High Efficiency and High Current Inductor Design for 20 kHz Parallel Resonant AC Link

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ABSTRACT

Initial results for high efficiency and high current 20 kHz AC link inductor design are presented. Various inductor designs are investigated to reduce the high inductor losses that are typical for medium range ac link power conversion applications. A quite economical hallow copper wire is utilized to design various types of air core inductors. Initial results show improvements in reduction both in link losses and cost.

I. INTRODUCTION

Smaller size, lighter weight and lower cost are the attractive features for systems particularly in aviation and space station applications. The 20 kHz ac link technology provides convenient means for obtaining high power densities and power management in a multi-terminal converter distribution system. It offers isolation, flexibility in accomplishing voltage level changes, fast system response and freedom from acoustic noise [1-12]. Zero voltage switching capability of the ac link converters offers reduction in converter losses and high band width operation.

The LC tank circuit constitute the ac link part of the system. The tank circuit in the HF ac link system perform similar function to the capacitor in the dc link system. The higher the energy storage capacity of the link elements, the lower the peak link voltage variation during the instant power variations. Hence, the ac link, which serves as an intermediate energy storage medium, helps maintaining relatively constant peak link voltage during the power transfer between the input and output. As the level of power transfer between input and output increases so does the need for more energy storage capacity and the size of the tank circuit elements.

The major drawback of the 20kHz parallel resonant HF ac link system is its high operating link losses. The ac link inductor constitutes the major portion of these losses [8], and the link capacitor contributes to the losses.

In dc link based systems the major current from the capacitor is drawn whenever there is a power transfer between input and output and an instant mismatch between the two. When there is no power transfer, no fluctuation in the dc link voltage would be observed. Since zero dv/dt would cause no current through the link capacitor, there would be almost no loss in the dc link at no load operation. This is an advantage of the dc link system.

However, in HF AC link based systems, the link voltage and the circulating link current always resonates at a resonant frequency determined by the LC tank circuit elements, and they always carry ac currents resulting in considerable loss even if the system operates at no load just to maintain the HF AC peak link voltage.

Here in this study, the ways to reduce the ac link losses by various types of inductor designs are investigated. A 30 kW single-phase power converter and its associated ac link tank circuit is designed and constructed. Required control circuitry to establish the ac link voltage across the ac link is designed and built. A quite economical hollow copper wire instead of highly expensive litz wire is utilized during the designs of various types of inductors.

II. POWER CIRCUIT OF THE SYSTEM

Power circuit diagram of a 30kW dc to HF AC single phase power converter used to establish and maintain a 20kHz, 500V peak ac link voltage across the resonant tank circuit elements is shown in Figure 1.

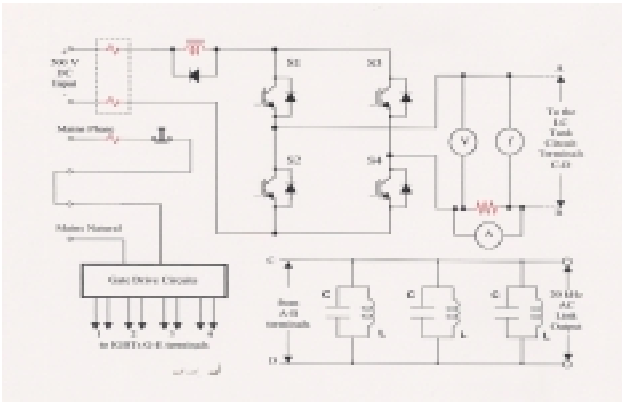

Fig. 1. Power Circuit Diagram of the System Used to Establish and Maintain a 20kHz AC Link Voltage Across the Resonant Tank Circuit Elements.

The performance of the inductors designed for high efficiency operation are tested at the 20kHz ac link side. A single phase bridge converter is used to convert 0-500V dc to 20kHz, 0-500V ac link voltage.

1200V, 75A IXYS IGBTs and, 1200V, 52A IXYS fast recovery epitaxial diodes are used in the single phase bridge shown in Fig. 1. The dc side energy is stored in an interface inductor L_S and then it is pumped to the 20kHz ac link with appropriate switching patterns. For the ac link resonant tank circuit elements shown in Fig. 1, various types of inductors are designed, built and tested. The link capacitor C is constructed by paralleling 140 of 18nF, 2000V capacitors.

