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High Voltage, Wireless Power Transfer based DC Power Supply

Suraj Jagannath Manur[1], Reza Mirzadarani[1], and Mohamad Ghaffarian Niasar[1]

[1] High Voltage Technologies, TU Delft, Netherlands

***Abstract*-- This paper discusses the prototype development and testing of a load invariant, high voltage gain DC power supply using inductive power transfer. The developed supply is intended to power the submodules of the CHB based arbitrary waveshape generator for testing high voltage components and materials. Using the Series Parallel topology, a load invariant voltage gain of 15 is obtained from a 350 V input DC Bus, with an efficiency of 88% and a load regulation of 18%. The obtained 5 kV output can conduct DC breakdown of dielectrics with a damping resistor and can test insulation aging, breakdown under high frequency AC.**

***Index Terms* — Load Invariant Voltage, Power Supply, Series-Parallel, Wireless Power Transfer**

I. Introduction

Distributed generation using grid connected power converters brings new and unique propositions involving testing of high voltage components with unconventional waveforms. The High Voltage Technologies Lab at TU Delft is developing an Arbitrary Waveshape Generator (AWG) for this application [1]. A suitable topology shortlisted for the AWG is the Cascaded H Bridge (CHB) as shown in Fig.1.

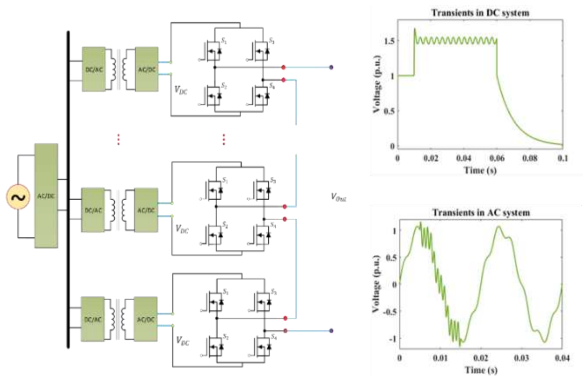

Fig.1: Cascaded H Bridge (CHB) based AWG.

Each stage of CHB requires isolated transformer-based DC voltage sources. Having a magnetic core complicates the insulation design of such transformers. Isolated high voltage power supplies such as the spellman supply [2] are bulky, heavy and cannot provide floating voltages necessary for the CHB based AWG.

Inductive power transfer (IPT) provides a suitable solution to the above conundrum. With air as an insulation medium an isolated, floating DC power supply can be developed. The developed supply is also capable of testing dielectrics for DC breakdown as well as breakdown and aging tests under high frequencies. The key requirements for such a system are Load Invariant Voltage, High Voltage Gain and Soft switching of the switches in the inverter.

II. Topology Overview

A. One component compensation

One component compensation topologies involve single capacitors connected in series or parallel on the primary and secondary sides to compensate the leakage inductance introduced by the air cored transformers. Primary parallel compensation is not preferred due to the requirement of a current source input. The series-series topology is commonly used in EV applications [3]; however, a constant current (CC) charging profile which fits the load independent current output required for battery charging, makes it less suitable for the intended application aimed in this paper.

Alternatively, series-parallel topologies provides a constant voltage (CV) profile which are used in biomedical applications such as powering artificial hearts [4]. For the application discussed in this paper, a Series Parallel (S-P) topology is suitable as it provides load invariant voltage with high voltage gain as shown in (1), where k is the coupling coefficient between the coils. Moreover, the S-P topology also provides soft switching with zero voltage switching for the MOSFETs of the inverter [5].

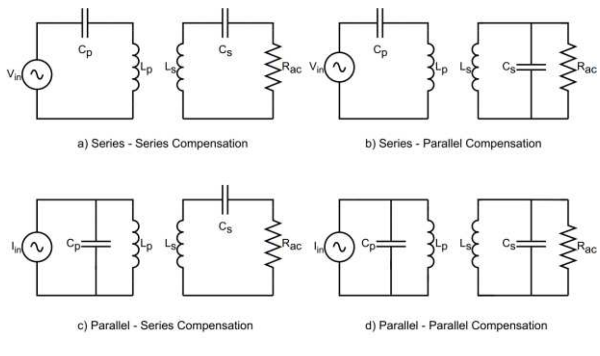

Fig. 2: First order compensation topologies

$$G_{vs-p} = \frac{1}{k}\sqrt{\frac{L_s}{L_p}} = \frac{n}{k} \qquad (1)$$

$$G_{vs-s} = \sqrt{\frac{L_s}{L_p}} = n \qquad (2)$$

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The load invariant voltage gains indicated above are obtained by eliminating the load component in the gain equation as seen in [6] . This leads to a non-zero phase angle with gain limited to turns ratio for series-series while for series-parallel a zero phase angle with an enhanced gain is observed. Additionally, higher efficiencies are seen in load invariant voltage condition for series-parallel topology vis-à-vis the series-series topology.

