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Computer-Aided Electromagnetic Analysis of a Multi-Winding Transformer for SST Applications

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Richard Mauricio Quevedo Castellano

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Richard Mauricio Quevedo Castellano

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Firma del profesor

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Derechos de Autor

Firma del estudiante: _______________________________________

Nombres y apellidos: Richard Mauricio Quevedo Castellano

Código: 00118735

Cédula de Identidad: 1723728075

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RESUMEN

Este artículo propone una simulación y el análisis de un transformador de potencia multidevanado con cuatro puertos y a alta frecuencia, que utiliza el software de análisis electromagnético de elementos finitos. El modelo considera una configuración geométrica bidimensional. El modelo permite el análisis de los mecanismos de pérdida electromagnética dentro del dispositivo. El resultado de la simulación permite verificar las especificaciones de diseño y estimar las pérdidas en los devanados. Los resultados indican una ligera correlación con el aumento de frecuencia dentro del rango de frecuencia estudiado. Esto se debe a la selección del núcleo. El modelo de transformador propuesto podría aplicarse en proyectos de convertidores de potencia para investigación o diseño.

Palabras clave: Transformador multidevanado, Método de elementos finitos, Software de Análisis electromagnético, Transformador de alta frecuencia.

ABSTRACT

This paper reports on the simulation and analysis of a high frequency multi-winding four port power transformer using Finite Element Electromagnetic Analysis software. The model considers a two-dimensional geometric configuration. The model allows for the analysis of electromagnetic loss mechanisms within the device. Simulation result allow to verify the design specifications and estimate the losses in the windings. Results indicate a slight correlation with frequency increase within the frequency range of study. This is due to the selection of the core. The proposed transformer model could be applied in power converters projects for research or design.

Key words: Multi-winding Transformer, Finite Element Method, Electromagnetic Analysis Software, High Frequency Transformer.

TABLA DE CONTENIDO

Computer-Aided Electromagnetic Analysis of a Multi-Winding Transformer for SST Applications

Richard Quevedo
Universidad San Francisco de Quito USFQ
Colegio de Ciencias e Ingenierías
Campus Cumbayá, PO-Box 17-1200-841
Quito, Ecuador
Email: richard.quevedo@estud.usfq.edu.ec

Alberto Sánchez
Universidad San Francisco de Quito USFQ
Colegio de Ciencias e Ingenierías
Campus Cumbayá, PO-Box 17-1200-841
Quito, Ecuador
Email: asanchez.sanchez@usfq.edu.ec

***Abstract*—This paper reports on the simulation and analysis of a high frequency multi-winding four port power transformer using Finite Element Electromagnetic Analysis software. The model consider a two dimensional geometric configuration. The model allows for the analysis of electromagnetic loss mechanisms within the device. Simulation result allow to verify the design specifications and estimate the losses in the windings.**

I. Introduction

Transformers are electrical machines that are commonly used to supply a variety of voltage levels for different equipment or components in electronic circuits and electrical networks. A common and very useful application of multi-winding transformers is in power converters, as for example in distributed energy sources integration[1].

A power transformer in power supplies serves the purpose of transferring energy efficiently and instantaneously from one external electrical source to another external source while providing galvanic isolation. The relation between the primary and secondary windings in a two port transformer, can be established to efficiently accommodate widely different input and output voltage levels. Multiple secondaries with different number of turns can be used to achieve multiple outputs with different voltage levels. In addition, the separated primary and secondary windings facilitate isolation between circuits coupled to their windings.

Several articles address the problem of power flow and losses in multi-winding transformers. In [2] the authors address iron core saturation in a transformer with multiple windings. Their document shows that the interaction between the non-linear magnetic behavior of the iron core combined with the unbalanced parameters of the circuits, and the secondary coils of the transformer can cause the saturation of the iron core, even when connected to passive circuits.

The choice of magnetic materials for the core is wide, and the designer can choose the most appropriate ones for the application[3].

