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Review on Magnetic Components: Design & Consideration in VHF Circuit Applications

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ABSTRACT

When converters operate in megahertz range, the passive components and magnetic devices generate high losses. However, the eddy current issues and choices of magnetic cores significantly affect on the design stage. Apart from that, the components' reduction, miniaturization technique and frequency scaling are required as well as improvement in thermal capability, integration technique, circuit topologies and PCB layout optimization. In transformer design, the winding and core losses give great attention to the design stage. From simulation work, it is found that E-25066 material manufactured by AVX could be the most suitable core for high frequency transformer design. By employing planar geometry topology, the material can generate significant power loss savings of more than 67% compared to other materials studied in this work. Furthermore, young researchers can use this information to develop new approaches based on concepts, issues and methodology in the design of magnetic components for high frequency applications.

Keywords: Magnetic component, Transformer design, VHF converter

1. Introduction

The development for size reduction of passive components such as inductors and transformers in line with the increase in switching speed has reached a critical barrier limit. In megahertz frequency, the presence of high current and voltage will produce harmonic components. Even efforts to develop highly cost and volumetric effective magnetic components with significantly improved performance do not solve interconnect impedance (parasitic) at these frequencies [1]. In addition, the height of magnetic components also becomes the issue with regards to volume and power density. One solution is to increase the frequency but this will then increase power loss.

Magnetic components are important in the study of very high frequency (VHF) power converters. The increase in frequency signifies the reduction of magnetic and electrical energy storage in power converters, but this gives rise in high losses. The losses are mainly due to the loss in the winding material (eddy current effect), especially in transformers [2, 3]. This is one of the major problems in the design of magnetic components, primarily caused by skin and proximity effects other than the

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magnetic core itself. Therefore, the improvement of the winding conductor and the magnetic core are required to satisfy VHF operation of power converters.

2. Winding Loss Optimization

The eddy current effect increases an effective resistance of the conductor in line with current frequency and therefore, generates higher dissipation in the conductor as well as proximity effect which can complicate the design of magnetic components at high frequency. So, due to these constraints, winding optimization is required. The study first started in 1883 by Horace Lamb for spherical conductors, and the work continued for the generalized shape by Oliver Heaviside in 1885 [4]. The winding of conductor around the core requires comprehensive understanding in order to prevent the losses which can be optimized by:

i) using a smaller diameter wire to increase DC resistance and hence reduce proximity effect.

ii) removing the winding from the area with strongest field for lowest loss shape on total winding loss.

Among the conductors, Litz wire has been tested in magnetic component windings for up to 1 MHz frequency [5]. On contrary, in order to minimize eddy current loss, the numbers of strand wires have to be optimized to avoid reduction in DC resistance.

3. Magnetic Core Loss

The choice of magnetic core material depends on its ability to operate in certain frequency range. If the application of frequency is too high, the core will generate heat and hence produce losses. The magnetic cores are commonly used in standard transformers and inductors. The suitable size and shape of the core must be carefully designed for the application prior to the fabrication because using different shape of material used may result in different outcomes. More detailed geometrical factors on the shape of materials for the use in application are tabulated in Table 1.

3.1 Shape of Materials

From Table 1, the best shape of material that is suitable for VHF operation is the planar core because of its lower leakage inductance due to high value perimeter area ratio of conductors and low profile.

Table 1 Description of shape of materials in design selection

Shape of material	Description of use (Pro / Cons)
Cylindrical rod	Inductor tuning for radio technology. Electromagnetic interference (EMI) is present and can cause problems.
"U" type	Easiest way to form a closed magnetic circuit. Some with sharp or rounded corners.
"E" and "I" types	Low profile design for transformer and inductor. Have centered leg with different size and shape. Possible air gap required to shorten the middle leg to reduce fringing.
Pot core type	Having rounded with internal hole and is used for shielding effect to prevent radiation.
Toroidal core	Keeping magnetic field strength within core material and minimize EMI. Highly efficient for high power and small volume transformer and inductor.
Planar core	Consists of two flat pieces of magnetic materials used with flat coil for printed circuit board (PCB). A coreless planar transformer can be produced for a high frequency operation especially in MHz range and it can also be integrated in an IC based design [6]

3.2 Magnetic Core Materials

There are many types of magnetic core materials available and their descriptions of use are summarized in Table 2. More detailed explanation is described in [7]. Choosing the best type of core material is important to ensure the reliability and efficiency in high frequency applications, especially when high current and voltage are concerned.

