology was chosen with an input of 400V. In the decision to chose 400V over 700V the issues of the AC/DC rectifier were more critical and are explained in [11].

III. FIXED FREQUENCY OPEN LOOP LLC RESONANT TOPOLOGY

The LLC-FB topology chosen for the application will work at a fixed normalized frequency of 1, meaning it will work at resonant frequency in open loop. The voltage gain M will have a value of 1 for all operating conditions. The converter will work as a DC/DC transformer in the first quadrant. The output voltage regulation can be then by the voltage loop of the AC/DC upstream in the system. This facilitates the design as the converter is going to work at fixed frequency and fixed duty cycle in open loop.

Fig. 9. Voltage Gain M at different Q_T factors

In this specific operating mode for the LLC, ZVS is achieved in primary devices with almost zero current, which is the magnetizing current of the transformer as the sinusoidal waveform reaches zero, we call this mode quasi-Zero Current Switching (q-ZCS). The ZVS condition is needed to avoid electromagnetic noise. A correct design of the magnetic inductance of the transformer has to be done to ensure the energy needed to achieve the ZVS transitions with the minimum amount of current and have optimal switching losses.

The output rectifier full-bridge can be implemented with diodes or with MOSFET for synchronous rectification. For this application, the active bridge is chosen to improve the efficiency. However, the bidirectional operation that the active bridge provides is not necessary, it is even discourage in aircraft system, to avoid propagating electrical issues upstream, towards the generator. In secondary side ZCS is occurring naturally with the anti-parallel diodes and ZVS is only possible with negative current in the transitions, this is not desirable because of magnetizing current dc bias balancing issues, this is explained further in another section.

IV. CRITICAL ISSUE: QUALITY FACTOR OF RESONANT TANK AND CONVERTER

The operation and design of the LLC converter is widely studied and known [8], the quality factor of the resonant converter is usually defined:

$$Q = \frac{1}{R_{Load}^*} \sqrt{\frac{L_r}{C_r}} \quad (1)$$

Where, L_r and C_r are the resonant tank inductance and capacitance, and R_{ac} is the reflected load resistance taking into account the full-bridge rectification.

$$R_{Load}^* = \frac{8}{\pi^2} \cdot n^2 R_{Load} \quad (2)$$

Where n is the turn's ratio and R_{Load} is the load resistance at the output of the converter, considering a full wave rectifier. This value of quality factor influences the voltage range for the regulation of the LLC. As it can be seen in figure 9, the effect of the quality factor is in the voltage gain. However, as this

Fig. 10. Resonant current at different Q_T factors, magnetizing current not included.

converter is working at normalized frequency 1 and in open loop, the voltage gain is always going to be 1 and thus this quality factor is not relevant to the design of this converter. Because of the high power nature of the application, the design of this converter is influenced by another quality factor. The series resonant tank quality factor is defined as follows:

$$Q_T = \frac{1}{R_{Tank}} \sqrt{\frac{L_r}{C_r}} \quad (3)$$

Where R_{Tank} is the resistance in series with the resonant tank, it includes the resistance of the transformer, resonant inductor and capacitor, but also the resistances of primary side and the secondary devices applying turn ratio squared n^2 .

$$R_{Tank} = R_{M1} + n^2 \cdot R_{M2} + R_{cap} + R_{ind} + R_{ac} \quad (4)$$

The effect of a bad resonant quality factor Q_T can be seen in figure 10. The resonant current is distorted with a Q_T lower than 1. This creates an undesired turn-off current that takes away the ZCS benefits of the resonance. The distortion is generated by the bad filtering of the resonant tank. This can be seen in figure 11, the harmonics of the square wave applied to the resonant tank are badly filtered if the quality factor Q_T is low. This resonant tank quality factor is not usually used in the literature, as it is not relevant in low power application. This quality factor can be increased with high values of inductance. However, low values are desirable in order to minimize the losses and volume of the magnetic component. Ideally, the