III. VARIOUS INDUCTOR DESIGNS

The research studies is reported to show that the air-core inductor designs are less lossy compared to their ferrite-core counterparts for a 20kHz operating frequency and 0.375 joule peak energy storage requirement [8]. Therefore, the inductor designs tested here comprises only of air-core inductors.

Initially, an appropriate size litz wire is intended to be utilized for the construction of various tank circuit inductor designs that could operate at 20kHz and 500V peak link voltage. Later, due to funding difficulties, a holow copper wire which is a lot cheaper than the litz wire is preferred for the construction phase. The hollow copper wire is not only cheap, but also provides an opportunity for water cooling. The thickness of the hollow copper wire used in the construction of the inductors is 0.7mm and the outside diameter is 1cm.

Mainly, three different types of inductor designs are tested. One of them is a simple multiple turns straight cylindrical form, another is a half-circle shaped cylindrical form, and the third is a toroidal shaped cylindrical form air-core inductor designs.

III.A. The Simple Multiple Turns Straight Cylindrical Form Air-Core Inductor Design

The simple multiple turns straight cylindrical form air-core inductor design is constructed as shown in Fig. 2. The specs of this air core inductor design is given in Table 1. A 25µH single tank circuit inductor which is capable of operating at 20 kHz, 500 V peak link voltage and around 200A peak current is formed out of 24 turns. Due to its structure the simple straight cylindrical air core inductor design has its main flux completing its path outside and around the inductor [7-12]. The large circulating flux in the air around the inductor would not only impose quite a lot of electromagnetic radiation to the environment around the inductor, but also induce eddy currents on the metal parts around it and cause extra losses. Since the number of parallel resonant tank circuit would increase for the increased power levels, this means the circulating flux level in the air, its side effects and losses would increase for high power levels of operation. Therefore, there is a great deal of interest to keep the large circulating flux around as low as possible.

III.B. Multiple Turns Half Circle Shaped Cylindrical Form Air-Core Inductor Design

A step towards achieving a reduced circulating flux around the inductor is to partly confine the flux by designing the inductor in the form of a half circle shape cylindrical form. Flux path outside and around the inductor would be reduced somewhat, but still it would not be completely confined. This second inductor design is constructed as shown in Fig. 3. The 25µH inductor which is capable of operating under the same operating conditions as the first design is formed out of 33 turns this time. The main reason of increased number of turns is the reduction of main air flux path around the inductor. So although the flux circulating outside and around the inductor is partly confined and its bad effects are reduced, the increase in number of turns, length, volume, weight and cost comes as a disadvantage. To have the same value of inductor with the new design, the number of turns increases from 24 to 33, the volume from 4.247dm^3 to 9.189dm^3, weight from 1.74kg to 2.393kg, and the price linearly with the length of the wire used. The specifications of the second inductor design is given in Table 2.

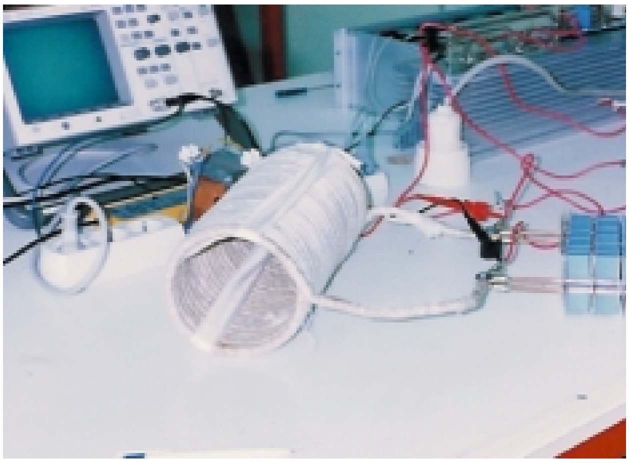

Fig. 2. A Simple Multiple Turns Straight Cylindrical Form Air-Core Inductor Design Capable of Operating at 20 kHz, 500 V_{pk} and 200 A_{pk}.

Simple Multiple Turns Straight Cylindrical Form Inductor Design:

Inductance	: 25µH
Equivalent Series dc Resistance	: 0.03Ω
Number of Turns	: 24
Weight	: 1.74kg
Single Turn Outer Diameter	: 13cm
Inductor Length	: 32cm
Volume	: 4.25dm^3
Rated Current	: 200 A peak

Table 1. The Specs of the Simple Multiple Turns Straight Cylindrical Form Air-Core Inductor Design Capable of Operating at 20 kHz, 500 V_{pk} and 200 A_{pk}.