In [4] the estimation of a power transformer losses are considered upon the design stage of the power converter. Traditionally, the design transformers considers sinusoidal excitation. When the transformer operates at high frequency with non-sinusoidal excitation, several loss mechanisms must be considered, like; proximity effects in the windings, increase of eddy currents and the hysteresis losses in the core. In most power converters, waveforms have a broad spectrum, and the analysis based on sinusoidal excitation is conservative. In circuit theory, the common approach is to obtain the Fourier components and determine the winding losses at each frequency. Total losses can be estimated as the sum of partial losses at different frequencies, as the core losses obey the same rule[5].

According to Valkovic [6], three-phase transformer losses can be calculated using analytical methods which take into account three-phase excitation, hysteresis and nonlinearity. Results indicate that the arrangement of the amperes-turn in the winding considerably influences the losses.

In the literature, there are many related studies to determine and calculate transformer losses. In this paper, The Finite Element Method (FEM) is presented as a computational alternative to determine transformer losses. FEM is an efficient and powerfull tool to perform electromagnetic analysis. The simulation studies presented in this work use COMSOL Multiphysics. COMSOL incorporates different modules, with many physical models available. Thus, most of the typical field problems are supported. Numerical routines and solvers are implemented efficiently and effectively, to solve large problems in a multi-core computer or in a group of computers. In addition, all equations and numerical formulations are visible.

The developed model has been designed to serve as the core of a Quad Active Bridge (QAB) converter with a power handling capability of 1 kW at 600V. It is important to highlight the value of electromagnetic analysis and its subsequent corrective measures, to increase performance, reduce losses and avoid energy and economic costs.

The model presented in this paper describes the simulation of a multi-winding transformer. The paper is organized in the following way. Section II presents a description of the transformer design; the winding geometry, materials and core used. Section III presents a description of the model in the electromagnetic simulation tool. Section IV analyzes the simulation results. Finally, conclusions are drawn in section V.

TABLE I: Power throughput for different core types.

Power Range (W)	Core Type
< 5	RM4; P11/7; T14; EF13; U10
5 to 10	RM5; P14/8
10 to 20	RM6; E20; P18/11; T23; U15; EFD15
20 to 50	RM8; P22/13; U20; E25; T26/10; EFD20
50 to 100	ETD29; ETD34; EC35; EC41; EFD25
100 to 200	ETD34; ETD39; EC41; RM14; E30; E42
200 to 500	ETD44; E55; EC52; E42; P42/29; U67
> 500	E65; EC70; U93; U100; PM87; T140

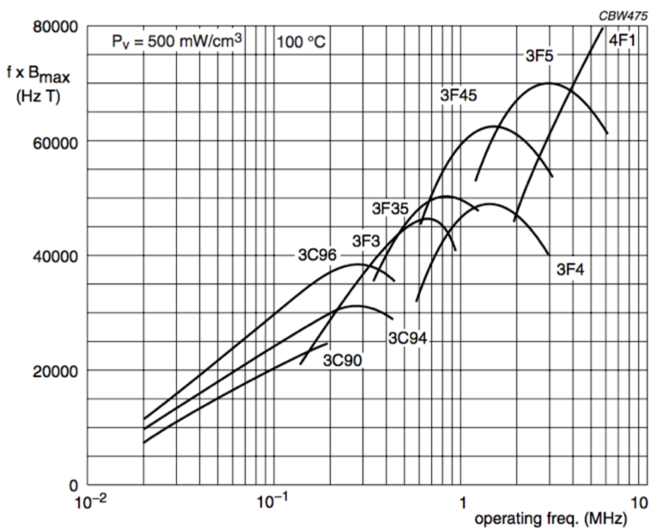


Fig. 1: Core Materials for high frequency [8]

II. Theoretical Design

Transformer design specifications imposed by the QAB requirements are 1 [kW] power handling capability operating in the 100 - 200 [kHz] range. Table I taken from [7] shows the power range of different commercial core types. The EC70 core complies with the required power range.

The performance factor $f \times B_{max}$ is a measure of the power throughput that a ferrite core can handle with a certain loss level. From Fig. (1), for low frequencies there is no much difference between materials, because the cores are saturation limited. Cores exhibit considerable different behaviours for higher frequencies [8].

