Performance Improvement Investigations for High Current 20 kHz AC Link Inductor

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ABSTRACT

Various air-core inductor designs made out of litz wire are investigated to reduce the 20 kHz paralel resonant AC link losses that are typical for medium range ac link power conversion applications. Inductors are tested in a dc to 20kHz ac link converter designed and built as a lab prototype and the performance results of the various air core litz wire inductors are compared to their counterparts made out of hallow copper wire reported in an earlier study. Results show significant improvements in loss and volume reduction.

I. INTRODUCTION

Applications utilizing resonant power technologies such as induction heating and parallel resonant ac bus inescapably needs to utilize an LC tank circuit or a combination of LC tank circuits where small size, light weight, low cost and low loss become critical factors in deciding whether to use this technology is worth or not in the considered field of applications.

In these resonant power technologies the LC resonant tank circuit constitute the ac link part of the system where the tank circuit in HF link functions more or less the same way as the capacitor does in the dc link system. The higher the energy storage capacity of the ac link elements, the lower the peak link voltage variations during the instant power mismatches between the input and output. 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 instant power mismatch increases while the power transfer level increases between the input and output so does the need for more energy storage capacity and the size of the LC tank circuit elements.

The major disadvantages of the LC resonant tank circuit used in resonant power systems are its high operating link losses, high volume and weight. The ac link inductor is the major contributor to these disadvantages [8].

On the other hand, there are attractive features of parallel resonant ac link 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.

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

Whereas, in parallel resonant AC link systems, there is always a link voltage and a circulating resonant link current determined by the LC tank circuit elements even if there is no power transfer between the input and output and system operates at no load. Circulating current in the resonant tank circuit always contributes to the operational losses of the system depending on the equivalent series resistance of the LC tank circuit elements. This property of parallel resonant ac link is a disadvantage when compared to its dc link counterpart.

Here in this study, the ways to reduce the ac link losses by various types of inductor designs utilizing litz wire 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.

II. BACKGROUND

In various studies conducted at University of Wisconsin-Madison the performance of the 20kHz parallel resonant ac link technology is investigated. But during those studies the focus of attention was not to reduce the link losses of the ac link tank circuit elements since the feasibility of certain ac link based systems are investigated [1-12]. That is why during those studies no significant effort is spent to improve the performance of the ac link tank circuit elements. In one of those studies a total of 1.75kW ac link tank circuit losses is reported for a 10kW power level of system utilising three parallel resonant tank circuits operating at around 400V peak ac link voltage [8, 9]. The inductors used in this study was air core, litz wire, multiple turn, multiple layer, straight cylindrical type. Since the inductor was of a straight cylindrical air core type the circulating flux outside and around the inductors were tremendous especially with three parallel resonant tank circuit case. Due to this high flux level outside and around the inductors extra losses were induced in the form of eddy losses around the high permeability material parts and chassis of the system resulting increased link losses.

Later in another study carried out at Ege University-Izmir to improve the performance of the ac link tank circuit a total of 1.5kW ac link tank circuit losses is reported for a 10kW system utilising three parallel resonant tank circuits operating at around 500V peak ac link voltage [13]. The inductor in this study however was made out of hollow copper wire, again air core, multiple turns, single layer but with a toroidal design. Since litz wire could not be obtained initially, hollow copper wire is preferred to carry out the study. The advantage of the hollow copper wire is its being very cheap and easy to obtain compared to its litz wire counterpart, whereas the disadvantages are its being quite hard to shape and work with, relatively high equivalent series resistance, and not exactly being suitable for HF operations. The advantage of using air core toroidal type of structure on the other hand is to confine the circulating flux inside the toroid and to prevent extra losses induced around the iron composite parts and chassis of the system. It is however worth to mention here that there are disadvantages of the toroidal design such as increasing number of turns, volume and weight for the same value of the inductor. In the same study, some other inductor designs and related performance results are reported and they will be used in this paper for comparison purposes as their time comes.

III. POWER CIRCUIT OF THE SYSTEM

The power circuit diagram of the system to obtain, maintain a 20kHz, 500V peak ac resonant link voltage from a dc supply is shown in Figure 1.

