SUPERCONDUCTING SELF-RESONANT AIR-CORE TRANSFORMER

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Abstract - This paper presents a concept of air-core transformer using superconducting and self-resonant techniques. Magnetic property is examined here. Experimental results will be used to verify the theoretical prediction. This transformer is important for future conversion and its applications are for elimination of the core and reduce the power loss and eliminate the core saturation.

1. INTRODUCTION

This paper investigated power transformers that have been used in large-scale power converter system where the power rating handled by the transformers are in order of kilowatts, and a new design concept was proposed to construct the power transformers, it was however verified by a small-scale prototype. Generally speaking, efficiencies of the power transformers are more than 90% and are obtained by using ferrite core to couple the primary and secondary windings. Losses in transformer are generally classified into winding losses and core losses [1], winding losses are due to skin and proximity effects taken place in transformer winding; core losses include hysteresis loss and eddy current loss in core. The losses of even 0.5% of the power transmitted may generates large amounts of heat, which requires some cooling provisions, such as air cooling system and liquid cooling system. Therefore, if the power transformer can be designed without the use of cooling system, it not only reduces the production cost, but also increases the overall efficiency of power system. From the point of view on energy losses, to design an efficient power transformer has to minimize the core losses and winding losses. Some systematic methods [1,2,3] were proposed for optimal design of transformers, where the winding losses were assumed to be equal to the core losses. That is to say, if no transformer core is used, the power losses will be cut down to a half. For this reason, air-core transformers [4,5,6] were recommended. However, it has drawback of low magnetizing inductance, this results in large number of turns required for transformer windings and large magnetizing current that cannot be negligible, so we proposed to apply self-resonant technique to maximize the magnetizing inductance of transformer.

Moreover, the winding losses cannot be eliminated but it is possible to minimize them. Typical methods for reduction of winding losses include use of Litz wire/thin foil and operation with lower switching frequency, such that the skin and proximity effects can be minimized. Some latest research works [5,6,7] have been done to find out that superconductor is a good candidate to make up the transformer windings; it is able to reduce conduction loss. With the integration of air-core transformer, self-resonant technique and superconductor, we therefore worked out the proposed design for power transformer.

2. FERRITE CORE TRANSFORMER

This section presented some experimental results, it was to demonstrate that power transformers with ferrite core constructed by using superconductor is not recommended, because the permeability of the soft ferrite changes substantially as temperature drops from room temperature to -196°C, where the transformer is immersed in liquid nitrogen, as a result, the major function of ferrite core to increase flux density is not predominant. The experiment measured magnetising and leakage inductances of a transformer using superconductor and ferrite core of grade 3C85 at both room temperature and -196°C. The dimensions of the transformer as shown in Figure 1 are D_{out} = 21.8mm, D_{in} = 17.5mm, D_{core} = 12mm and H = 22.3mm.

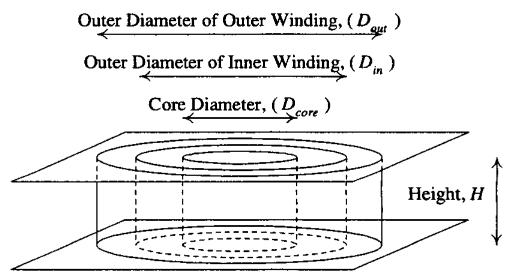

Figure 1: Ferrite Core Transformer with Superconductor

Figure 2(a) and (b) shown the magnetising and leakage impedances of the transformer respectively at room temperature and Figure 3(a) and (b) for the case when the transformer was immersed in liquid nitrogen. Moreover, Table 1 summarized all the measurement results and parameters of equivalent circuit models.

