Proceedings of the International Conference on
Robotics, Vision, Information and Signal Processing ROVISP2005

Design And Development Of High Frequency High Power Transformer For Renewable Energy Application

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Abstract

This paper presents a design and fabrication of a high frequency transformer for 5 kW power rating. Within an operating frequency of 25 kHz, a MnZn P type core has been utilized. Two set of E-E geometry cores had to be stacked in order to achieve the calculated 64.14 cm^4 *of the* W_AA_C *volume. Test and validation of the designed shows that the prototype designed transformer had proven to be very compact, higher fill factor, smaller in size, lighter in weight if compared to other winding approaches which utilizing copper round wires. The measured overall losses of the transformer itself were remain below the expected value of 32.974 W. The efficiency of the transformer was found to be at 93% average. Overall test results also show that the design and implementation of this high frequency power transformer is applicable especially for renewable energy system..*

Keywords
Ferrite core, magnetizing current, DC-DC converter, DC-AC inverter, transformer

I. INTRODUCTION

In order to simulate the real application of the high frequency power transformer, a complete high power DC-AC inverter system has been built. The full bridge of DC-DC converter and DC-AC inverter for 5 kW rating has been fabricated thus the efficiency and overall capability of the transformer can be evaluated. Figure 1 shows the schematic diagram of the designed system.

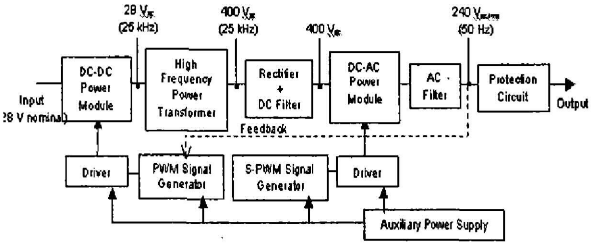

Figure 1: The schematic diagram of the developed renewable energy inverter system.

Typically, it comprises of a high frequency power transformer, power modules, PWM signal generators, filters, drivers and the auxiliary power supply [1,2].

II. TRANSFORMER CONSTRUCTION

At the first place, the high frequency power transformer was designed to handle a throughput of 5 kW power. The incoming voltage level of the system is expected to be at 24 to 32 V. This transformer will step-up the voltage to 400 V before next conversion into 240 V rms taking place. The diagram of the proposed transformer is shown in Figure 2.

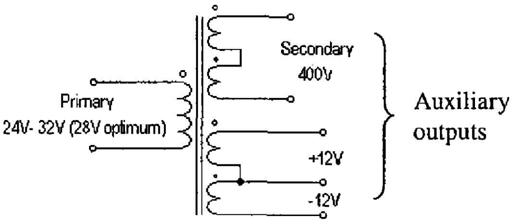

Figure 2: Schematic of the high frequency power transformer with 2 auxiliary outputs.

The transformer primary number of turns (N_{pri}) can be calculated from Faradays law:

$$N_{pri} = \frac{V_{nom} x 10^4}{k B_{max} A_c f} \qquad (1)$$

Where;

V_{nom}	is the nominal transformer input voltage (V),
B_{max}	is the maximum flux density for core material (T),
A_c	is the transformer core c.s.a.(cm^2),
f	is the DC-DC regulator switching frequency (Hz), and
k	is the constant [k= 4.44 (sine wave), k= 4.0 (rectangular wave)]

While the additional voltage drop caused by switching pattern and the involved discreet components also have to be considered in the secondary turns calculation. Thus, the secondary turns (N_{sec}) should be determined as:

$$N_{sec} = \frac{1.1(V_{out} + V_{fwd})(N_{pri})}{(V_{in\_min})(\delta_{max})} \qquad (2)$$

Where;

N_{sec}	is the secondary number of turns
V_{out}	is the required output voltage
V_{fwd}	is the voltage forward drop of the rectifier
V_{in_min}	is the minimum input voltage (24V)
δ_{max}	is the maximum allowable duty-cycle (Typically 0.95).