The performance of various resonant tank circuit inductors designed for high efficiency operation at 20kHz ac link are tested in the laboratory prototype whose power circuit diagram is shown in Fig.1. The single tank circuit capacitor C shown in Fig 1 is constructed by paralleling 140 of 18nF, 2000V capacitors. Only a single power switch is used to convert 0-500V adjustable dc to 20kHz 0-500V adjustable ac link voltage. On the other hand, 1200V, 75A IXYS IGBT and 1200V, 52A IXYS fast recovery epitaxial diode are used for the power switches in the prototype. The dc side energy is stored in an interface inductor L_S and then is pumped to the output to

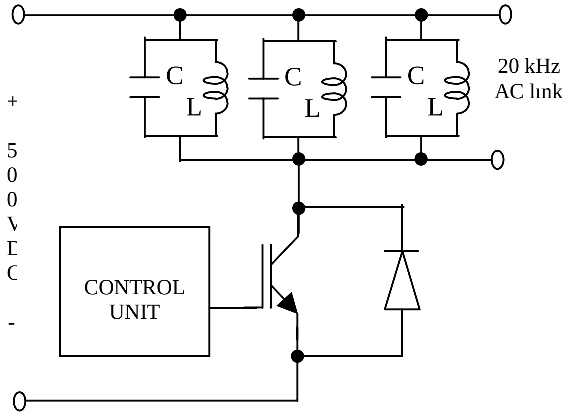

Fig. 1. Test Power Circuit Diagram of the System Used to Establish and Maintain a 20kHz AC Link Voltage Across the Resonant Tank Circuit Elements.

obtain and maintain the 20kHz ac link with appropriate switching patterns.

IV. 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.

Since in an earlier study conducted at Ege University-Izmir air core hollow copper wire is utilized due to the unavailability of litz wire to design various tank circuit indictors, upon the availability of appropriate litz wire similar inductor designs are constructed and tested with the litz wire. Litz wire used in these constructions is 3xAWG-1 (6x5x4x28/36) type. On the other hand, the diameter of the hollow copper wire used in the earlier study is 10mm with a skin thickness of 0.7mm.

Here in this study, mainly two different types of litz wire inductor designs are tested one of which is an air core, multiple turns, multiple layers, straight cylindrical design and the other is an air core, multiple turn, multiple layer, toroidal design. Later, litz wire inductor design test results obtained in this study are compared with those of hollow copper wire counterparts reported in the earlier study.

IV.A. Air-Core, Multiple Turns, Multiple Layers, Straight Cylindrical Inductor Design

This type of inductor constructed from a litz-wire as five layers is shown at the front left of Figure 2. The specs of this inductor is given in Table 1. A 25µH single tank circuit inductor which is capable of operating at 20 kHz, 500V peak link voltage, and around 200A peak current is formed out of 25 turns.

The same type of but hollow copper wire inductor design made in the earlier study is shown in Fig. 3. The specs of that inductor is given in Table 2. The inductor capable of operating at the same operating conditions was formed out of 24 turns.

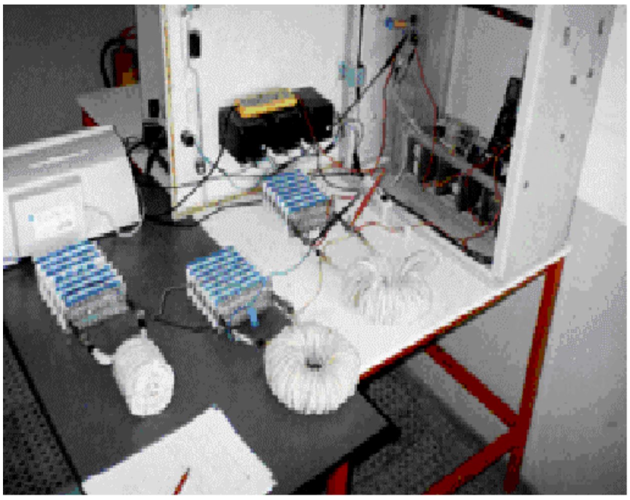

Fig. 2. At Left Front: Air-Core, Multiple Turns, Five Layers, Litz-Wire, Straight Cylindrical Inductor Design; At Right Front:, Air-Core, Multiple Turns, Multiple Layers, Litz-Wire, Toroidal Inductor Design. Both Capable of Operating at 20 kHz, 500 V_{pk} and 200 A_{pk}.