Fig. 11. Admittance at different Q_T factors

use of an inductor can be avoided by integrating it in the leakage of the transformer, which is also typically of low value in order to avoid undesirable high frequency effects, that increase losses. Typical achievable minimum values for the leakage inductance of transformers at this power level are in the range of $0.5\mu H$ to $10\mu H$. Typical values of R_{DSon} for primary MOSFET are in the range of $50m\Omega$ to $100m\Omega$ and for secondary MOSFET it can be from $1m\Omega$ to $10m\Omega$ which in primary side can be reflected to primary side with a range from $196m\Omega$ to 1.96Ω . The secondary side MOSFET's are more critical than the primary because of the high turns ratio. The total resistance of the tank R_{Tank} can be estimated to have a range from $125m\Omega$ to $750m\Omega$, accounting for transistors in parallel for a reasonable efficiency. These two ranges of R_{Tank} and L_r give a range of possible Q_T of 0.4 to 50.

V. SERIES-INPUT PARALLEL-OUTPUT SOLUTION

A variation on the LLC topology involving Series/Parallel connection of two transformer has recently appeared in the literature [15]. The variation consist in dividing the transformer into two transformer with half the power and turns ratio, which is giving the same conversion ratio if the connection is series in primary and parallel in secondary. However,

Fig. 12. Series/Parallel LLC resonant converter

Fig. 13. Effect of number of switching devices on turn-off current, total transistor power losses and Q_T at different resonant inductances

the connection in secondary is not made directly but after the rectifier bridge. This creates an additional output bridge. One of the advantages of the topology explained in previous research is high conversion efficiency, by the use of additional parallel devices for the output which is the high current side. Moreover, in this application, this topology gives the following benefits: Better turn's ratio, increase of secondary components, better height to width ratio, and better magnetic integration, and also creates the additional issue of the current sharing in each secondary output.

A. Turn's ratio

To achieve the same conversion ratio with the two Series/Parallel transformers, they need half the turn's ratio. For this application it means 7:1 instead of 14:1. This makes the interleaving of windings easier. Undesired high frequency effects are better mitigated with this lower turn's ratio. A better ratio of leakage inductance to AC resistance of the transformer can be achieved which leads to an improved Q_T factor.

B. Number of secondary devices

The parallel connection of the transformer is not made directly but after the secondary full-bridge. The bridges can be driven independently, making easier to have more transistors in parallel, divided in two bridges, the driving circuit can then be divided in two smaller driver with smaller driving leakage path [13]. As it can be seen in figure 13, the number of secondary devices is more critical to the total power losses than primary. So the series/parallel topology is allowing for

more devices in parallel, avoiding driving issues, improving Q_T and the efficiency. For the final prototype, a solution of $L_r = 8\mu H$ $N_1 = 2$ and $N_2 = 8$ (divided into two bridges) was chosen, in order not to have more than 4 devices driven by the same driver, which can be problematic.

C. Height to width ratio

A limiting factor in the design of airborne converters is not only the volume of the overall system but also the specific shape of the effective volume available. In the case of this application, the maximum height is 80mm. With the series/parallel transformers, a solution with the same volume but less height can be achieved.

$$R_{th} = \rho_{Eq} \cdot \frac{h_T}{2 \cdot A_T} \quad (5)$$

Where ρ_{Eq} is the equivalent thermal conductivity of the transformer as if it was made only of one equivalent material, with the mixed properties of ferrite, copper and paper isolation. h_T and A_T are the height and total vertical projection area. Designs with less height and more area will have better thermal resistance and thus better thermal dissipation.