Meanwhile, other secondary number of turns ($N_{sec\ (n)}$) shall be determined by the equation of:

$$N_{sec(n)} = \frac{(V_{out(n)} + V_D)N_{sec(1)}}{(V_{out(1)} + V_{D1})} \qquad (3)$$

Where;

$V_{out(n)}$	is the additional output voltage, and
V_D	is the anticipated rectifier's forward voltage drop.

However, since the flux density (B_m) depends typically on the type of material to be utilized, the core has to be decided first before further calculation can be made.

III. TRANSFORMER CORE SELECTION

Transformer design basically consists of core and coil indeed. Existing in the market, there were many types of materials for the core that was designed with their own criteria and optimum operating parameters. As the transformer has been decided to be at high frequency switching yet to retain any switching losses, a 25 kHz operation was considered as an ideal value [3].

Basically, an ideal core material for a high frequency power transformer should have a high flux density, low coercive force and high permeability as shown in the core B-H loop of Figure 3 [4,5].

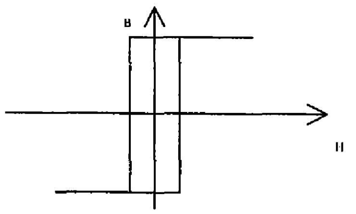

Figure 3: Ideal B-H loop for magnetic core

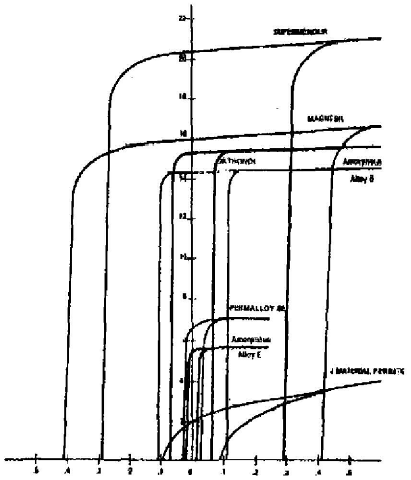

Figure 4: B-H Loops of various materials for power transformer application

It can be seen from Figure 4 that, Supermendur (cobalt-iron) material hold the highest flux density compared to others, therefore, as if size become the most important to be considered in the particular design, this material will offer the smallest core size

a. Core Losses Consideration

The heat generated within the core usually caused by loss characteristic of the material itself. This core loss characteristic was basically referred to the combination of Eddy current loss, hyteresis loss and residual current loss. However, as for the power transformer application and also with the frequency range remains below 100 kHz, the Steinmetz Formula is given by the following equation:

$$P_c = K_1 * f^{K2} * B^{K3} \qquad (4)$$

Where

P_c	is the core power loss density (mW/cm^3),
f	is the frequency (kHz),
B	is the flux density (kG), and
K_1, K_2, K_3	is the loss coefficients.

The curve fit graph of the related core loss characteristics was then plotted using equation (4) with the loss coefficient from Magnetics and can be observed in Figure 5. After the comparison has been made, only P, R and F material were seemed to be suitable for the application as the power transformer core. It shown that even though J and W material hold the highest permeability, they would emit too high core loss at the frequency of 20 kHz and above. Only P, R, F and K materials remained within the acceptable range core loss of 300mW/cm^3 (IEEE std, 1992) [5,6]. Meanwhile, the permeability for K material was too low thus it has to be exempted due to the economic consideration for the required frequency range.