Air Core, Litz-Wire, Multiple Turns, Multiple Layers, Straight Cylindrical Form Inductor Design:

Inductance	: 25µH
Equivalent Series dc Resistance	: 0.0012Ω
Number of Turns	: 25
Weight	: 2.950kg
Outer Diameter	: 11cm
Inductor Length	: 12cm
Volume	: 1.35dm^3
Rated Current	: 200 A peak

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

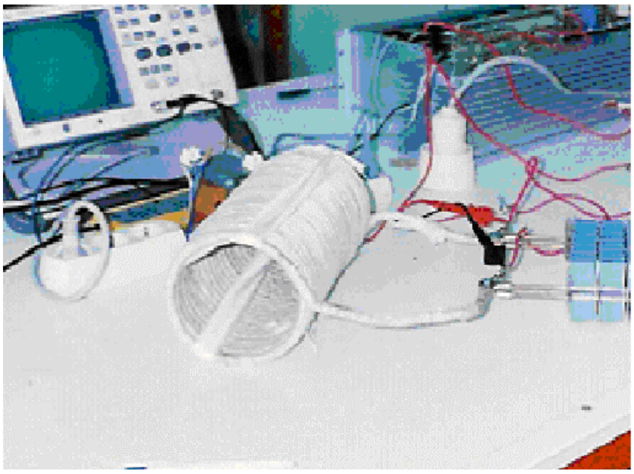

Fig. 3. Air-Core, Multiple Turns, Single Layer, Hollow Copper Wire, Straight Cylindrical Inductor Design Capable of Operating at 20 kHz, 500 V_{pk} and 200 A_{pk}.

Air Core, Hollow Copper Wire, Multiple Turns Single Layer, Straight Cylindrical 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 2. The Specs of Air-Core, Multiple Turns, Single Layer, Hollow Copper Wire, Straight Cylindrical Inductor Design Capable of Operating at 20 kHz, 500 V_{pk} and 200 A_{pk}.

When these two tables are compared for the straight cylindrical designs, it can be seen that the same 25µH inductor has a very low equivalent series resistance of 0.0012Ω when it is made out of litz wire as compared to 0.03Ω when it is made out of hollow copper wire. Number of turns are close to each other, but a smaller volume of 1.35dm^3 can be obtained with the litz wire while almost three times volume of 4.25dm^3 is obtained with the hollow copper wire since it is almost impossible to give shape and work with for a smaller volume. Due to same reasons outer diameter is reduced from 13cm to 11cm by the utilization of litz wire. On the other hand though, the weight increases from 1.74kg to 2.95kg with the utilization of litz wire, besides the cost of the litz wire is very much higher than the cost of the hollow copper wire.

This comparison show that if low loss and low volume are more important parameters than the weight and the cost it is wiser to use the litz wire for the application, but if low cost and low weight are more important parameters than the losses and the volume then hollow copper wire is the way to go for the same inductor design.

IV.B. Air-Core, Multiple Turns, Multiple Layers, Litz Wire, Toroidal Inductor Design

Toroidal type of inductor constructed from a litz-wire as three layers is shown both at the front right of Figure 2 and in Figure 4. A 25µH single tank circuit toroidal litz wire inductor which is capable of operating at the same operating conditions as before this time is formed out of 44 turns. The specs of this inductor design is given in Table 3.

The same type of but hollow copper wire inductor design made in the earlier study is shown in Fig. 5. The specs of that inductor is given in Table 4. The inductor capable of operating at the same operating conditions was formed out of 38 turns.

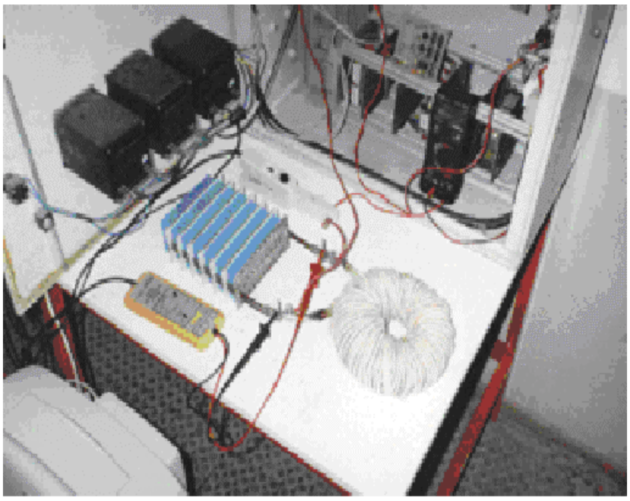

Fig. 4. Air-Core, Multiple Turns, Multiple Layers, Litz-Wire, Toroidal Inductor Design Capable of Operating at 20 kHz, 500 V_{pk} and 200 A_{pk}.