D. Magnetic integration

Magnetic integration is a key factor in achieving an optimal power density. In the LLC topology, the transformer's leakage inductance can be used as the resonant inductor. However, it has to be estimated accurately in order to design the resonant tank frequency accordingly, there are some methods in the

Fig. 14. Transformer windings design

literature [14]. This avoids the use of an external inductance and minimizes the overall volume of the converter. However, designing a transformer with high leakage inductance has issues regarding high frequency effect in the windings that increase total losses in the component. That is why the value of resonant inductance and thus leakage inductance has to remain moderately low. As seen in the previous section, a low value of inductance is responsible for a low quality factor Q_T . With series/parallel transformer and the resonant tank in primary side, both values of leakage are added since they are in series in primary side. This allows for double the resonant inductance for the same amount of leakage inductance, as it is spread in two components. This allows for a better Q_T factor with less leakage in the transformers, which will lead to a better R_{AC} in the transformer increasing a second time Q_T . The series/parallel topology is then an adequate improvement on the regular topology regarding the Q_T issues.

E. Current Sharing

The main issue with the parallel output bridges is the current sharing between them. However, in this case, the current sharing is ensured by the series connection in primary side, having the same ampere-turn cancellation in each transformer because they have the same number of primary turns. Unbalance in currents will be given only by the difference in the resistance of each path. This difference can be limited if the design of the path are designed carefully. Also, the positive temperature coefficient for the copper resistance value is a natural equalizer for the current.

VI. DC MAGNETIZING CURRENT BIAS

Eliminating the magnetizing current dc bias is a typical issue in isolated DC/DC converters. In a series resonant converter like the LLC there is no bias because of the series capacitor which absorbs the DC component of the current. This is true for the primary side, where the series resonant tank is usually located for most LLC design [10]. In secondary side, these designs have diode rectifier, which has a negative feedback against DC bias of the current.

$$\Delta I_{bias} = -\frac{1}{L_m} \cdot \int_0^T V_{out}.dt \quad (6)$$

Fig. 15. Prototype

If the Volt-second balance condition is met, there is no DC bias in the magnetizing. With a diode bridge rectifier, where the current and voltage are always of the same sign, if there is a positive bias in the current the diode bridge forces more time for the positive pair of diodes to conduct and forces a magnetizing DC bias of the opposite sign, correcting it. For a sinusoidal resonant shape of current the equation for the DC bias is the following:

$$\Delta I_{bias} = -\frac{2 \cdot V_{out}}{L_m} \cdot \frac{\sin^{-1}\left(\frac{\Delta I_{bias}}{I_{reso}}\right)}{2 \cdot \pi \cdot f} \quad (7)$$

This equation only has solution for $\Delta I_{bias} = 0$.

In the case of synchronous rectification, the Volt-second balance is only met if the transistors are driven exactly the same amount of time to completely eliminate the DC bias. Additionally, if the turn-off current is negative, the voltage applied to the transformer and its current is no longer of the same sign, unlike in the diode rectifier case, so the volt-second balance is not met. In order to avoid that, the transistors need to switch off with additional dead-time to ensure that the turn-off transition is made with the parasitic diode and maintain the DC bias elimination effect of the diode bridge behavior.

In [16], the negative current in the turn-off transition is avoided for a different reason. The negative turn-off current creates a reflow of current to primary side in the transition which annuls the ZVS in primary. Therefore, because of volt-second balance and ZVS in primary, it is desirable to avoid the negative current turn-off and since the topology is not controlling and there is no current measurement in secondary side, which is the high current side, will be bulky and will decrease the power density. The negative current can be avoided adding additional dead-time, or decrease the effective duty cycle from the ideal 50% to 47%.

VII. PROTOTYPE

A prototype has been built to validate the proposed solution for this specific application. This was done in collaboration with the company Indra and with the supervision of Airbus. The prototype, shown in figure 15 consists of three main stages: the input board, the transformers and the output board.

TABLE I
PROTOTYPE COMPONENTS

Component	Reference	Quantity
Input Capacitors	B32656S2683J408	5
Primary Transistors	IPW65R037C6	8
Resonant Capacitors	C4532C0G2E473J320KA	6
Resonant Capacitors	C3225C0G2E103J160AA	3
Transformer Cores	E80/38/20 3C95	2
Secondary Transistors	IPP100N04S2L-03	32
Output Capacitors	B32774D4226J000	12

TABLE II
PROTOTYPE SPECIFICATIONS

L_r	C_r	R_{Tank}	Q_T	f_r	P_{out}	V_{in}	V_{out}
$8\mu H$	$312nF$	$255m\Omega$	20	$101kHz$	$10kW$	$405V$	$28V$

A. Input bridge

In the input board there is an additional space for external inductor and current transformer to measure current if needed, however it was not used and therefore the connections are short-circuited. This space can be optimized in the next version of the prototype. The primary transistors are connected to the heat-sink below.