B. *Multi component compensation*

A fixed, stationary unidirectional inductive power transfer system is desired as the power supply for the AWG. Multi component compensation topologies, such as the LCC topology are advantageous in dynamic coupling and bidirectional situations [7]. Therefore, these topologies are not suitable for a power supply application. Multi component topologies also involve multiple components on the secondary high voltage side which is undesirable. Table I provides samples of the appropriate type sizes and styles to use.

TABLE I
PARAMETERS OF THE S-P POWER SUPPLY

Parameter	**Unit**	**Value**
Primary inductance	uH	13
Secondary inductance	uH	125
Coupling coefficient	-	0.21
Distance between coils	mm	65
Switching frequency	kHz	320
Primary capacitance	nF	19
Secondary capacitance	nF	1.9
Filter capacitance	nF	3.3
Rated load	kΩ	18
Rated power	kW	1.5
Deadtime	nS	100

III. SETUP AND RESULTS

The S-P topology as highlighted in Fig. 3 and Fig. 4, is used to create a 5.2 kV DC or AC output respectively from a 350 V DC Bus input. The parameters of the developed resonant converter are mentioned in Table I. Voltage gain of around 15 is observed with a turns ratio of 3 and coupling coefficient of 0.21. The primary (1^0) capacitance is a polystyrene decade box while the secondary (2^0) capacitance are made with several polypropylene film capacitors connected in series and parallel to obtain the resonant capacitance value. The coupling coils are constructed using the litz wire with 2.7 mm diameter containing 400 strands of 0.1 mm diameter. The strands are grouped into 4 bundles with 4 sub bundles consisting of 25 strands each.

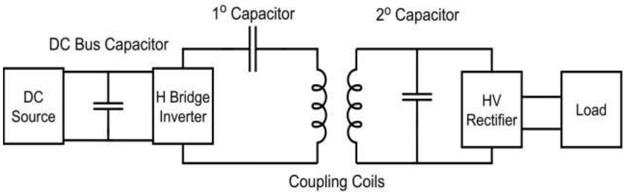

Fig. 3: Circuit Diagram of Power Supply

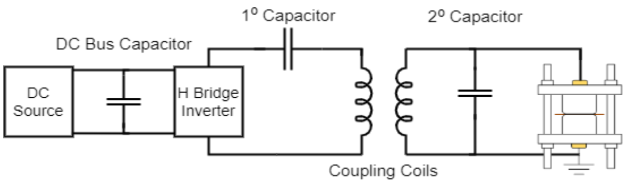

Fig. 4: High Frequency AC test of insulation materials

A. *Test Setup*

The test setup is shown in Fig. 5. The SM 1500-CP-30 power supply is the DC source providing input to the full bridge inverter. The switching device used for the H-Bridge is the GeneSiC G3R450MT17J capable of

