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Soft-Switching GaN-Based Isolated Power Conversion System for Small Satellites with Wide Input Voltage Range

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ABSTRACT

As we pursue the advancement of small satellites for space missions with more capabilities, there is a significant need for cutting-edge, modularly configurable, high density power converters. This article proposes a fixed switching frequency, high efficiency, compact isolated converter for sensitive loads such as radar, communication systems, or other instruments on small satellites.

INTRODUCTION

Generally, commonly used rad-hard isolated topologies such as the flyback and forward converter do not reach efficiencies above 90% due to hard switching losses and high parasitic losses of the rad-hard silicon FETs. Soft-switched converter topologies generally boast a very high efficiency while maintaining galvanic isolation made possible by taking advantage of the resonant interaction between inductor and capacitor components to obtain zero-voltage switching across all FETs [1]. Conventional soft switching resonant converters operate at highly variable switching frequencies that make designing filters for EMI/EMC more challenging, especially when the loads are sensitive to noise. Additionally, traditional resonant converters have limited gain, and therefore cannot regulate the output voltage for wide input voltage ranges, such as those experienced on an unregulated 28V spacecraft bus.

To address both of these challenges, this paper presents an initial comparative study and review of fixed switching frequency isolated converters and explores the advantages of a two-stage cascaded converter topology. Specifically, it studies several different candidate topologies for the first and second stages of the converter, including comparisons of orientation of fixed-frequency LLC and LCC converters and non-isolated boost and buck regulating converters. Evaluation of several different architectures based upon the input current ripple, inrush current control, efficiency, voltage stress, simplicity of control, transient response, and output voltage regulation, will be discussed, along with the final selected converter system. The converter control circuit that can be implemented using space qualified components and can support tight output voltage regulation (3%) for a wide input voltage range to support an unregulated spacecraft bus voltage of 22V to 36V. The system is designed to be rad hard, low cost and scalable to meet different missions' requirements. The whole system will be designed to achieve a bus to load power conversion efficiency of more than 95% across the whole load range of 5W to 100W, with future versions of the converter to support up to 1kW. Converter power density target of more than $2W/cm^3$ and specific power of more than 1kW/kg. The proposed converter is built with GaN switches for their superior performance in radiation, fast switching, and low losses.

RESONANT CONVERTER OPERATION

Resonant converters are generally not used in spacecraft applications due to the complexity of the designs and their limited operation range. Resonant converters take an input DC voltage and convert it to a very high frequency square wave signal using either a full-bridge or half-bridge switch network. The fundamental frequency of the AC square wave then excites a resonant tank consisting of inductive and capacitive components. When the AC voltage of the tank crosses the zero point, the switches can turn on/off with minimal switching power loss. The parasitic output capacitor of the FET needs to be completely drained before the switching can occur so it is desirable to operate in the inductive region of the resonant tank voltage gain curve where the current lags the voltage, draining this capacitor. This is called zero-voltage switching (ZVS) and is a highly efficient switching transition for FETs, reducing switching loss to almost zero. The switch network voltage is AC and is therefore very easy to incorporate a high frequency transformer in the converter to achieve galvanic isolation. On the secondary side of the transformer is a rectification network that converts the AC voltage back into DC. An output filter is added to smooth the voltage usually consisting of just a simple capacitor or LC filter.

Cascaded Topology

To address the wide input range of a typical spacecraft bus from 22V to 36V, a front-end converter is cascaded with the LLC converter in order to generate an intermediate bus voltage. A capacitor is used in between the two converters in order to provide bus voltage support between the two converters. The switching interactions between the resonant converter and the input converter create challenges when trying to regulate the output voltage due to the load dependence of the resonant converter and its slower output response [2].

RESONANT CONVTERTER TOPOLOGIES

There are several types of resonant converter topologies that all use slightly different resonant tanks. The two most common being the LCC and the LLC topologies shown in Figure 1 and Figure 3. Both of these topologies have a parallel circulating path for current to flow on the primary side for voltage regulation when operating at light loads. Either converter can be designed to buck or boost the output voltage based on the turns ratio of the transformer. The resonant tank's key parameters are the quality factor Q and the resonant component ratio m or A defined below in (1a-b) and (3a-b) for the LCC and LLC topologies, respectively.