Other factors that should be investigated include the effects of air gap level in the magnetic core, operating temperature and hysteresis loss. All of these factors come together as a basis of magnetic core loss consideration.

Table 2 Types of Materials and their description of use

Type of material	Description of use
Laminated silicon steel	Iron is widely used. It can sustain a high level of magnetic field however it cannot be applied in bulk since high loss is expected due to high eddy current effect.
Lamination	Contains insulated iron sheet around the core that gives many fractions of small individual sections. This leads to higher resistance and hence lower eddy current loss.
Silicon alloy	Combination of iron and silicon to make a core improve resistivity. A type called grain-oriented is suitable for core as being anisotropic and offers better magnetic properties.
Carbonyl iron	Better properties, stable and can operate at high temperature and magnetic field levels. It is widely used in broadband inductors. Perm alloy is the best.
Iron powder	Kool Mμ® has high permeability but low Q factor. Commonly used for EMI filters and chokes.
Ferrite / Ferrite Powder	Used for high frequency applications. For example, Ferrite 3c92 [8], having high resistivity and does not suffer from additional eddy current loss due to fringing air-gap. Ferroxcube materials that can operate up to 10 MHz [9]. NiZn ferrites have low permeability, higher resistivity and hence lower loss [10].

3.3 Thermal conductivity

Due to different level of conductivity, the operating limit of temperature in the conductor is also different. For lower thermal conductivity, heat sink is required to sustain the rise of temperature as the cooling device (apart from natural air, forced air and cooled water) heat sinks. Normally, power rating of magnetic components determines the type of heat sinks used. However, discrete heat sink materials are space consuming. Thus, there is a need to study embedded cooling system for the magnetic components.

4. Issues in Magnetic Component Design

When operating frequency increases, more design dilemmas come into picture. The magnetic components radiate energy or can be known as 'radiation source.' They take about 30% to 50% of the converter volumes [11]. In a high density converter design, the ability to remove the heat from the magnetic component surface will decrease. This results in higher core and winding losses.

Minimization of eddy current is essential. One way is to have correct core materials selection, which inhibits low electrical conductivity or laminations. However, the size and cost of magnetic components have to be ensured in addition to the optimized magnetic core calculations [12, 13]. Realizations of flat magnetic together with thin flex foils windings have been introduced with the help of integration methods [14]. Here, PCB fabrication can be adopted by integrating the windings and converter circuitry. Even though the height of components is reduced, the application of PCB technology results in greater footprint size area [15, 16].

5. Design Approach

5.1 Analytical Method

There are many methods available in the design approach. However, at earlier stages, they suffered from major drawbacks. In other words, the analytical methods require CAD simulation to justify the design. The earliest method introduced was the McLyman Method. This method relates the design of magnetic component based on the device ratings. The ability of core material to carry magnetic flux and coil windings determines the suitability of the core. The formula derived for this approach is given by (1):

$$A_P = \left(k \frac{VA}{fB_m} \right)^{\alpha} \qquad (1)$$

where

A_p = area product of given core, m^2,
k = combination of material constant,
VA = apparent power, W,
B_m = maximum flux density, 580 mW/in^3
f = maximum operating frequency, Hz, and
α = constant dependent on core material.

From (1), the size of area product of the core material can be calculated having known the other parameter values. This approach is used to determine the size of area product of material. However, this approach lacks control on skin and proximity effects in the windings which constitute major drawbacks. The solution came from the introduction of the Vandelac-Ziogas Method [17]. This method determines the magnetomotive force (mmf) distribution in the coil winding at the cost of heavy computational efforts.