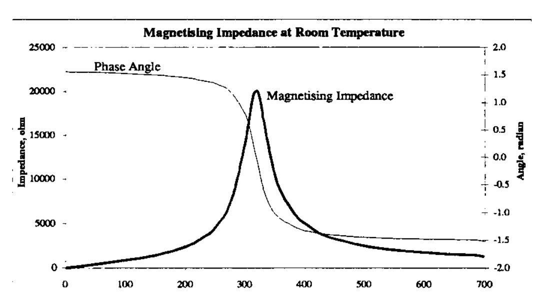

Figure 2(a): Magnetising Impedance at Room Temperature

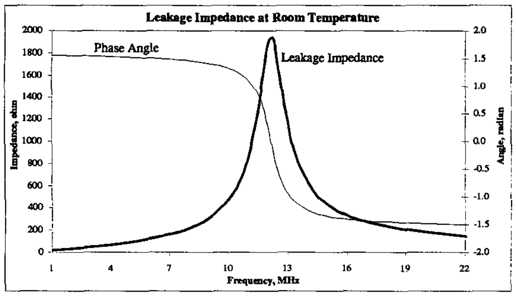

Figure 2(b): Leakage Impedance at Room Temperature

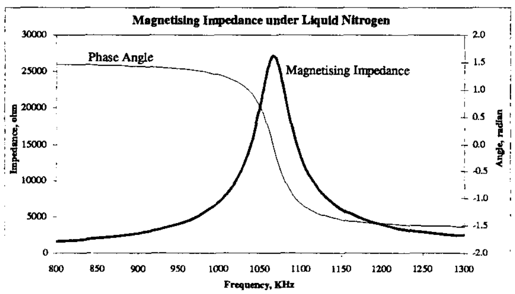

Figure 3(a): Magnetising Impedance under Liquid Nitrogen

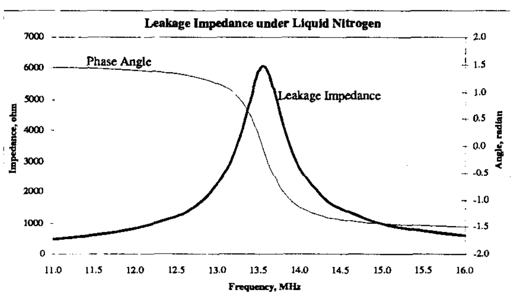

Figure 3(b): Leakage Impedance under Liquid Nitrogen

Table 1: Summary of Measurements

Measurments		Room Temperature	-196°C
Maximum Magnetising Impedance		20.11KΩ	27.37KΩ
Resonant Frequency		318.86KHz	1.067MHz
Magnetising Impedance Equivalent Circuit	Parallel Capacitance	214.77pF	158.90pF
	Parallel Inductance	1.16mH	140.01μH
	Parallel Resistance	20.11KΩ	27.37KΩ
Maximum Leakage Impedance		1.96KΩ	6.07KΩ
Resonant Frequency		12.13MHz	13.56MHz
Leakage Impedance Equivalent Circuit	Parallel Capacitance	68.81pF	57.61pF
	Parallel Inductance	2.50μH	2.39μH
	Parallel Resistance	1.96KΩ	6.07KΩ

From , it is obvious that the inductance of equivalent circuit model of the transformer drops from 1.16mH to 140.01μH as temperature changes from room temperature to -196°C, this substantial difference in the inductance may cause trouble for a power system using such a transformer. The reason is that power supply for cooling system (for cooling of liquid nitrogen) is usually provided by the same power system that is using the superconductor transformer, and the cooling temperature for superconductor cannot reach -196°C when the power system is being initialized, consequently the transformer may not function well as designed for condition of -196°C. In addition, in case of failure of cooling system, the overall power system may also not work any more. It therefore sets a temperature constraint for the power system. Furthermore, if we considered the coupling of transformer, it was shown that the transformer used in this experiment has a poor coupling coefficient at -196°C, which were plotted in Figure 4 against switching frequency at room temperature and -196°C, it can be seem that the coupling of transformer at room temperature is better than that at -196°C.

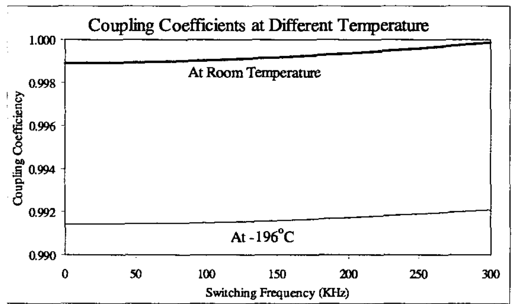

Figure 4: Coupling Coefficients vs. Switching Frequency

To conclude that the disadvantages of power transformer using superconductors as windings and soft ferrite as core include: (a) unpredictable inductance of transformer winding, and (b) poorer coupling between transformer windings under extremely low temperature.