LCC Topology

The LCC topology uses a capacitor for its parallel path and is better at regulating its output voltage when operating with a wide input voltage range, shown in, [3]. An LCC resonant tank's frequency response places its secondary resonant peak at a lower frequency than its highest resonant peak as seen in Figure 2. This makes operation in optimal range of the converter easy by staying above the secondary resonant peak to stay in the inductive region. The LCC topology however has higher RMS currents and therefore typically lower efficiency than the LLC topology, however it can still be useful when needs exist to regulate over a wide input voltage range. The voltage gain of the LCC topology is given by (2).

$$Q_{LCC} = 2\pi f_r \left(\frac{C_p}{1+A}\right) R_{ac} \tag{1a}$$

$$A = \frac{C_p}{C_r} \tag{1b}$$

$$R_{ac} = \frac{8\, N_p^2}{\pi^2\, N_s^2} R_{load}, \tag{1c}$$

$$f_r = \frac{1}{2\pi\sqrt{\frac{C_p+C_r}{C_p C_r L_r}}} \tag{1d}$$

$$\frac{V_{out}}{V_{in}} = \frac{\frac{4\,N_S}{\pi N_P}}{\sqrt{(1+A)^2\left(1-\left(\frac{f_S}{f_r}\right)^2\right)^2+\frac{1}{Q_{LCC}^2}\left(\frac{f_S}{f_r}-\frac{f_r A}{f_S(1+A)}\right)^2}} \tag{2}$$

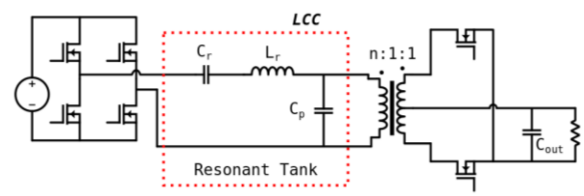

Figure 1: LCC Resonant Converter Topology

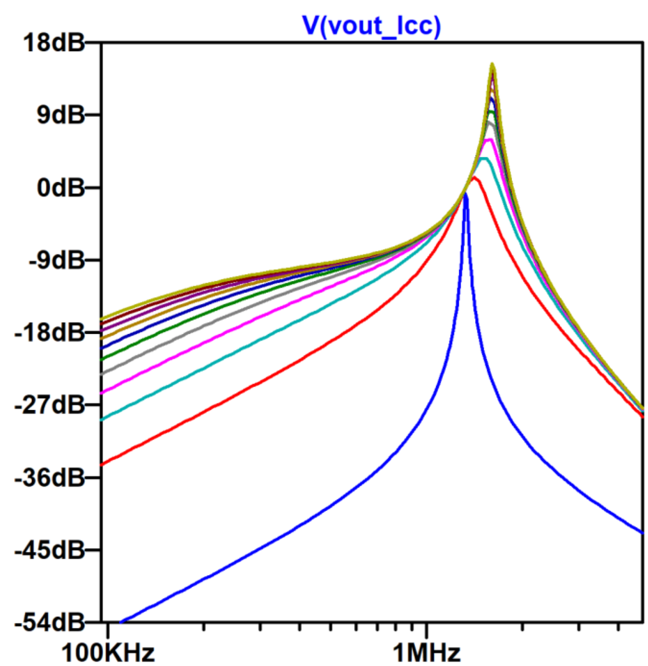

Figure 2: LCC Resonant Tank Gain Curve

LLC Topology

The LLC topology uses the magnetizing inductance of the transformer for its parallel path and has a wide ZVS range when operating at or above its resonant frequency point [4]. The transformer in the LLC converter can combine three passive elements into one with the resonant inductor, parallel path inductance, and the transformer itself being represented by the leakage