According to Fig. (1) each materials has a distributive operating frequency in which the $f \times B_{max}$ is maximum. Choosing a material with the highest possible $f \times B_{max}$ provides a high power throughput and higher power density. Fig. (1) suggests that for the specified frequency range the core material 3F3 is a good choice.

A. Design Methodology

The transformer has voltage limit of 600[V] peak and the low limit of the operating frequency range will have a period T of $10\,[\mu s]$.

TABLE II: Core Losses at $100°C$ and $100kHz$ according B_m

Losses at $100°C$ and $100k\,(Hz)$	Bm
$75w/m^3$	$0.1T$
$450w/m^3$	$0.2T$

According to [9], the flux within the core is given by:

$$\varphi = \int_{t}^{t+T} v\left(t\right) \cdot dt \tag{1}$$

The input voltage wave has a peak voltage value of $600\,[V]$, with a period T of $10u\,[s]$. According to [9], the flux can be approximated to:

$$\widehat{\varphi} \approx \left(V_{rms} \cdot \frac{T}{2} \right) \tag{2}$$

In order to obtain the number of turns (n_1) for the winding, it is necessary to calculate the peak to peak magnetic flux density ϕ_{pp}. The following expression allows for this.

$$\widehat{\varphi} = n_1 \cdot \phi_{pp} \tag{3}$$

The peak to peak magnetic flux is then calculated as:

$$\phi_{pp} = A_e \cdot 2 \cdot B_m \tag{4}$$

where A_e is the effective area core, and B_m the peak to peak magnetic flux density.

To calculate the peak to peak magnetic flux density it is necessary to calculate the permitted dissipation P_h. The permitted dissipation P_h is calculated using equation (5).

$$P_h = K_A \cdot a \cdot b \tag{5}$$

where the k_A is a typical coefficient value of $2500[W/m2]$; and, a and b are the dimensions of the chosen core.

According to [9], core losses are calculated with the allowed dissipation.

$$P_{h,cu} = \frac{P_h}{2} \tag{6}$$

The specific core losses $P_{fe,sp,v}$, are given by equation (7), where V_c is the core volume which has a value of $4.01 \cdot 10^{-5}\,\left[m^3\right]$ according to the manufacturer [8].

$$P_{fe,sp,v} = \frac{P_h/2}{V_c} \tag{7}$$

The peak to peak magnetic flux density B_m can be calculated as,

$$B_m = 0.1 \cdot \left(\frac{P_{fe,sp,v}}{75} \right)^{\dfrac{1}{\beta}} \tag{8}$$

where β can be estimated by performing a logarithmic interpolation between two points in the characteristic magnetic loss curve of the material. Two possible points, for this interpolation are shown in Table II as provided by [9].

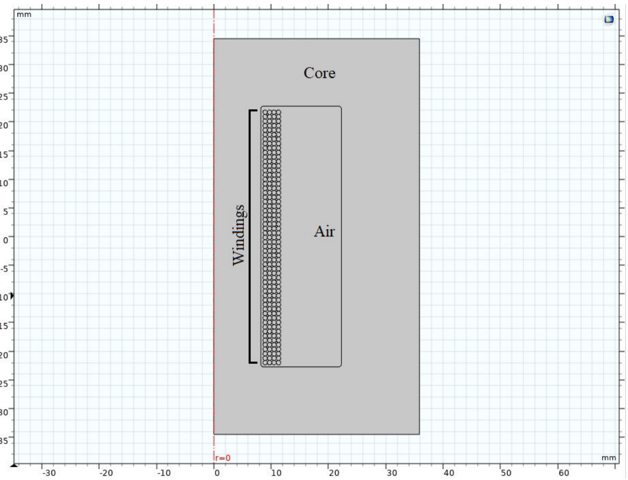


Fig. 2: Multi-winding transformer geometry built with comsol CAD tools in two dimensions.