3. Design of the Proposed Transformer

As above-mentioned the problems of using ferrite core in superconducting transformer leads to difficulty in design of power converters, we therefore propose a design of power transformer, which offers several excellent advantages including higher coupling coefficient, easy fabrication, low leakage inductance, no core loss and no saturation of flux density. Though the design of the proposed transformer similar to [8,9] but it actually took into account mainly of two aspects, namely winding losses and maximum inductance obtained.

Winding losses are due to skin and proximity effects. Eddy current losses due to skin effect in transformer winding losses were calculated using an effective core diameter concept [10], and it was found that the eddy current losses in multiple strands conductors are higher than that in single strand conductors. Moreover, research work on the proximity losses in multiple strands conductors was done in [11], and the result indicated that the total proximity losses increase as the square of the number of strand, and even for small numbers, they will exceed the eddy current losses. Therefore, the proposed transformer was designed to use single foil wire in order to minimize eddy current and proximity losses. In addition, a detailed study about inductor design in the aspect of maximum inductance obtained with minimum wire was published in [12], where the calculations indicated multiple layer inductors use significantly less wire than single layer inductors to achieve the same inductance and are much more compact, so that we use multiple layer design in the proposed transformer.

A) High Frequency Superconducting Air-Core Transformer

The proposed power transformer is constructed by using superconductor wound on an air core, the primary and secondary windings as shown in Figure 5 are spiral in shape, and they are made in bifilar way [13] and interleaved each other. Each layer contains only one turn and the number of primary and secondary are both 19 turns. The inner and outer diameters are 42mm and 70mm respectively, and the height is 3mm. The superconductor is high temperature superconducting material YBCO with rectangular shape 0.28mm × 3mm and the winding is insulated by polyester.

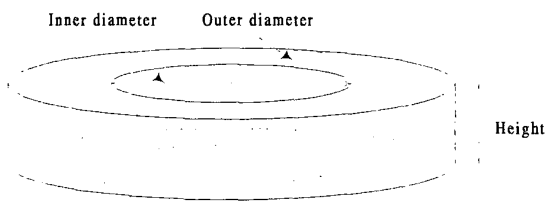

Figure 5: Superconducting Air-core Transformer

The bifilar and spiral arrangements are important because the external field due to the primary and secondary windings can be cancelled and hence the leakage field is small, this arrangement is also to ensure the 'critical magnetic field' does not exceed.

B) Leakage field and mmf

The transformer proposed here is slightly different from Ref [8,9], which suggested an air core pulse transformer for gate drive circuit, which is not fabricated in a bifilar method [14] where the interleaving of the primary and secondary winding causes the cancellation of the leakage field. As a consequence, the leakage field and mmf generated by the proposed transformer windings are lessened. Leakage field and mmf of the transformer are of main concern in design consideration because the former causes problem of EMI, and the later increases eddy current losses [1]. The leakage field has been simulated in Figure 6 by finite element package – ANSOFT, it can be seen that the maximum flux density is 1.06mT, the flux density at the fringe of windings is 0.35mT around, and the leakage flux density is as low as 0.3pT. As the leakage field is very weak and can be confined to a very small region, so the EMI problem will not be severe.

C) Transformer with Parallel Capacitor

The magnetising impedance of the proposed transformer was measured using HP-4194A. With the secondary side of transformer open-circuited and the magnetising impedance was shown in Figure 7. Since the relative permeability of air is unity, so the magnetising impedance of the transformer is very small at low frequency, but it increases to its maximum of 51.9KΩ at resonant frequency of 16.62MHz.