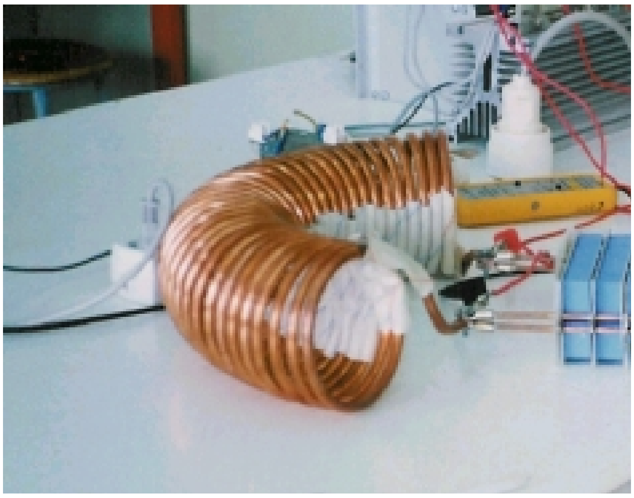

Fig. 3. A Multiple Turns Half Circle Shaped Cylindrical Form Air-Core Inductor Design Capable of Operating at 20 kHz, 500 V_{pk} and 200 A_{pk}.

Fig. 4. A Toroidal Shaped Cylindrical Form Air-Core Inductor Design Capable of Operating at 20 kHz, 500 V_{pk} and 200 A_{pk}.

Multiple Turns Half Circle Shaped Cylindrical Form Inductor Design:	
Inductance	: 25µH
Equivalent Series dc Resistance	: 0.035Ω
Number of Turns	: 33
Weight	: 2.39kg
Single Turn Outer Diameter	: 13cm
Half Circle Form Outer Diameter	: 45cm
Volume	: 9.19dm^3
Rated Current	: 200 A peak

Table 2. The Specs of the Multiple Turns Half Circle Shaped Cylindrical Form Air-Core Inductor Design Capable of Operating at 20 kHz, 500 V_{pk} and 200 A_{pk}.

Multiple Turns Toroidal Shaped Cylindrical Form Inductor Design:	
Inductance	: 25µH
Equivalent Series dc Resistance	: 0.038Ω
Number of Turns	: 38
Weight	: 2.77kg
Single Turn Outer Diameter	: 13cm
Toroidal Form Outer Diameter	: 40cm
Volume	: 15.32dm^3
Rated Current	: 200 A peak

Table 3. The Specs of the Multiple Turns Toroidal Shaped Cylindrical Form Air-Core Inductor Design Capable of Operating at 20 kHz, 500 V_{pk} and 200 A_{pk}.

III.C. Multiple Turns Toroidal Shaped Cylindrical Form Air-Core Inductor Design

An advance step towards achieving more reduced circulating flux around the inductor is to completely confine the flux by designing the inductor in the toroidal form. There would be no more main flux circulating outside and around the inductor anymore with this design, but only some leakage flux. The pay-off of this design is heavier than the second design though. The 25µH toroidal shaped cylindrical form air-core inductor which is capable of operating under the same operating conditions as the first and second designs is constructed as shown in Fig. 4, this time out of 38 turns. Again the main reason of increased number of turns is the further reduction in the main flux path. Altough the main flux path outside and around the inductor is completeley confined in the toroidal structure, and its side effects are almost removed, the penalty is the heaviest. To have the same value of inductor with the toroidal design, the number of turns increases from 24 in the 1st, 33 in the 2nd to 38 in the 3rd design, the number of turns increases from 24 in the 1st, 33 in the 2nd to 38 in the 3rd design, the volume from 4.25dm^3 in the 1st, 9.19dm^3 in the 2nd to 15.32 dm^3 in the 3rd design, and the weight from 1.74kg in the 1st, 2.39kg in the 2nd to 2.77kg in the 3rd design, the price linearly with the length of the wire used. The specs of the third design is given in Table 3.