The extension of the work provides numerically based solution using computer, called Finite Element Method (FEM). It uses the Vandelac-Ziogas algorithm to obtain low core and copper losses by correlating results to the conventional techniques.

5.2 Computer Aided Design Simulation

Designing magnetic components for VHF applications is not easy due to the loss effects. In VHF design, the magnetic components are constrained by their losses in the winding and core losses. Modeling to estimate these losses under various excitations is important. It eventually gives further difficulties in modeling the core loss due to modeling hysteresis loss [18, 19].

CAD tools are used to predict efficiency in the design stage where skin effects inside the windings of VHF transformers and resonant inductors are considered. In the earlier stage of CAD development, the tools did not work in VHF applications due to the skin effects in magnetic components. Magnetic core losses were not considered with good accuracy [20, 21]. Further development has improved transformer design and loss calculation using Fourier Series Method (FSM) [22].

The modeling of the windings, inductors and study of stress analysis can be represented in block system as suggested in [23]. One of the tools used to model the magnetic components via simulation is the PExpert6, developed by Ansoft Corporation which is freely available for evaluation. For winding design optimization technique, the tools can also be adopted as reported in [24].

a) Transformer Design

Practically, designing transformer is painstaking. However, the design stage can be preliminary done using the CAD simulator. This will ensure the fabrication work satisfies the theoretical and simulation analysis. In VHF operation, designing passive components is at stake. Leakage inductance increases switching loss in the circuit and thus reduces efficiency. Moreover, current distributions inside the winding conductors increase copper losses [25]. Some of the modeling methods introduced in literature is described in Table 3.

Table 3 Magnetic Modeling Techniques and Their Dcription

Modeling Techniques	Descriptions
Reluctance Model [26]	Flux distribution within the core structure that includes geometry and energy representation. This work did not consider winding resistance and applicable for lower frequency range.
Vandelac-Ziogas Model [18]	Development of magnetic field calculation and current distribution in the windings resulted in better design.
Finite Element Analysis [14]	Best solution to develop magnetic component design however it is time consuming. Accurate method to calculate leakage inductance and resistance.

On top of that, there are several problems in the transformer design. Prior to the simulation work, designers have to understand issues in the designing process. The limitations can be described as below [27]:

i) Core loss constraint – increasing β_m causes core loss to increase rapidly.

ii) Flux density – changing flux density polarity makes primary turn windings to be chosen appropriately.
iii) Copper loss – decrease rapidly as β_m increases
iv) Total power loss – there is an exact numerical value of β_m that minimizes total power loss.
v) Finding an optimum flux density β_{opt}

b) Integration of Magnetic Components

It has been known that there are barriers limiting the growth of power conversion techniques. The packaging technique, control, thermal management and system integration have become important issues [28]. This is due to the need of new technology for multi-kilowatt power electronics [29]. Multilayer interconnect structure is one of the candidates where metallization device technology can be applied to make the power bus network and other circuitry within the board compacted and well integrated.
Studies have shown that lots of efforts have been made to integrate magnetic components in high frequency environment [30]. Compact and efficient magnetic designs are crucial to ensure the overall weight and volumes are reduced in power converters. Furthermore, an efficient cooling method is needed to reduce heat loss, thus leads to better efficiency [31].

6. Frequency Scaling & Miniaturization Effects

As switching frequency increases, the methods in volume reduction of power converters have been extensively studied in the past decades [32]. The efficiency of the converter systems cannot be sacrificed as a result of increase in frequency. The advancement in magnetic design has reached its limit in VHF power conversion [33]. No major breakthroughs have been achieved in passive materials design. Table 4 tabulates the significant factors which are necessary in the design towards miniaturization of efficient converters [34].

These higher levels of integrations are crucial towards miniaturization to improve power densities. The main key element is governed by volume of isolating power transformer and resonant inductor. From literature, planar inductors were used to let magnetic components run at higher frequencies [36], but unfortunately, high frequency operation induces losses mainly due to eddy current. One way to solve this problem is by having the wound structured type of inductor and magnetic components. They have to be small, compact enough to suit on small-scaled PCB and capable to work in high frequency operation preferably with coreless magnetic.