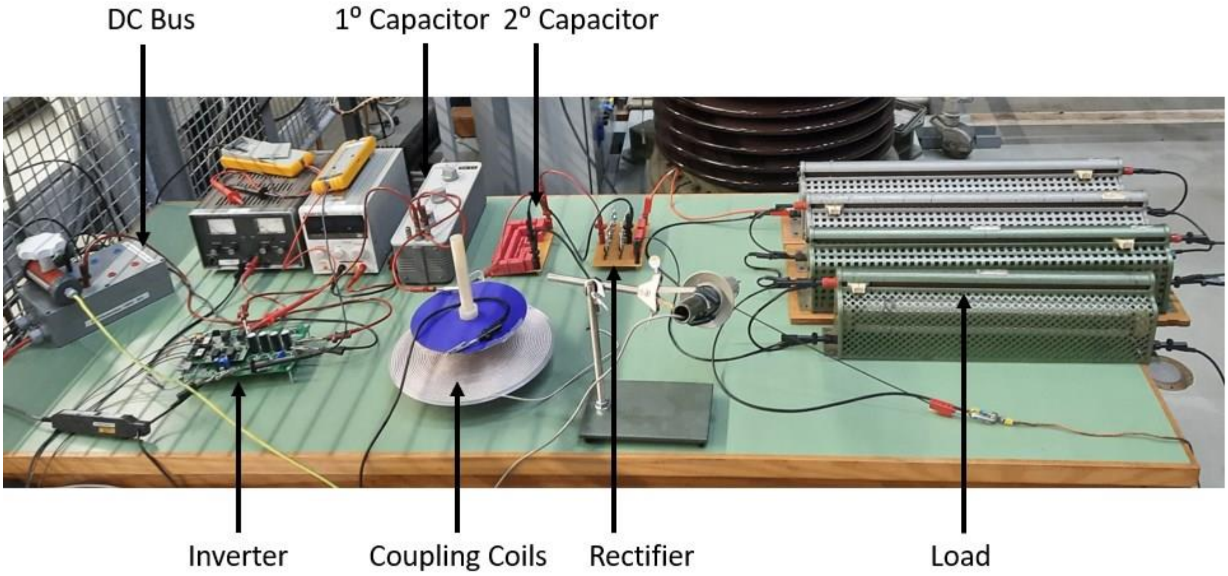

Fig. 5: Prototype Layout

switching 320 kHz with rise and fall times lesser than 10 ns. A deadtime of 100 ns is implemented to ensure zero voltage switching and prevent turn ON losses of the MOSFETs. The primary and secondary coils are spiral planar coils with 10 and 30 turns respectively. To ensure compactness of the supply a size constraint of 15cm radius is considered.

B. *Test Results*

The developed power supply is tested from no load to rated load by inducing a breakdown of air as indicated by the test object in Fig. 6. The DC output voltage (pink) drops from 6.12 kV at no load to 5.16 kV at rated load showing a load regulation of 18%. The blue waveform is the input current from the H-Bridge which transition from a no-load 90° shifted inductive current to a loaded current of 4.63 A. The designed power supply thus achieves 88% efficiency at the rated load. Therefore, the developed DC supply can provide 1.5 kW as a floating source for the CHB.

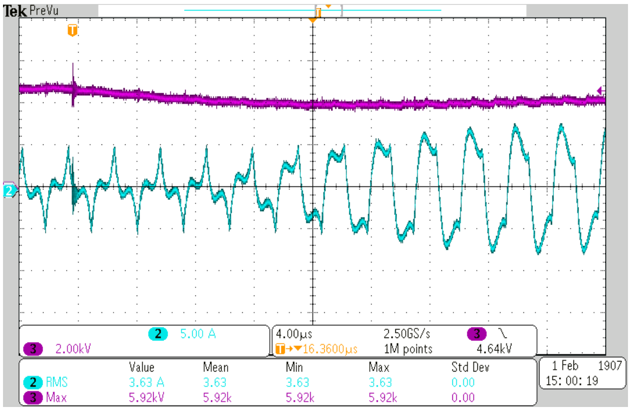

Fig. 6: Waveform of open circuit condition to breakdown condition (pink waveform - output voltage across load ; blue waveform - input current at primary)

Alternatively, the supply is also tested at no load and rated load condition separately. The no load condition in Fig. 7 has an inductive input current which correlates to the losses across the coil parasitics along with diode rectifier and MOSFET switching losses.

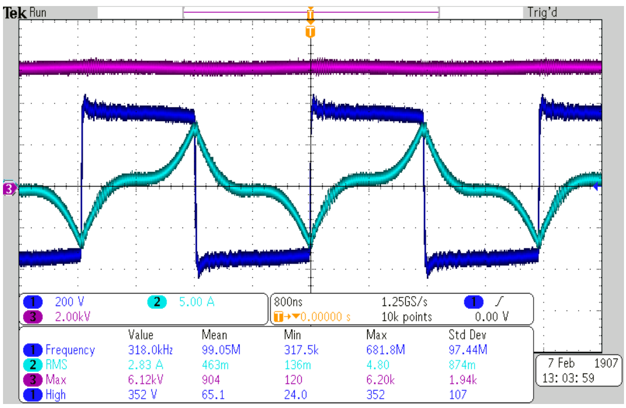

Fig. 7 : Waveform of no load condition (pink - output DC voltage; blue - input current; dark blue - full bridge square wave input voltage)

The rated load waveform in Fig. 8 on the other hand indicate an efficiency of 88% with the input and output powers being 1655 W and 1469 W respectively. The input power at no load is 160 W which is almost equivalent to the power lost at rated load. The difference in the output DC voltage highlights the load regulation between no load and rated load.