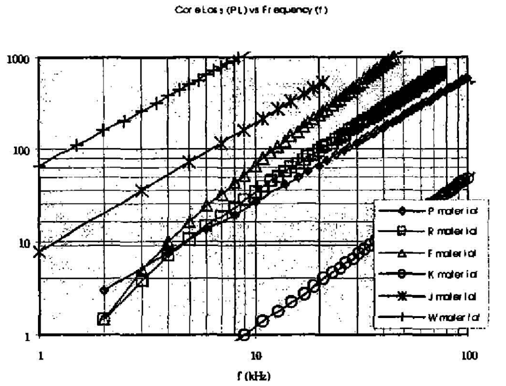

Fig. 5. The magnetic power loss for P,R,F,K, and W MnZn material as a function of frequency.

b. Core Size Consideration

Once the core material has been determined, the next step to be considered is the selection of core size within the operating frequency range and output power. Therefore, it is better in a certain cases to select a core with a smaller diameter, but with the same cross-sectional area, to insure that the windings will completely fill the core window. Total power handling capability of the core usually characterized by their area product (W_aA_c). Consequently, most of the designed transformers were referred to the same equation (5) for their required W_aA_c.

$$W_aA_c = \left(\frac{P_o}{K\Delta B f_{sw}} \right)^{4/3} \qquad (5)$$

The value of window utilizing factor (k), is depending greatly on the effective winding area of the core (W_a), the fill factor and the laminating thickness of the conductor that sharing the particular window area (DeMaw,1981). As for the project the value of k was considered as 0.4 also with the assumption that the operating waveform would be in rectangular.
As a result, the value of $W_aA_{c\_total}$ then becomes:

$$W_aA_{c-total} = \frac{P_{total} x10^4}{1.6 B_m f J} \qquad (6)$$

As for the first R material from Magnetics, the W_aA_c of 2 x 30.8 = 61.4 cm^4 would be constructed by stacking two cores together. Therefore, by rearranging equation (3.9), the maximum flux density then becomes:

$$B_m = \frac{P_{total} x10^4}{1.6 W_a A_c f J} = 0.209T$$

c. Winding Implementation

Based on the evaluation, the combinations of E-E or E-C Ferrite cores had to be implemented. However, there were no bobbin or any special coil former was accompanied. Thus, the winding has to be directly applied on the cores or the initial bobbin can be modified accordingly with a high safety precaution, so that the required transformer safety standard (IEEE, 1988) is complied. As a result, in order to minimize the effects of high frequency operation and also to keep the winding arrangement firm within the core, foil type winding implementation was chosen rather than a solid wire or a bunch of litz wire [7,8,9]].

Figure 7 shows the expected 3D picture of 5 kW high frequency power transformer designed with foil interleaves winding on the double-stacked E-E Ferrite cores.

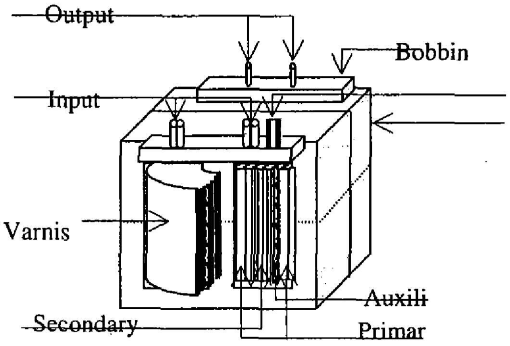

Fig.7. The 3D picture of a 5 kW high frequency power transformer

IV RESULTS AND DISCUSSIONS

The objective of the transformer designed was for 5 kW rating for inverter applications, therefore the calculated parameters for the system can be summarized as in Table 1.

Table 1. Parameters for the inverter system

Parameters	Magnitude	Unit
Rated Output Power	5000	W
Nominal DC Input	28	V
Rated DC Input Current	197.86	A
AC Output Voltage (V_{rms})	240	V
Rated AC Output Current (I_{rms})	20.83	A
AC Output Frequency	50	Hz

The pictures of the fabricated high frequency power transformer are shown in Plate 1 and 2.

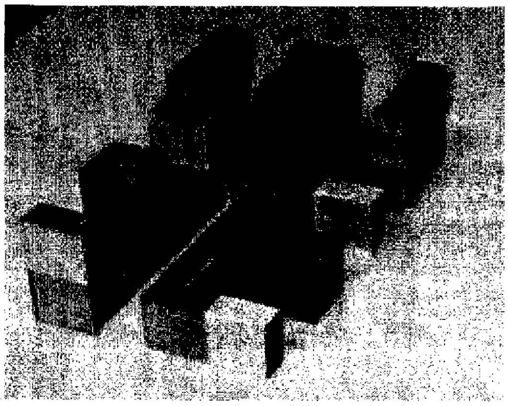

Plate 1. Combination of four P-material E-E type ferrite cores.