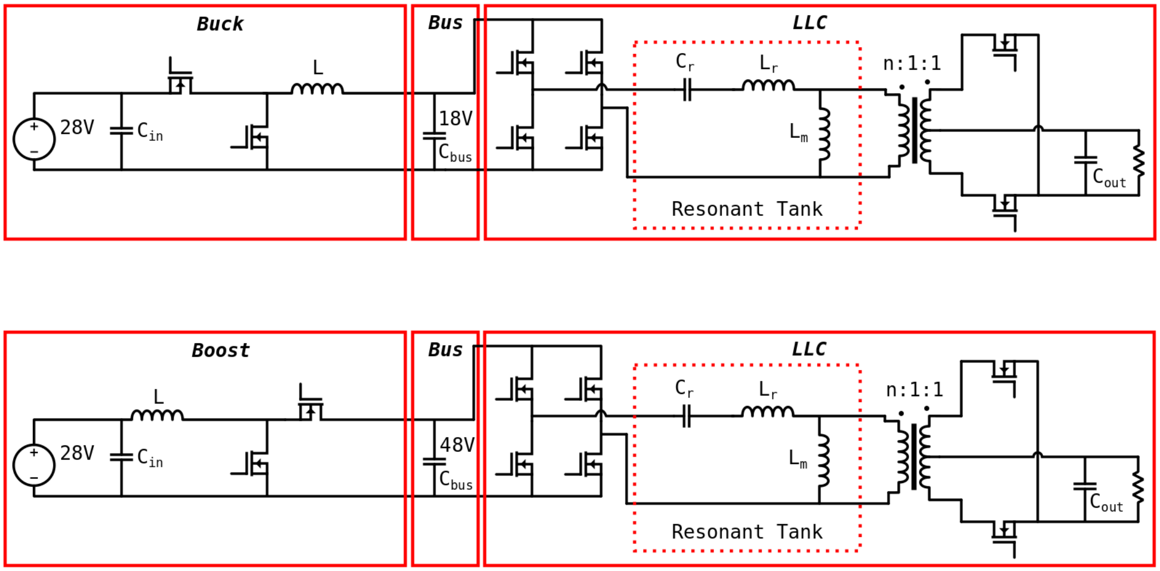

Figure 3: a) Cascaded Buck-LLC Configuration b) Cascaded Boost-LLC Configuration

inductance, magnetizing inductance and turns ratio of the transformer, respectively, as shown in Figure 3. An LLC resonant tank's frequency response places its secondary resonant peak at a higher frequency than its highest peak, thus the desirable frequency operation range of the converter is between the two resonant peaks as shown in Figure 4. The resonant tank of the converter on the primary side will either operate at unity or higher gain for zero voltage switching in the inductive region of the gain curve. The voltage gain equation of the LLC is given below in (4), [5].

$$Q_{LLC} = \frac{\sqrt{\frac{L_r}{C_r}}}{R_{ac}} \tag{3a}$$

$$m = \frac{L_r + L_m}{L_r} \tag{3b}$$

$$R_{ac} = \frac{8\, N_p^2}{\pi^2\, N_s^2} R_{load} \tag{3c}$$

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{3d}$$

$$\frac{V_{out}}{V_{in}} = \frac{\frac{4 N_s}{\pi N_p}\left(\frac{f_S}{f_r}\right)^2 (m-1)}{\sqrt{\left(m*\left(\frac{f_S}{f_r}\right)^2 - 1\right)^2 + \left(\frac{f_S}{f_r}\right)^2 \left(\left(\frac{f_S}{f_r}\right)^2 - 1\right)^2 * (m-1)^2 * Q_{LLC}^2}} \tag{4}$$

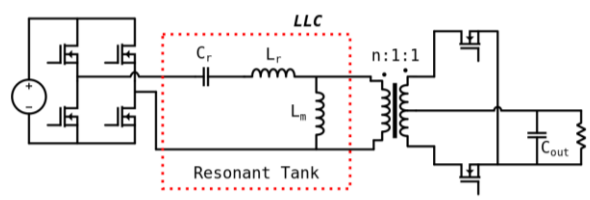

Figure 3: LLC Resonant Converter Topology

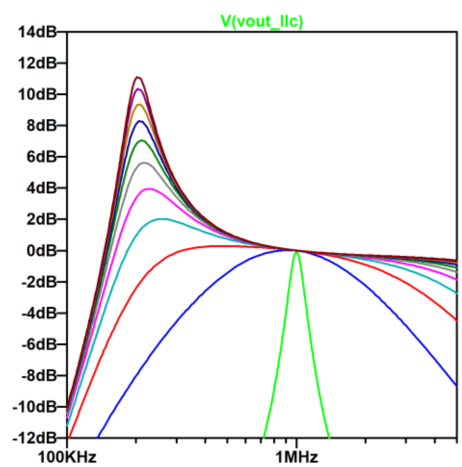

Figure 4: LLC Resonant Tank Gain Curve

For the converter proposed in this paper the LLC topology is used to achieve the highest possible efficiency with minimal additional components combined with a front-end cascaded converter for both input and bus voltage regulation.