Then, with the Steinmetz equation [10], and the calculated β value, it is possible to calculate the the magnetic flux density peak value and therefore the magnetic flux peak value.

$$\beta = \frac{\log\left(\dfrac{450}{75}\right)}{log\left(\dfrac{0.2}{0.1}\right)} \tag{9}$$

Finally, the number of turns n_1 using the equation (3) is,

$$n_1 = \frac{\widehat{\varphi}}{\phi_{pp}} = 57$$

The multi-winding transformer is considered to have a 1:1 relationship between all its ports, thus all windings will have the same number of turns.

III. Construction of the model in COMSOL

This study focuses on simulating a transformer with 4 ports, with a power handling capability of 1[kW] and operating frequency range between 100[kHz] to 200[kHz]. The electromagnetic analysis performed by simulation will focus in determining the electromagnetic losses of the device.

The model in COMSOL is developed using the design calculations presented in section II. The model is assembled employing COMSOL CAD tools, specific measures of the core chosen, and the coil turns for the windings. Figure (2) shows the transformer geometry in two dimensions.

The materials used for the transformer are: copper for the windings, air for the transformer window and the material 3F3 for the core. Copper and air are found in COMSOL library, whilst 3F3 material was created using the manufacturer datasheet. Fig. (3) shows the resulting B-H curve of the 3F3 material.

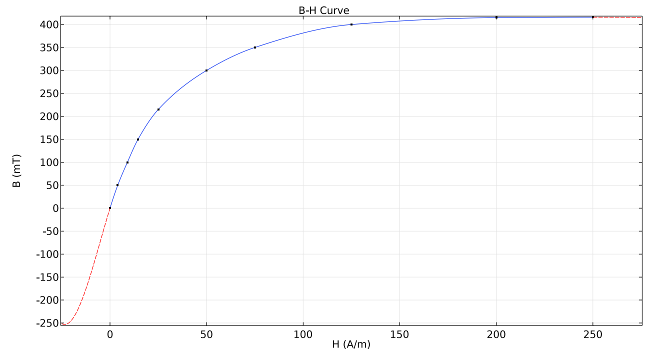


Fig. 3: B-H Curve of 3F3 Material.

The modules employed in COMSOL are Magnetic Fields and Electric Circuits. The implemented mesh for the two dimension model is constructed using the extremely fine pre-configured option for better results. The resulting model has 75880 degrees of freedom with the selected mesh configuration.