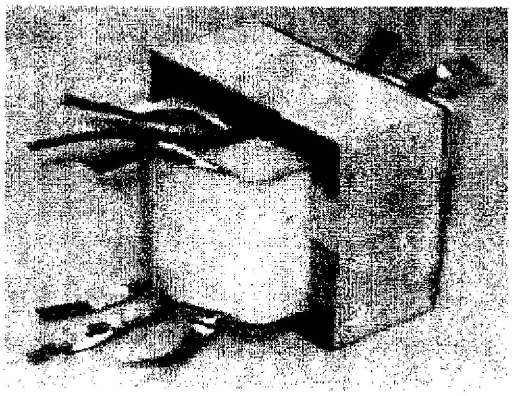

Plate 2. Fabrication of a 5kW power transformer.

The measured data of the primary and secondary winding were recoded as in Table 2.

Table 2. Verification of losses components for the fabricated interleave foil winding transformer

Parameter		Calculated	Measured
Magnetizing inductance, L_m		-	28.0 μH
Primary DC resistance, R_{dc}	$R_{dc(p1)}$	270.29×10^{-6} Ω	18×10^{-3} Ω
	$R_{dc(p2)}$	380.29×10^{-6} Ω	27×10^{-3} Ω
Secondary resistance, R_{sec}		3.10×10^{-3} Ω	1.574 Ω

Table 3 shows the comparison between calculated and measured losses components of the high frequency power transformer

Table 3. Calculated and measured losses.

Parameter	Calculated	Measured
Total Core loss, P_{core}	15.8 W	15.96 W
Total Winding losses, P_{wdg}	25.425 W	17.64 W

Figure 8 shows the measured efficiency of the prototype DC-DC part, high frequency power transformer part and DC-AC inverter part. It shows that the DC-DC converter seemed to have lower efficiency at the light loads. However, it rose accordingly after 1000 W load was applied. This situation was actually due to higher switching loss as the duty cycle had been decreased at lower loads. When the applied loads had elevated, the duty cycle become wider and the switching loss was at minimum as compared to conduction loss.

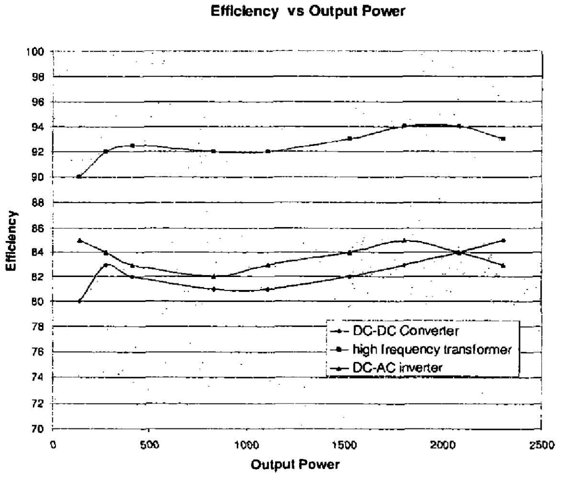

Fig 8. Efficiency versus output power of the complete system

V. CONCLUSIONS

Test and validation of the designed shows that the prototype designed transformer had proven to be very compact, higher fill factor, smaller in size, lighter in weight if compared to other winding approaches which utilizing copper round wires. The measured overall losses of the transformer itself remain below the expected value of 32.974 W. From the measurement the efficiency of the transformer was found to be at 93% average. Overall test results also show that the design and implementation of this high frequency power transformer is applicable for 5 kW applications.

ACKNOWLEDGEMENT

The authors would like to thank USM for its sponsorship under USM short term grant.

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