IV. HF AC LINK CAPACITOR DESIGN

Part of the AC link losses are generated in the AC link tank circuit capacitor. The tank circuit capacitor losses vary depending on the operating link voltage, the level of circulating current and the equivalent series resistor of the capacitor. Since the losses and the stored energy across the capacitor are proportional to the square of the peak link voltage, the higher the peak link voltage, the higher the capacitor losses. In the experimental prototype, a single 2.5µF, 200 A peak, 2000V peak ac link tank circuit capacitor is constructed by paralleling 140 of 18nF, 2000V capacitors. The technical specs of this designed capacitor is provided in Table 4.

AC Link Tank Circuit Capacitor Design	
Capacitance	: 2.5µF
Voltage	: $2000V_{peak}$
Current	: $200A_{peak}$
Weight	: 1.98kg
Volume	: $2.16dm^3$

Table 4. The Specs of a Single 2.5µF AC Link Tank Circuit Capacitor Capable of Operating at 20 kHz, 500 V_{pk} and 200 A_{pk}.

V. PERFORMANCE ANALYSIS OF THE AC LINK

The performance of the AC link is tested by means of the constructed experimental prototype whose power circuit diagram is given in Fig 1. The dc input power to the system is obtained from a 30kW, 3-phase controlled rectifier. The individual ac link tank circuits shown in Fig. 1 are constructed from a single 25µH inductor and a single 2.5µF capacitor. This single tank circuit is reported to handle around 3.3kW power transfer level between input and the output [8-10]. Therefore, for a 10kW power transfer between input and output three of these tank circuits are paralleled.

Here in this study, initially a single tank circuit composed of a single inductor with various designs and a single capacitor is tested. When the single tank circuit performance results are obtained, three of these resonant tank circuits are paralleled to obtain the related tank circuit performance. Since the previous study reports results on such a resonant tank circuit, the related performance results would be useful for comparison purposes.

V.A. Performance Results with the First Inductor Design Utilising Only a Single Resonant Tank Circuit:

With the experimental prototype having only a single resonant tank circuit employing the first inductor design whose specs are given in Table 1, the ac link voltage is gradually increased and the loss performance of the link is recorded. Figure 5 shows the total link and converter losses at various operating peak link voltages. Since the AC link is operated at no load, the losses in the figure shows only the amount of active power required to maintain the ac link voltage at the related peak link voltage.

V.B. Performance Results with the Second Inductor Design Utilising Only a Single Resonant Tank Circuit:

The second inductor design whose specs are given in Table 2 is tested with a single resonant tank circuit. Figure 6 shows a similar performance graph as in Fig. 5 with only a difference in the inductor design. When Fig. 5 and 6 are compared to each other there is not a significant improvement observed with the employement of second inductor design, but, only a little reduction in losses.

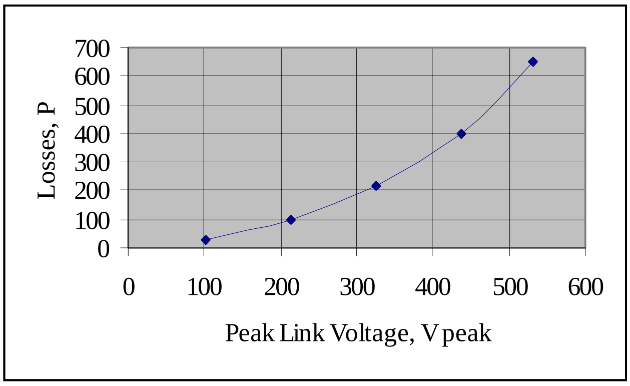

Fig. 5. Performance of the 20 kHz HF AC Link with a Only Single Tank Circuit Employing Simple Multiple Turns Straight Cylindrical Air-Core Inductor.

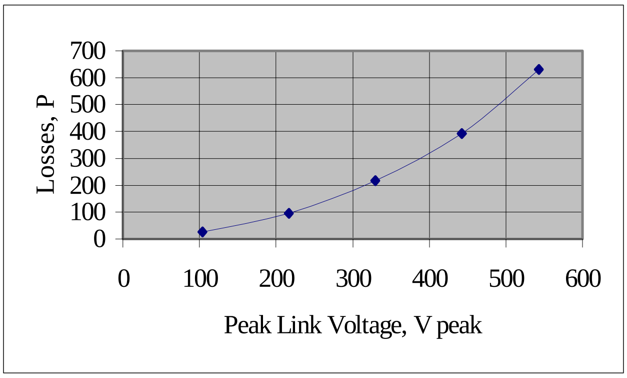

Fig. 6. Performance of the 20 kHz HF AC Link with a Only Single Tank Circuit Employing Half Circle Shaped Cylindrical Air-Core Inductor.