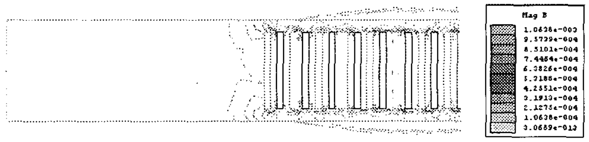

Figure 6: Simulated Leakage Field

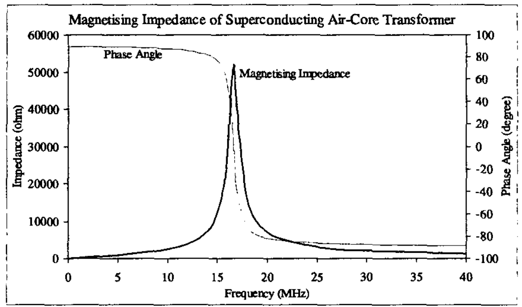

Figure 7: Magnetising Impedance

Deducted from Ref [8,9], it is possible to operate the transformer at its self-resonant frequency so that the magnetising current can be minimized, but this self-resonant frequency is very high, and the switching losses are huge if the active switches of converter operate under such high frequency, also the energy required for gate drive circuits cannot be neglected. Additionally the increasing difficulty and complexity to build a gate driver circuit for such high frequency operation make production cost of converter higher and higher. It is therefore impossible for engineers to design SMPS without any limits on switching frequency. To reduce the self-resonant frequency of air-core transformer, we therefore inserted a 0.01uF capacitor in parallel with the transformer's primary, and the resultant frequency response was demonstrated in Figure 8. Although the maximum impedance decreases to 18.92kΩ, the self-resonant frequency is now reduced to 287.8kHz, which is much more practical for engineers to design their commercial products. Though many research studies were published regarding converters with switching frequency of megahertz, the commercial converters are still mainly operating in range of kilohertz.

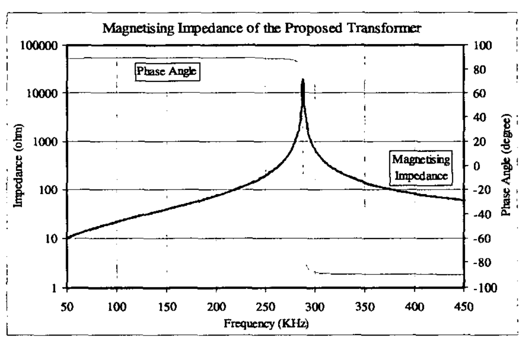

Figure 8: Magnetising Impedance with Capacitor of 0.01μF

D) Liquid Nitrogen

To further reduce the power loss in transformer, the air-core transformer made up of superconductor is immersed into liquid Nitrogen, where the temperature is at -196°C. Under such condition, the measured equivalent series resistance of air-core transformer is less than 5mΩ at 1kHz. The magnetising inductance also changes but resonance frequency remains the same.

With the self-resonant technique and superconducting material, we are therefore able to design a power transformer for a converter such that it operates at the self-resonant frequency of transformer to minimize the power loss.

4. Experiments and Analyses

Since the design of the proposed transformer was based on an assumption that power loss in transformer will be minimum if it operates with its self-resonant frequency, so we had to prove this hypothesis by means of experiments, which demonstrated the conversion efficiencies of a converter using the proposed transformer under a wide range of switching frequency, but it shown that the optimal operating frequency of the converter depends on not only the switching frequency of the proposed transformer, but also the switching loss of active devices, therefore a guideline for choice of the optimal switching frequency was suggested. In order to identify the efficiency of a converter at a specific switching frequency, so the converter must be able to operate at constant frequency. Therefore, a constant switching frequency phase-shifted DC-DC converter [15] was utilized in the experiments.

A) Experiments

The converter is comprised of two full bridges, namely the inverter-bridge and rectifier-bridge, which are connected with the proposed transformer. The gate signals applied to the two legs of inverter-bridge have a phase shift that controls the output voltage. Figure 9 shows the topology of the converter, where V_{in} and V_{out} are input and output voltage, Q_1 to Q_4 are MOSFETs IRF530N, D_1 to D_4 are rectifier diodes MBR1045, L_{out} and C_{out} are inductor and capacitor of output filter, R_L is load resistance and the turn ratio N_1:N_2 of the proposed transformer is 19:19.