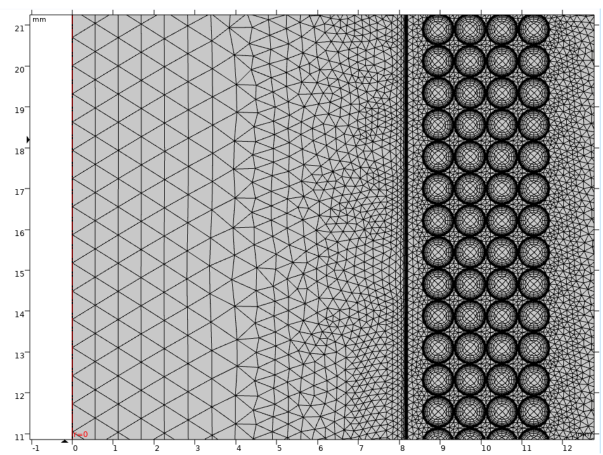


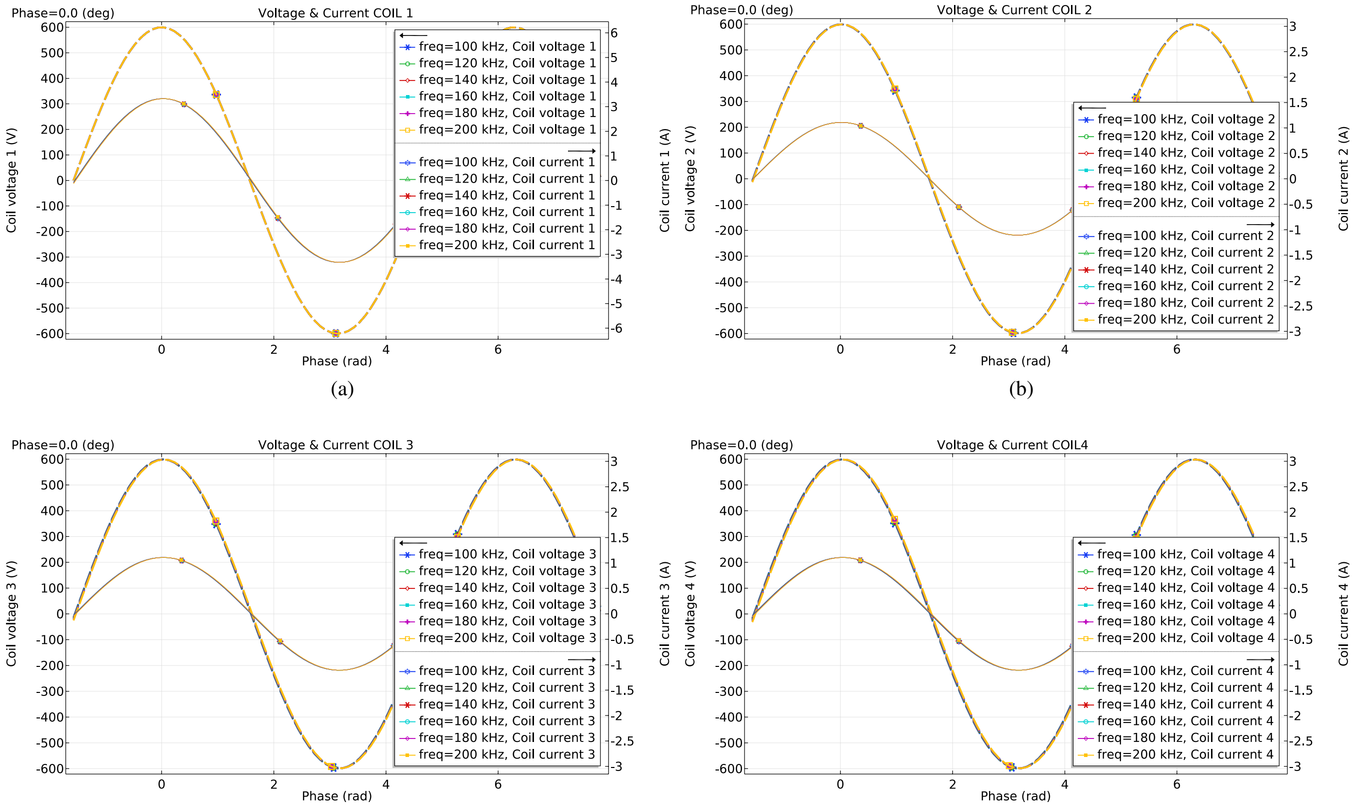
Fig. 4: Mesh constructed for the 2D model.

The selected studies for the 2D dimension model are chosen according to the electromagnetic characteristics we pursue in the analysis, such as frequency response, stationary and time dependent to check for voltage, current, power and flux leakage.