Due to the non-ideal nature of components in the converter, the gain of the LLC converter is slightly below unity at the designed resonant frequency leading to an iterative tuning process. For a stable output voltage regulation at the resonant frequency the turns ratio of the transformer is increased accordingly to allow for sufficient bus voltage variation feeding the resonant tank and regulating to the correct output voltage.

INPUT CASCADED CONVERTER

In order to regulate the input voltage going into the resonant converter, a front-end cascaded converter is used to generate an intermediate bus voltage that is then varied accordingly to set the desired output voltage. For simple rad-hardened solutions, currently available controllers are being explored with more advanced control solutions being looked at in the future [6].

Buck Converter

A buck converter at the front end of the LLC converter can convert the 22V to 36V bus voltage down to a range of 12V to 18V, with a nominal voltage of 16V as shown in Figure 3a. The duty cycle variation for a Buck converter ranges between $0.3<D<0.8$ for the specified range of input voltages and bus voltages. The lower input voltage on the LLC converter makes for lower voltage stresses on the switches and capacitors with a 1:3 turns ratio on the transformer. Buck converters intermittently draw current from the input source which can be a loss of efficiency in the overall system especially when used with solar panels and other constant current sources. The output current of a buck converter is very smooth which provides a good input for the resonant converter by having a low ripple input current and voltage. Several radiation-hardened controllers exist for buck converters that are capable of being modified to drive GaN HEMTs.

Boost Converter

A boost converter at the front end of the LLC converter can generate a bus voltage of 46V to 50V, with a nominal voltage of 48V as shown in Figure 3b. The duty cycle variation for the boost converter ranges between $0.2<D<0.6$ for the specified range of input voltages and bus voltages. This allows for the usage of standard 100V rated capacitors and switches de-rated to 50%. A higher input voltage to the LLC converter decreases the current on the primary side at higher loads when using a 5:1 step down transformer, when compared to a lower input voltage. The boost converter has the added benefit of drawing a continuous current from its input voltage source which can provide better efficiency at a system level. Radiation-hardened PWM controllers are available that can be used in a boost configuration.

CONVERTER DESIGN

The input converter and resonant tank converter were designed to operate together in order to achieve the highest end to end efficiency using available rad-hard parts over a wide temperature range with the full specifications shown in Table 1. The two versions of the converter were designed and simulated using a buck and boost front end with an input voltage of 22V to 36V and an output voltage of 12V at 100W output power with a target efficiency of 95%. The maximum temperature range was selected at -55°C to 125°C with a TID of 100krad.

Table 1: Converter Specifications

Specification	Buck-LLC	Boost-LLC
Input Voltage	22V-36V	22V-36V
Output Voltage	12V	12V
Front End Converter Switching Frequency	900kHz	900kHz
LLC Resonant Frequency	1MHz	1MHz
Output Power	100W	100W
Temperature	-55°C to 125°C	-55°C to 125°C
Radiation	100krad	100krad
Nominal Bus Voltage	18V	48V

Switch Selection

All switches used in the converter were GaN Systems GS61008T HEMTs. GaN HEMTs have shown to have extremely high radiation and temperature tolerances while maintaining very low on resistance and high switching frequency. GaN HEMTs do not have a reverse body diode and therefore there is no reverse recovery loss. However, when operating in a resonant switch network the usage of the body diode can allow for a reverse current path when the LC network is commutating which is important for half-bridge switch network designs. GS61008T HEMTs do not have a body diode but do allow for reverse conduction, effectively operating as a body diode [7, 8].

Passive Selection

Two capacitors are placed in parallel to meet the correct resonant capacitive amount while maintaining full load current full load RMS current and up to 100V operation. The resonant capacitors are under high stress due to the relatively high Q factor of the LLC converter operating at high frequencies. Resonant inductors are shielded to reduce EMI and to have sufficient RMS and DC current ratings de-rated by 50%.