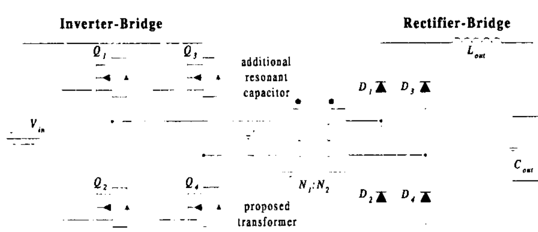

Figure 9: Phase-Shifted DC-DC Converter

The experiments were the carried out with V_{in} = 60V, V_{out} = 24V, output power = 96W, switching frequency = 50kHz to 450kHz, and power transformer operates under superconducting and non-superconducting conditions. The experimental results were shown in Figure 10.

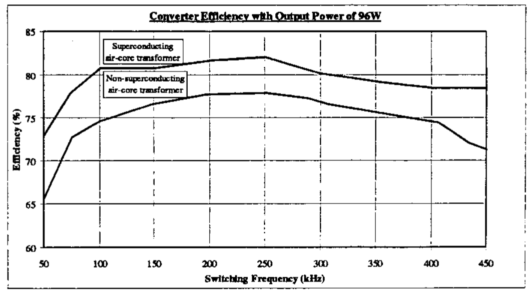

Figure 10: Converter Efficiency with Output of 96W

Some main points can be summarized from the above experimental results: (a) under low and high frequencies, the converter efficiencies were decreasing, (b) the maximum efficiency occurred at about 250kHz, but not at the self-resonant frequency of 287.8kHz, however it remained more or less constant around 250kHz, and (c) there was about 5-10% increase in efficiency when the transformer was immersed in liquid nitrogen.

The first and second points of observations seemed to be a little different from our expectations, but the discrepancy will be explained in next section of loss analysis. However, the third point is clear since the resistance of superconductor drops to nearly zero ohm under extremely low temperature, therefore the I^2R loss will be minimized.

B) Loss Analysis

A great effort was done in working out the different types of power loss in the same frequency range. These power losses include losses in MOSFETs and diodes, winding loss, switching loss and some unidentified losses.

As the waveforms of voltage and current of the converter are not independent on switching frequency, so it is necessary to include the phase shift in the calculations of power losses. This incurs a lot of measurements and computations with trivial accuracy; therefore we applied root mean square (rms) values in calculating the losses and made an assumption that all the waveforms are sinusoidal. The loss analysis was made for the case at room temperature only.

Winding Loss

Calculations of winding loss were tabulated in Table 2.

Table 2: Winding Loss

Frequency (kHz)	Total Leakage Resistance (ohm)	Magnetising Impedance (ohm)	Magnetising Current (A)	Winding Loss (W)
49.81	0.505	10.29	5.83	24.41
75.54	0.519	16.52	3.63	15.12
100.10	0.532	23.07	2.60	11.58
147.90	0.556	40.40	1.49	8.36
197.20	0.581	79.52	0.75	6.57
251.70	0.611	383.38	0.16	5.28
288.90	0.634	378.10	0.16	5.48
306.90	0.645	200.37	0.30	5.96
406.50	0.719	61.86	0.97	8.88
434.50	0.744	54.65	1.10	9.67
518.10	0.832	35.50	1.69	13.47

where:

$$\text{Magnetising Current} = \frac{\text{Input Voltage}}{\text{Magnetising Impedance}} \quad (1)$$

$$\text{Winding Loss} = (\text{Magnetising Current})^2 \times \frac{\text{Total Leakage Resistance}}{2} + (\text{Output Current})^2 \times \frac{\text{Total Leakage Resistance}}{2} \quad (2)$$

Switching Loss

Table 3 listed the measurements of switching currents and hence the switching loss.