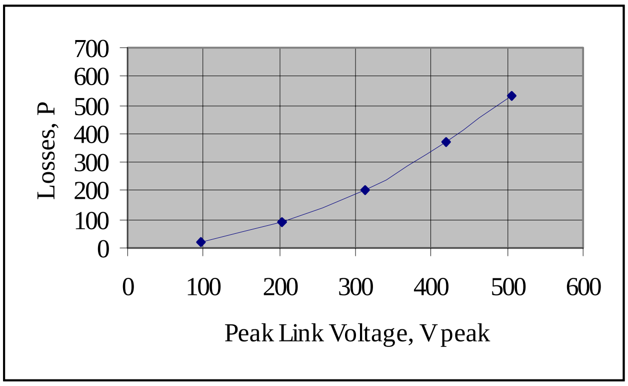

Fig. 7. Performance of the 20 kHz HF AC Link with a Only Single Tank Circuit Employing Toroidal Shaped Cylindrical Air-Core Inductor.

V.C. Performance Results with the Third Inductor Design Utilising Only a Single Resonant Tank Circuit:

The third inductor design whose specs are given in Table 3 is tested with a single resonant tank circuit. Figure 7 shows a similar performance results as in Fig. 5 and 6 with the third inductor design. When Figures 5, 6 and 7 are compared to each other there is not a significant loss reduction observed for various inductor designs with a single tank circuit employment.

V.D. Performance Results with Three Resonant Tank Circuits Employed:

In a previous study a total of 1.75kW ac link tank circuit losses is reported for a 10kW system utilising three paralleled resonant tank circuits operating at around 400V peak ac link voltage [8,9]. The inductor in the previous study was of the first design type utilising litz wire. Since the inductor was a straight cylindrical air core type the circulating flux outside and around the inductors were tremendous especially with three paralleled resonant tank circuit case. Due to this high flux level outside and around the inductors extra losses around the metal parts of the system were induced in the form of eddy losses resulting increased link losses.

Here in this study, since the third inductor design which is the toroidal type would confine the main fluxes of the inductors within the related toroids and no extra losses would occur due to the circulating fluxes outside and around the inductors, there is a quite appreciable loss reduction expected. Figure 8 shows the total converter and link losses utilising the third inductor design with respect to the peak link voltage with the employement of three resonant tank circuits. Here in this figure, it can be clearly observed that the total operating losses of the link is certainly below 1kW at 400V peak link voltage as opposed to 1.75kW at 400V peak link voltage in the previous system.

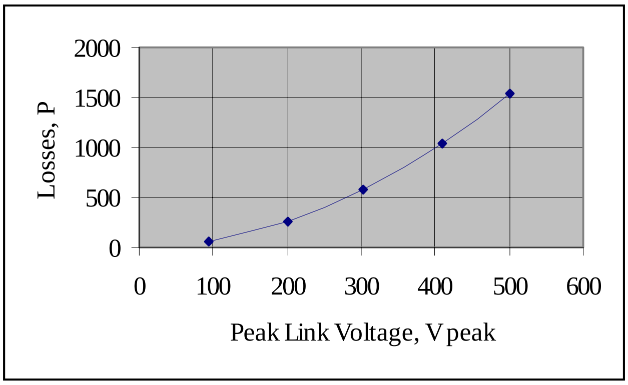

Fig. 7. Performance of the 20 kHz HF AC Link with Three Tank Circuits Paralleled Employing Third Toroidal Inductor Design Utilizing Hallow Copper Wire.

VI. CONCLUSIONS

The utilization of hollow copper wire and the toroidal air-core inductor design for a 20kHz parallel resonant HF AC link tank circuit capable of handling 10kW power transfer level shows that there is a significant improvement in terms of loss reduction, efficiency improvement, and cost.

For a 10 kW power conversion level the link losses are reduced from 1.75 kW [8,9] to below 1 kW for the same ac peak link voltage operation. This reduction in link losses means an improvement in link efficiency from 82.5% to 90%.

On the other hand, utilisation of hollow copper wire significantly reduces the cost compared to the utilization of litz wire.

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