Air Core, Litz-Wire, Multiple Turns, Multiple Layers, Toroidal Inductor Design:

Inductance	: 25µH
Equivalent Series dc Resistance	: 0.0009Ω
Number of Turns	: 44
Weight	: 4.760kg
Single Turn Outer Diameter	: 8cm
Toroidal Form Outer Diameter	: 22cm
Volume	: 3.04dm^3
Rated Current	: 200 A peak

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

Fig. 5. A Toroidal Shaped Cylindrical Form Air-Core Inductor Design With Hollow Copper Wire Capable of Operating at 20 kHz, 500 V_{pk} and 200 A_{pk}.

Multiple Turns Toroidal Shaped Cylindrical Form Inductor Design With Hollow Copper Wire:

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 4. 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}.

When these last two tables are compared for the toroidal designs, it can be seen that the same 25µH inductor has a very low equivalent series resistance of 0.0009Ω when it is made out of litz wire as compared to 0.038Ω when it is made out of hollow copper wire. Number of turns is 44 for the litz wire case and 38 for the hollow wire case. Comparatively a very smaller volume of 3.04dm^3 can be obtained with the litz wire, while almost five times volume of 15.32dm^3 is obtained with the hollow copper wire since it is almost impossible to give shape and work with for a smaller volume. Due to same reasons outer diameter is reduced from 13cm to 8cm by the utilization of litz wire. On the other hand though, the weight increases from 2.77kg to 4.76kg with the utilization of litz wire, besides the cost of the litz wire is very much higher than the cost of the hollow copper wire.

Again, this comparison show that if low loss and low volume are more important parameters than the weight and the cost it is wiser to use the litz wire, but if low cost and low weight are more important parameters than the low loss and low volume then hollow copper wire is the way to go.

When a cross examination is made with the toroidal design versus straight cylindrical design for the litz wire case, it can be seen from the related tables that for the same inductor value toroidal design somehow has a little less equivalent series resistance: 0.0009Ω versus 0.0012Ω eventhough it has more number of turns: 44 versus 25, toroidal design has a little over two times volume: 3.04dm^3 versus 1.35dm^3, and it has almost twice weight: 4.760kg versus 2.950kg. So, lower loss, higher volume, higher weight, and higher cost comes with the toroidal design. When low loss is the critical parameter then the toroidal design is the way to go.

V. HF AC LINK CAPACITOR

Some portion 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 capacitor is provided in Table 5.

Since the focus of this study is to reduce the ac link losses by designing appropriate tank circuit inductor, no special effort is spent for the capacitor design. The capacitors are purchased and brought together to obtain the desired capacitor value anyhow. But it is possible to make research to reduce the capacitor losses, too.

<u>AC Link Tank Circuit Capacitor Design</u>

Capacitance	: 2.5µF
Voltage	: $2000V_{peak}$
Current	: $200A_{peak}$
Weight	: 1.98kg
Volume	: $2.16dm^3$

Table 5. 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}.

VI. PERFORMANCE ANALYSIS OF THE AC LINK

The performance of the AC link is tested by means of an experimental prototype whose power circuit diagram is shown 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 output [8-10]. Therefore, for a 10kW parallel resonant power converter three of these tank circuits are paralleled.

Here in this study, initially a single tank circuit composed of a single inductor and a single capacitor is tested for various inductor designs. After the single tank circuit performance results are obtained, three of these resonant tank circuits are paralleled to obtain the related tank circuit performance since University of Wisconsin-Madison study results were not lineer with the number of tank circuits. The losses were increasing more than the linearity requires for increasing number of tank circuits. That is why, here in this study increased number of tank circuit performance is also investigated for comparison purposes.

VI.A. Performance Results with the Straight Cylindrical Inductor Design with a Single Tank Circuit:

With the experimental prototype having only a single resonant tank circuit employing a litz wire 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 6 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 at the corresponding peak link voltage.