Table 3: Switching Loss

Frequency (kHz)	$I_{(no\ load)}$ (A)	$I_{(xfmr)}$ (A)	$I_{(rectifier)}$ (A)	$I_{(converter)}$ (A)	$I_{(total)}$ (A)	Switching Loss (W)
49.81	0.220	0.210	0.010	0.005	0.015	0.900
75.54	0.125	0.110	0.015	0.008	0.023	1.368
100.10	0.110	0.075	0.035	0.010	0.045	2.700
147.90	0.120	0.090	0.030	0.016	0.046	2.760
197.20	0.166	0.135	0.031	0.020	0.051	3.060
251.70	0.205	0.110	0.095	0.024	0.119	7.140
288.90	0.300	0.210	0.090	0.038	0.128	7.680
306.90	0.320	0.203	0.117	0.040	0.157	9.420
406.50	0.340	0.180	0.160	0.041	0.201	12.060
434.50	0.370	0.170	0.200	0.043	0.243	14.580
518.10	0.503	0.300	0.203	0.050	0.253	15.180

where:

$I_{(no\text{-}load)}$ = Input current with no-load

$I_{(xfmr)}$ = Input current with transformer secondary open-circuited

$I_{(rectifier)}$ = Switching current of rectifier-bridge referred to transformer primary

$I_{(converter)}$ = Input current with converter bridge open-circuited (i.e. switching current of converter-bridge)

$I_{(total)}$ = Total Switching Current

Switching Loss = ($I_{(total)}$) × (Input Voltage)

Loss in MOSFETs

Turn-on resistance of IRF540N, $r_{DS(on)} = 0.11\Omega$

Current (rms) flowing through MOSFET ≈ Input current, I_{in}

Loss in MOSFETs = $I_{in}^2 \times r_{DS(on)}$

Loss in Diodes

Forward volt drop of diode inside IRF540N, $V_{drop} = 0.57$V

Current (rms) flowing through diode ≈ Output current, I_{out}

Loss in Diodes = $I_{out}^2 \times V_{drop}$

Power Losses

Summarizing all the different power losses, Table 4 finalized the losses analyses. Figure 11 plotted the data in Table 4 demonstrating the distribution of different power losses, which include all the above losses as well as some unidentified losses. The unidentified losses take account of (a) I^2R losses due to equivalent series resistance (ESR) of circuit components and cables/wires, (b) error in measurements of experimental readings and (c) error caused by assumptions in calculations of losses.

After analyzing the results in Figure 11, the following phenomena can be concluded: (a) Power loss in MOSFETs is fairly constant; it is because the turn-on resistances of MOSFETs are independent on switching frequency so the loss is determined by the square of the current that flows through the MOSFETs, and this current has a small change over the range of switching frequency; (b) As the forward volt drop in body diode is unchanged and the RMS value of output current is fixed, so the power loss in diodes is constant; (c) The switching loss increases as frequency, it is due to the fact that switching loss is directly proportional to frequency; and (d) At low frequencies, winding loss is relatively large, and achieves a minimum of about 10% of rated power about 260kHz. Beyond this frequency, this loss is increasing. While operating at the self-resonant frequency of the transformer, the converter has a minimum magnetising current that increases when the frequency further increases or decreases. As a result, the primary current increases at low and high frequencies, such that the winding loss enlarges due to (primary current)^2 × (leakage resistance).

Table 4: Power Losses

Frequency (kHz)	Input Current (A)	Converter Efficiency (%)	Loss in MOSFETs (W)	Loss in Diodes (W)	Winding Loss (W)	Switching Loss (W)
49.81	2.440	65.57%	1.310	4.560	24.410	0.900
75.54	2.200	72.73%	1.065	4.560	15.116	1.368
100.10	2.145	74.59%	1.012	4.560	11.581	2.700
147.90	2.090	76.56%	0.961	4.560	8.363	2.760
197.20	2.060	77.67%	0.934	4.560	6.572	3.060
251.70	2.055	77.86%	0.929	4.560	5.281	7.140
288.90	2.070	77.29%	0.943	4.560	5.479	7.680
306.90	2.090	76.56%	0.961	4.560	5.962	9.420
406.50	2.150	74.42%	1.017	4.560	8.883	12.060
434.50	2.220	72.07%	1.084	4.560	9.671	14.580
518.10	2.350	68.09%	1.215	4.560	13.475	15.180

Spec.: Input Voltage = 60V, Output Voltage = 24V, Output Current = 4A, Output Power = 96W

Since the unidentified losses are only 10% or less, this ascertains the results of loss analyses, and some research works [4,16] have proved the power loss in air-core transformer is typically larger than that in ferrite core transformer, and the average efficiency is around 70-85%.