IV. Results

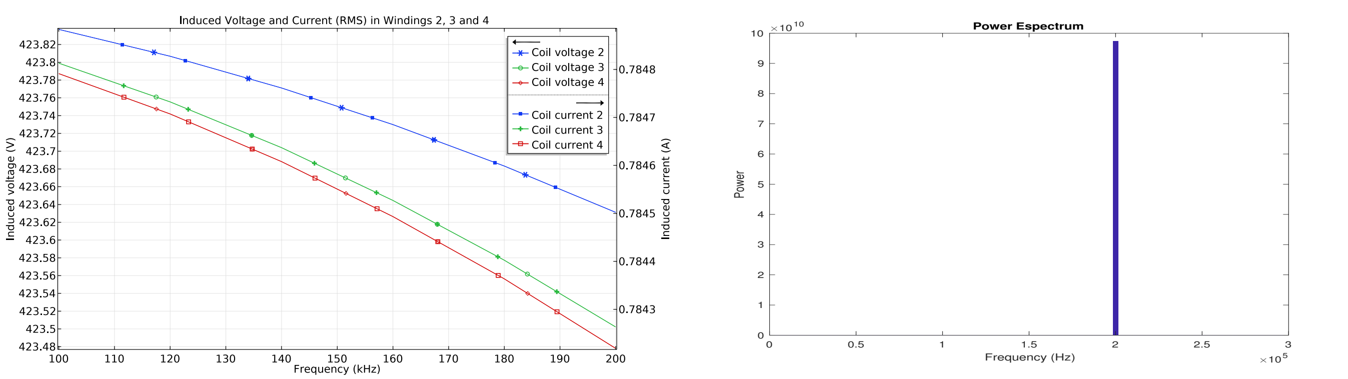
Simulations were performed on a machine with 16 cores and 128GB RAM running at 3.5 GHz. Voltage and current curves in each winding at different frequencies within the study range are shown in Figure (5), were it can be observed that both waves are in phase. In windings 1, 2, 3 and 4, the voltage waves have a peak value of 600 [V]. For current, windings 2, 3 and 4 have a peak amplitude of 0,78 [A] respectively, whilst for winding 1, the current wave has a peak value of 3,33 [A]. The produced waveforms are consistent with the expected results.

Figure (6a) shows the voltage and current variation with frequency for windings 2, 3 and 4. It can be observed that winding 2 exhibits a slightly different behaviour than 3 and



(a) (b) (c) (d)

Fig. 5: Voltage and Current in Coils (a) Coil 1 (b) Coil 2 (c) Coil 3 (d) Coil 4



(a) (b)

Fig. 6: Waveform Analysis (a) Induced voltage and current in windings 2, 3 and 4 (b) Power spectrum of secondary voltage at 200 [kHz] excitation

4. This difference is about 0.1 [V] and 0.001 [A] which can be due to numerical errors. It can also be observed that there is a slight decrease in the voltage magnitude. This decrease can be due to Foucault current losses which are proportional to the square of frequency. Figure (6b) shows the Fourier decomposition of the secondary voltage waveform with a 200 kHz sine excitation in coil 1. The figure shows there is no distorsion in the waveform.

These results indicate that there is no significant waveform deformation, thus giving a clear indication that the transformer is working in the linear region of the core characteristic curve for amplitude and frequency variation of the magnetic flux. Figure (7) shows the flux distribution in the limit of the saturation boundary of the core which is is 0.250[T].

The active power losses for the four windings are presented in Figure (8) for all windings. The sum of the total active

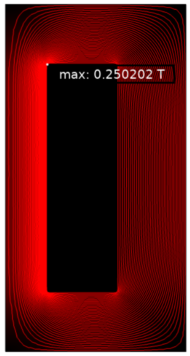


Fig. 7: Maximum magnetic flux density

TABLE III: Transformer Efficiency

Frequency (KHz)	Efficiency
100	99.85%
120	99.80%
140	99.76%
160	99.72%
180	99.69%
200	99.66%

power losses is 0,86[W], where winding 1 has a 72% share of total winding losses, meanwhile, the windings 2,3 and 4 have a 8% share each from the total. It is interesting to observe that the active power losses appear to be independent of frequency in the study range.

Figure (9) shows the leakage reactance in the four windings, for the frequency range of 100[kHz] to 200[kHz]. The leakage reactance is determined by calculating the surface integral of the magnetic flux density in each winding. The leakage reactance exhibits a proportional variation with frequency as expected.

Table III shows the calculated transformer efficiency for the 100[kHz] to 200 [kHz] frequency range. Results indicate and inverse relationship with frequency as expected, since most losses are proportional to frequency or its square value.

V. Conclusion

A finite element simulation model for a transformer for high frequency power applications has been constructed and its response analyzed. The model reproduces the interaction between electric and magnetic quantities that takes place in a real transformer. A comprehensive selection of important transformer effects are covered. In particular, transformer losses in windings and the leakage reactance in the frequency range of 100[Khz] to 200 [KHz] are determined and analyzed. Results indicate a slight correlation with frequency increase within the frequency range of study. This is due to the selection of the core. The proposed transformer model could be applied in power converters projects for research or design. Future improvements could consider the winding weave.