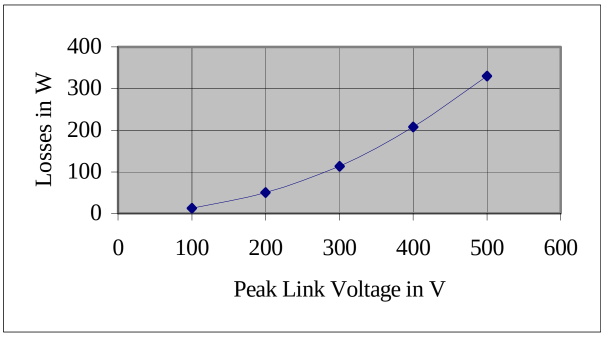

Fig. 6. Performance of the 20 kHz HF AC Link with a Single Tank Circuit Employing Simple Multiple Turns Straight Cylindrical Air-Core Litz Wire Inductor Design.

An earlier study conducted at Ege University-Izmir with an inductor designed from a hollow copper wire whose specs is given in Table 2 reports a loss profile as shown in Figure 7. When the two case is compared, the losses are reduced almost by a factor of two with the utilization of litz wire.

It is important to note however here that the chassis of the system constructed in Ege University-Izmir is not made from an iron type of material or its derivatives which was the case at University of Wisconsin-Madsion, rather it is made from a durable polyester type of material, so circulating flux induced eddy losses are almost eliminated in the Ege University studies.

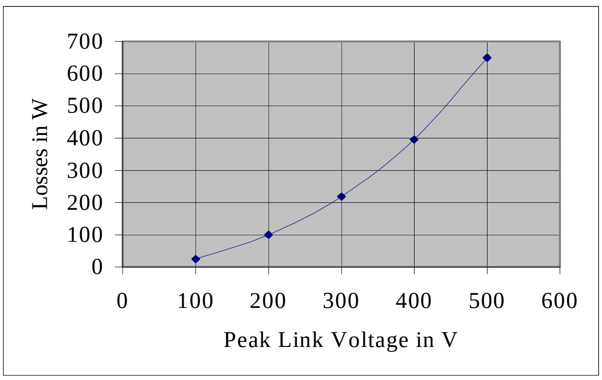

Fig. 7. Performance of the 20 kHz HF AC Link with a Single Tank Circuit Employing Simple Multiple Turns Straight Cylindrical Air-Core Hollow Copper Wire Inductor Design.

VI.B. Performance Results with the Toroidal Inductor Design with a Single Tank Circuit:

With the experimental prototype having this time a toroidal litz wire inductor design whose specs are given in Table 3, the loss profile obtained from the test results is shown in Figure 8. Again, the AC link is operated at no load, and the losses in the figure shows only the amount of active power required to maintain the ac link at the corresponding peak link voltage. Losses shown in this figure includes the total link and converter losses.

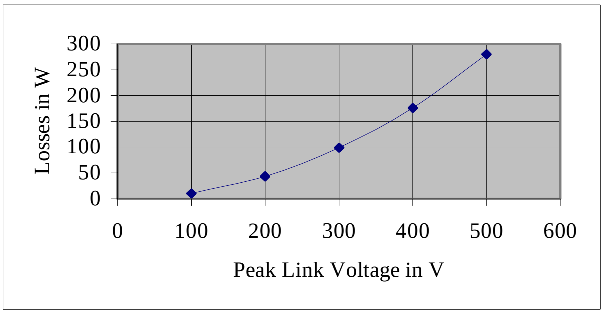

Fig. 8. Performance of the 20 kHz HF AC Link with a Only Single Tank Circuit Employing Multiple Turns Toroidal Shaped Cylindrical Form Air-Core Litz Wire Inductor.

In the earlier study conducted at Ege University-Izmir with an inductor utilizing a hollow copper wire whose specs is given in Table 4 reports a loss profile as shown in Figure 9. When the two case is compared, the losses are reduced almost by a factor of two with the utilization of litz wire for the toroidal inductor design as well.