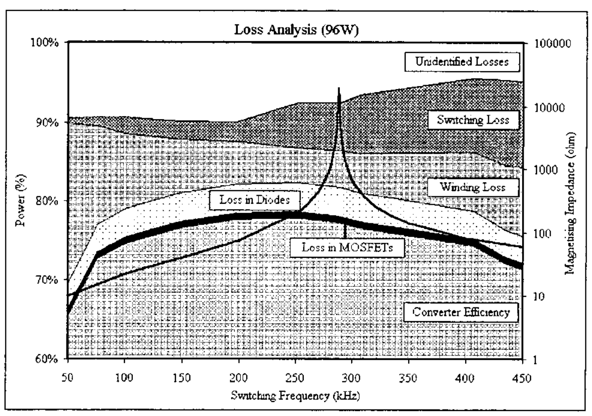

Figure 11: Loss Analysis

C) Choice of Optimal Switching Frequency

To reduce the switching loss, the converter should operate at lower switching frequency, nevertheless, the magnetising impedance of air-core transformer will exhibit low resistance at such low frequency; it then causes higher winding loss in transformer. On the contrary, if the switching frequency of converter is increased to higher range, the total power losses increase significantly due to both of large winding and switching loss. Therefore, a simple procedure described as follows provides a guideline for choice of the optimal switching frequency.

1. Specify the percentage of power loss in transformer,
2. Work out the magnetising current by (2),

3. Obtain the magnetising impedance by (1),
4. Find the optimal switching frequency from graph or equivalent circuit model.

Example:

We design a converter as used in the above experiments with V_{in} = 60V, V_{out} = 24V, output power = 120W and maximum winding loss allowed is 10% of rated power.

Then:

$$\text{Magnetising Current} = \sqrt{\frac{\text{Winding Loss} - (\text{Output Current})^2 \frac{\text{Total Leakage Resistance}}{2}}{\frac{\text{Total Leakage Resistance}}{2}}}$$

As the change of total leakage resistance is small around the self-resonant frequency, where the leakage resistance is thus assumed to be used in calculating the magnetising current.

$$\text{Magnetising Current} = \sqrt{\frac{12\text{W} - (5\text{A})^2 \frac{0.64\Omega}{2}}{\frac{0.64\Omega}{2}}} = 3.5\text{A}$$

And, the $\text{Magnetising Impedance} = \frac{60\text{V}}{3.5\text{A}} = 17.1\Omega$

From Figure 8, the optimal switching frequency is around 100KHz when the magnetising impedance is 17.1Ω. Moreover, the actual winding loss is 12.7% and the overall converter efficiency is 72.73% at 100KHz, this result is close to the maximum efficiency of 74.07%. Therefore, the switching frequency of a converter using the proposed transformer can be determined by this guideline.

5. CONCLUSIONS

The losses in MOSFETs and diodes are determined by the choice of components and the power rating of the converter, so that these losses cannot be reduced or eliminated technically. Moreover, the switching loss, though minimized greatly by soft switching technique, still contribute a lot to the overall power losses, it is due to the fact that leakage inductance of air-core transformer is higher than that of ferrite core transformer, such that the switching noise caused by the large leakage inductance and some other parasitic capacitance impairs the switching performance of MOSFETs, this eventually deteriorates the conversion efficiency. And the winding loss as the experimental results demonstrated confirms our hypothesis, that is the proposed transformer has a maximum efficiency while operating at its self-resonant frequency. However, the experimental results also revealed that the optimal switching frequency of a converter using the proposed transformer is not located at its self-resonant frequency, because the power losses depend on both winding loss and switching loss, therefore a simple guideline for the optimal switching frequency was suggested. In addition, it can be seen that using superconducting transformer, there is a saving of 6%-10% efficiency, this technique however is most suitable for high power system.

The followings list the advantages offered with the proposed transformer:

- No inrush current caused by magnetic saturation
- No higher harmonics induced by magnetic saturation
- Reduction in weight and cost of the converter by removing the ferrite core
- Minimization in consumption of winding copper used in construction of transformer, it therefore further cuts down the production cost of converter

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