Table 4 Factors to consider in miniaturization of converter design

Factors to consider	Descriptions
Devices & circuit topologies	Need improvement as circuit topology limits advancement of converter. Devices will be required to operate at higher frequency. Requirement aims at high current and voltage operating at MHz range or possibly at GHz.
Dielectric materials	Materials in magnetic components are frequency dependent and producing non-linear energy storage.
3 Dimensional integrated power electronics	Must be developed to improve characteristics of VHF converters. This lowers interconnection impedances, improves thermal management and reduces profile [35]. Planar metallization can be opted.

In order to make power converters small scaled in volume, the total size mainly relies on sizes of electrical components and the packaging technique so that it will allow for more efficient cooling, mechanical and interconnect functions. On the other hand, the efficiency of the converter has to be maintained regardless to the increase in frequency, temperature and decrease in volume areas.

7. Recent Work on Magnetic Loss Simulation

Software called PExpert6 circuit simulator is used in the work. Table 5 shows the list of respective manufacturers comparing the winding and core losses in each type of core material simulated at 1 MHz frequency. Using several types of magnetic core and winding models in the database, the results show that material core typed E25066 developed by AVX indicates significant reduction in both winding and core losses. Even though Ferroxcube produces the lowest winding loss using E25/16/16 core material, the mean value is still high. From the manufacturers' list of core materials, it is observed that RM1400B developed by AVX has the lowest core loss and is 99.57% better than E25/16/16 developed by Ferroxcube. However, E25/16/16 results in the lowest loss in winding loss, which is 61% loss savings compared to others. Nevertheless, E-25066 shows the prominent results in loss reduction by 67.6% from the mean difference shown in Table 5.

Table 5 Simulated Results of Winding & Core Losses

MANU-FACTURER	CORE TYPES	WINDING LOSS (W)	CORE LOSS (W)	Mean
AVX	RM1400B	0.5961	**0.0018 (LOW)**	0.2989
	E-25066	0.4532	0.0359	**0.2446 (LOW)**
MICROMETALS	E125	1.1600	0.3502	**0.7551 (HIGH)**
	E137	1.1550	0.3543	0.7547
MAGNETICS	RM12	0.5342	0.0298	0.2820
	EE43007	0.9555	0.2219	0.5887
EPCOS	RM12	0.5414	0.0120	0.2767
	E 30/15/17	0.4862	0.0404	0.2633
FERROXCUBE	RM12/ILP	0.5413	0.0317	0.2865
	E25/16/16	**0.4522 (LOW)**	0.4222	0.4372
TDK	RM12	0.5356	0.0095	0.2726
	EE30/30/7	0.4768	0.0470	0.2619
	EE 25.4/32.6.4	0.4532	0.0994	0.2763

Table 5 also presents tradeoffs between winding and core losses. The relationship between these parameters is not linear. In VHF transformer design, it is not easy to design with an expectation of having both low losses in winding and core. From the set of given models, the simulation result shows that from the optimum mean value of 0.2446, the E-25066 material core manufactured by AVX is the best choice of material for magnetic components.

8. Conclusions

There are issues in the design of magnetic components in high frequency. When converters operate at high frequency (MHz), the passive components and magnetic devices generate losses, mainly caused by eddy current. The suitability of magnetic core has to be simulated and analyzed to determine significant reduction in winding and core losses. The miniaturization technique and frequency scaling are required in high frequency environment. Apart from the magnetic design, the thermal, integration technique, circuit topologies and PCB layout optimization are required for improvement. From simulation work using PExpert 6 software, simulated in 1 MHz frequency, it is found that the E-25066 core material manufactured by AVX has the capability and suitable for high frequency in the design of magnetic components.

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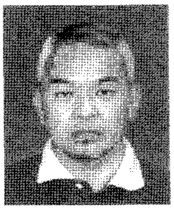

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