B. Transformers

The transformers are also connected to the heat-sink with an aluminum piece that partially encloses the core to better dissipate the heat from the core losses. The connection of secondary windings is tight and therefore it is impossible to insert current probes rated for 200A for each transformer output. Both primary and secondary copper windings use square-shape Litz wire. Multiple layers of parallel wires are used to decrease the AC resistance as low as possible. The windings are also interleaved as much as possible as it can be seen in figure 14. The leakage inductance is used as the primary inductor in the topology and the square shape of the wires allows for the same positioning of the windings in the window. This allows the repeat-ability of the design in order to obtain the same value of leakage inductance in each transformer.

C. Output board

The output stage consists of two PCB, one with the output capacitors and the other with the secondary bridge transistors, they are stacked on top of each other with two vertical copper pieces connecting them that make the 28 Vdc bus, and handle the 360A output current. The bottom board is filled with the 36 secondary MOSFET and is metal core PCB with a bottom part entirely in aluminum to connect to the heat-sink and improve the power loss dissipation.

VIII. EXPERIMENTAL RESULTS

Experimental waveforms at 10kW of output power are shown in figure 16. The quality factor of the resonant tank is validated with the sinusoidal current waveform and therefore

Fig. 16. 10kW; magenta, resonant current, blue, primary bridge voltage, green: gate-source voltage primary transistor

Fig. 17. Close-up of switching transient, ZVS transition

q-ZCS is achieved in all transitions for primary devices. Additionally ZVS is also achieved with the magnetizing current of the transformer in all transitions, as it can be seen in the square voltage shape without spikes; this is achieved. In figure 17, a close-up of the transition can be seen; the voltage is charging smoothly from low value to high with the help of the magnetizing current. In figure 16, the current is the primary current of the transformer and it has negligible average value, ensured by the series capacitor in primary side. In secondary side, the current cannot be measured but the unbalance of currents can be detected with an unbalance in power losses in the transformer which can be measured by an differential temperature in each transformer. To achieve a magnetizing current with no bias in both secondaries, the transistors have to be switched on only when the current is positive, this is achieved increasing the dead-time in the switching transition.

Measured efficiency is 94% with 400V/28.7V and 26.5A/347.5A with 10kW of output power. These measurements are made taking into account the whole system, with input and output capacitors losses included and also driving circuits and control board losses. This efficiency is lower than the one estimated in figure 8 because these

additional losses were not taken into account. This efficiency however can be increase up to 95% improving the layout and improving the heat dissipation of the overall system, especially the transformers and drivers.

IX. CONCLUSIONS

A comparison among different topologies has been developed for a 10kW aircraft application. The best topology is the fixed frequency series resonant LLC converter with active full-bridges. The merit of this topology is achieving q-ZCS and ZVS in all transitions. To simplify the design and complexity, the frequency is fixed and the voltage is controlled by controlling the input voltage with the input AC/DC three phase rectifier, which is part of the overall system. However, some issues with the quality factor of the resonant tank can be mitigated with the use of two series/parallel transformers. This work proposes an implementation of this modification to the LLC topology to achieve high conversion efficiency and power density. The value of inductance must be the lowest possible to achieve the best power density, for this magnetic integration of the leakage inductance is a must. To maintain a high enough quality factor Q_T , the resistance in series with the tank has to be lowered by putting more transistors in parallel. A prototype has been built to validate the design at the specified requirements for this aircraft application. Experimental results are given at nominal power, 10kW with a measured efficiency of 94%. This number can be improved with better heat dissipation, specially in the transformers.

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