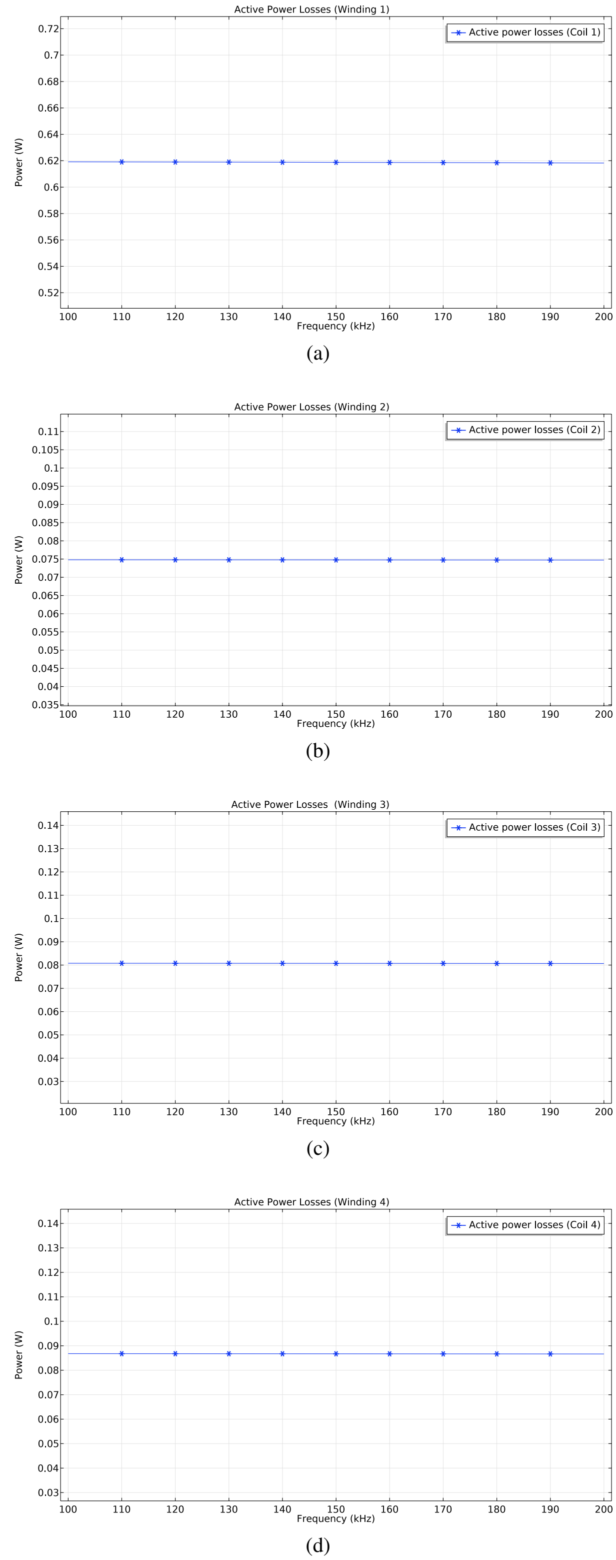


Fig. 8: Power losses with frequency (a) Coil 1 (b) Coil 2 (c) Coil 3 (d) Coil 4

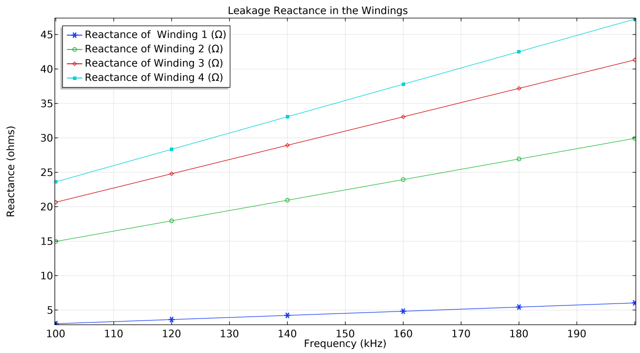


Fig. 9: Windings Leakage Reactance

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