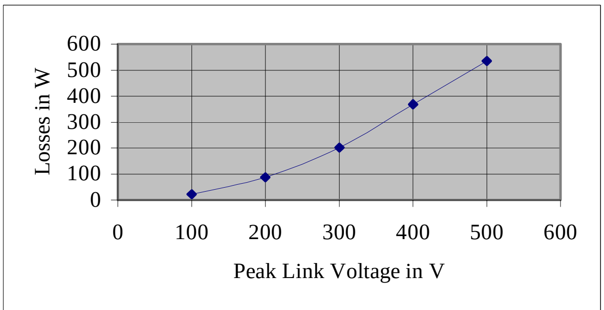

Fig. 9. Performance of the 20 kHz HF AC Link with a Only Single Tank Circuit Employing Multiple Turns Toroidal Shaped Cylindrical Form Air-Core Hollow Copper Wire Inductor.

VI.C. Performance Results with Three Resonant Tank Circuits:

In several studies conducted at University of Wisconsin-Madison 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 inductors utilized in these studies were air core litz wire straight cyldrical form designs but with chassis of the system made from an iron type of material. Since these inductors were straight cylindrical air core type the circulating flux outside and around the inductors especially with three paralleled resonant tank circuit case were tremendous and they were inducing appreciable amount of extra losses around the iron composite chassis of the system.

In the earlier study conducted at Ege University a total of 1.0kW tank circuit losses at around 400Vpk, and 1.5kW at around 500Vpk is reported for three parallel resonant tank circuit case [13]. Detailed loss profile is shown in Fig. 10 for this case. The inductors related with these results were of hollow copper wire toroidal type designs as can be seen from Fig. 5.

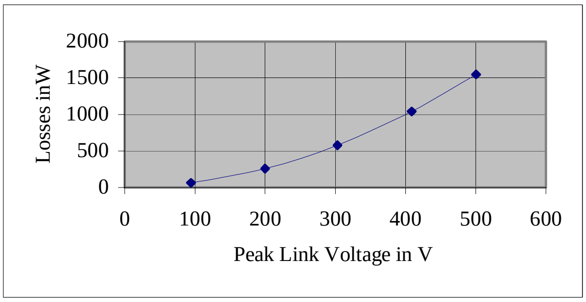

Fig. 10. Performance of the 20 kHz HF AC Link with Three Tank Circuits Employing Toroidal Inductor Design Utilizing Hallow Copper Wire.

Here in this study however, all three inductors in the tank circuits are made out of litz wire with one of them being straight cylindrical design and two of them being toroidal designs as can be seen from Fig. 2. The similar loss profile tests are carried out and the results are given in Fig. 11. From these figures, it can clearly be observed that the total operating losses of the link for the three resonant tank circuit case is 0.4kW at 400Vpk as opposed to 1.75kW at 400Vpk for the University of Wisconsin case, and 1kW at 400Vpk for the earlier Ege University case.

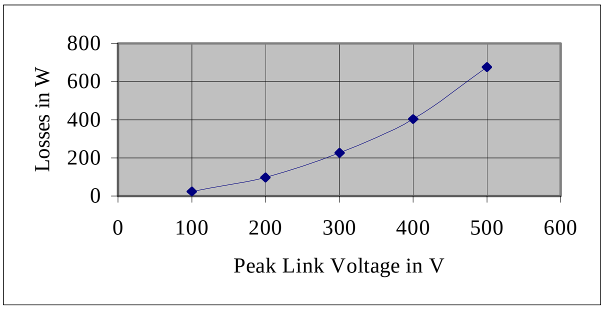

Fig. 11. Performance of the 20 kHz HF AC Link with Three Resonant Tank Circuit Paralleled Employing Toroidal Inductor Design Utilizing Litz Wire.

VII. CONCLUSIONS

In an earlier study conducted at Ege University[13], the utilization of hollow copper wire and toroidal air-core inductor design for a 20kHz parallel resonant HF AC link showed significant improvement in terms of loss reduction, efficiency improvement, and cost compared to the study conducted at University of Wisconsin-Madison [8, 9]. For a 10 kW power conversion level the link losses are reduced from 1.75 kW to around 1kW for the same ac peak link voltage level. This reduction in link losses meant an improvement in link efficiency from 82.5% to about 90%.

With this study, the utilization of litz wire and the new three layers toroidal shaped air-core inductor designs introduced more appreciable improvement in terms of loss reduction and efficiency improvement. For the same 10kW power conversion level the total link losses are reduced to 0.4kW from 1.75kW [8,9] of University of Wisconsin case, and 1kW [13] Ege University case for the same ac peak link voltage level. This further reduction in link losses means an extra improvement in link efficiency causing it to be 96% for a 10kW instant power transfer handling capability.

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