Table 2: Converter Components

Component	Buck-LLC	Boost-LLC
Cbus (100V, X7R)	50µF	50µF
Cout (100V, X7R)	100µF	100µF
Cr (100V, X7R)	2.5µF	2.76µF
Lr	10.2nH	9.1673nH
Lm	488nH	440nH
Turns ratio 1:n	3	0.2
Cin (100V, X7R)	20µF	20µF
L	0.47µF	0.47µF
Switches	GS61008T	GS61008T

The LLC resonant tank was designed with a Q of 0.05 and a K of 48 for a boost input and a *Q* of 0.05 and *m* of 48 for a buck input with resonant values shown in Table 2. This combination of Q and K provides high efficiency over the entire load range while achieving sufficient voltage regulation. The turns ratio of the transformer was selected to enable consistent voltage regulation while resonant values change temperature.

SIMULATION AND OPERATION

Both the Buck-LLC and Boost-LLC were simulated using LTSpice to confirm operation. Frequency sweeps of the LLC resonant tank were performed in order to ensure the switching frequency applied to the resonant tank using non-ideal parameter values for each of the components. The switching frequency of the LLC converter is set to operate at the resonant frequency, with slight variations in switching frequency to maintain output regulation of 12V with different loads and primary output voltage regulation being performed by the input converter by changing the bus voltage.

Output Voltage Regulation

Output voltage of the LLC converter is smooth at full load with a ripple voltage of 108mV or 0.9%. An intermediate bus voltage ripple of 400mV for the boost converter and 200mV for the buck converter is seen at full load as shown in Figure 5.

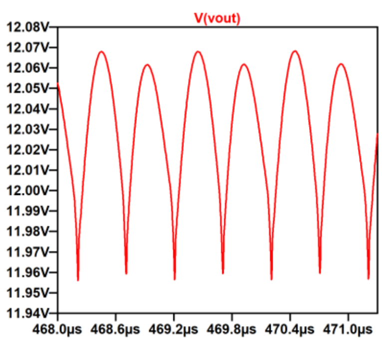

Figure 5: Output Voltage Regulation

Startup Transient

The unregulated LLC converter has a slow output voltage ramp up that follows the bus voltage of the front end converter, eliminating turn on overshoot transients as shown in Figure 6. The soft-start time of the input converter can be adjusted using the startup capacitor.

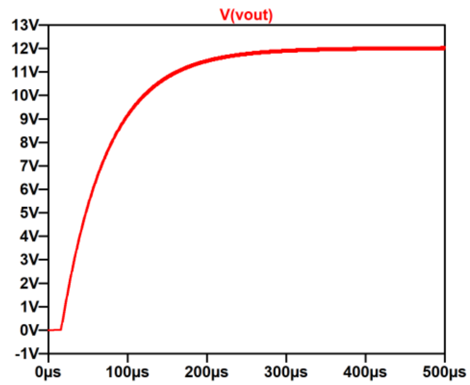

Figure 6: Startup Transient Response

Efficiency

The simulated efficiency of the converter ranged from 75% at light load to 94% at full load efficiency with a peak of 95% efficiency. Greater than 90% efficiency was achieved at 15% full load and above as shown in Figure 7.

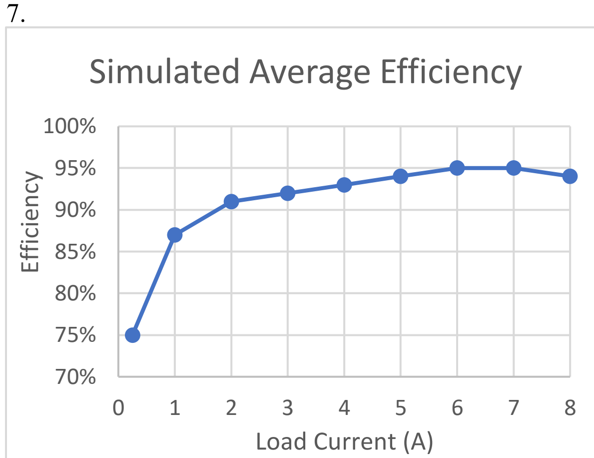

Figure 7: Simulated Average Efficiency

CONCLUSION

The development and initial design of an isolated, high-efficiency, rad-hard isolated converter utilizing a cascaded buck or boost converter and resonant LLC converter was presented. The developed architecture provides a framework to expand to higher power levels with a variety of available output voltages in order to meet mission requirements.

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