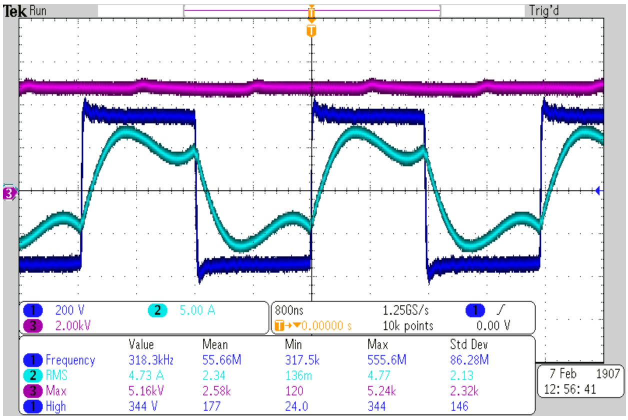

Fig. 8 : Waveform of rated load condition (pink - output DC voltage; blue - input current; dark blue - full bridge square wave input voltage)

According to the circuit diagram in Fig. 4, the inductive power transfer setup behaves as a load invariant AC source with 5 kV peak at an input voltage of 350 V. Operating at high frequencies of 320 kHz, this source can be used to test insulation aging and breakdown under high frequency AC. Using PTFE Teflon as the insulation material, AC discharges is observed when the test setup is connected parallel to the secondary capacitor (2^0) as seen in Fig. 9. During these discharges the input current profile is phase shifted similar to the no load current. This current provides the no load power required to maintain the AC voltage creating the discharges. Fig. 10 is the waveform captured during the AC discharges across PTFE Teflon.

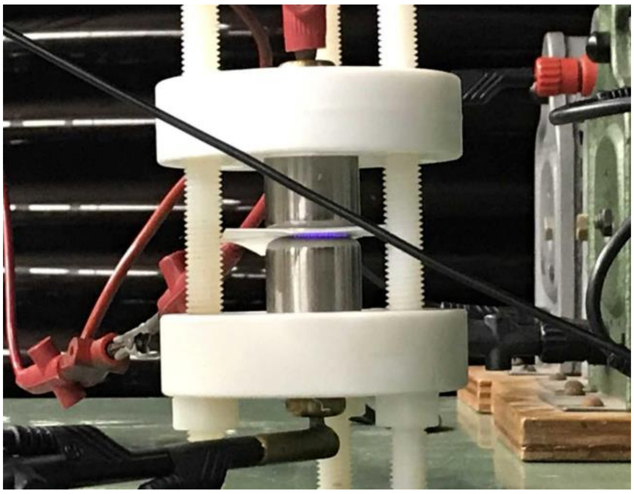

Fig. 9: AC Discharges on PTFE Teflon

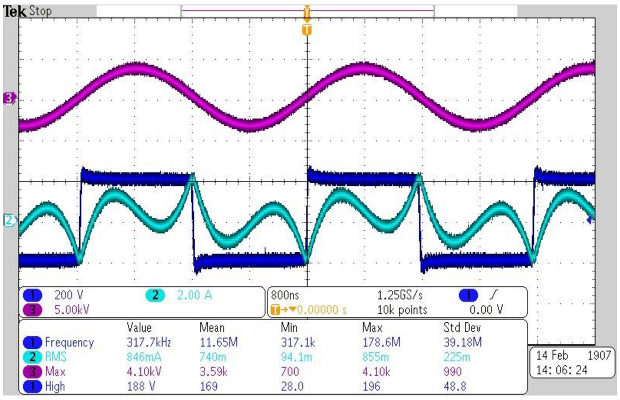

Fig. 10: Waveform during the AC Discharges (pink - output AC voltage; blue - input current; dark blue - full bridge square wave input voltage)

IV. Conclusions

This paper presents the development of a wireless DC power supply with a voltage gain of 15. This power supply is suitable for powering different submodules of the CHB AWG. The developed supply performs well in conducting DC dielectric breakdown tests with a load regulation of 18% and 88% efficiency. Alternatively, the supply can be used to conduct aging and breakdown test on insulation material under high frequency sinusoidal waveform.

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