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Research Article

Leakage Inductance Reduction Using the Interleaved Winding Technique in High-Frequency Toroidal Transformers

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Abstract: High leakage inductance in transformers is the main cause of excessive voltage spikes and ringing waveforms in dc-dc converters. Therefore, reducing leakage inductance is important in the design of power electronic devices. This paper provides an analysis of high-frequency leakage inductance in toroidal transformers. The leakage inductance is reduced by implementing an interleaved winding arrangement. Interleaved winding is a winding method in which the primary and secondary windings are positioned side by side in each 1 winding. The leakage magnetic field strength distribution is also analyzed in several winding arrangements using FEA simulation. The effect of leakage inductance on high frequency is also discussed. The frequency effect shows the difference in the magnetic energy leakage curves between conventional and interleaved windings. The results indicate that the interleaved winding technique reduced the leakage inductance from an initial value of 56.03 µH to 0.58 µH, representing a reduction of 98.9%. The high-frequency effects show a 9.01% reduction in the leakage inductance of the interleaved winding arrangement.

Keywords: High frequency; Interleaved winding; Leakage inductance; Leakage magnetic field; Toroidal transformers

1. Introduction

Energy conversion, especially in high-power applications, requires more attention to power electronics design for large-scale de current sources (e.g., PV, fuel cells, and batteries), offshore wind farms, and traction systems (Fouineau et al., 2018). Therefore, in designing a dc-dc converter, a low-frequency transformer that has quite large dimensions must be replaced with a high-frequency transformer that has small dimensions. However, at high frequencies, there are other losses due to eddy currents in the magnetic core (Zhao et al., 2020), winding losses due to increased skin effects (Bahmani et al., 2014), and parasitic elements, namely, parasitic capacitance and leakage inductance, which produce greater switching losses (De Leon et al., 2014). DC-DC converters can be categorized into two primary types: hard-switching PWM converters and resonant, soft-switching converters. PWM converters are widely used due to their high efficiency, straightforward control mechanisms, and minimalistic topology, which requires fewer components. PWM converters face considerable power losses when operating at high switching frequencies (Attia and Suan, 2024; Andreas et al., 2018). A phase-shift full bridge converter that uses a high-frequency transformer as one of its components is one type of dc-dc converter for high power (Lim et al., 2019). The main disadvantages of the dc-dc converters are losses from rectification, ringing, and voltage and current spikes due to

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the resonance between the parasitic capacitance and leakage inductance (Poongothai and Vasudevan, 2018). These weaknesses are a concern in designing components that produce parasitic elements. Parasitic parameters, such as leakage inductance and parasitic capacitance, have a particular effect on the potency and capability of power electronic devices. The leakage inductance should be estimated in the transformer design because high leakage inductance can influence the performance of the converter, especially on the switching components, and can shift the soft-switching area (Ataullah et al., 2022; Noah et al., 2020). Therefore, a high leakage inductance is disadvantageous because it causes unwanted power flow circulation in the converter, which ultimately lowers its efficiency and dissipates the active power. However, it can also increase the soft-switching zone (Ataullah et al., 2022; Noah et al., 2020).

Leakage inductance is a small parasitic element in a transformer that occurs due to an unacceptable flux connection between one and another coil. The leakage inductance in transformers is the main cause of excessive voltage spikes and ringing waveforms in flyback converters (Storus and Simonelli, 2019). Resulting in an additional component voltage and increased EMI. When the switch is turned off, the current flow is interrupted, and the energy stored in the leakage inductance causes a voltage spike in the mosfet (Storus and Simonelli, 2019). The energy oscillates between the leakage inductance and capacitance in the switching devices, causing the characteristic ringing observed in the waveform. Likewise, switching losses increase due to electromagnetic interferences (EMI), resulting in a decrease in system efficiency (Chen and Kumar, 2014; Muhammad and Lu, 2014; Choi et al., 2012; Stadler and Albach, 2006). Furthermore, parasitic capacitance causes current influx due to high frequency, thereby boosting EMI and creating electrostatic connections with other circuit components (Ataullah et al., 2022). Leakage inductance and parasitic capacitance are two important parameters in improving the waveform and switching efficiency in dc-dc converters (Zhang et al., 2019). High frequencies can help decrease the transformer dimensions. However, as the frequency increases, the parasitic components become significant, making it essential to accurately calculate parasitic parameters to attain optimal performance in RCs. Leakage inductance in transformers can also interfere with the control system (Rahman et al., 2022; Rothmund et al., 2018). Different core shapes and winding arrangements can also produce different leakage inductance characteristics (Ali et al., 2021; Nia et al., 2019). Poongothai and Vasudevan (2018) showed the differences in leakage inductance values from several winding configurations. Understanding the parasitic parameters of various transformer geometries and their applications is essential for optimizing these parameters (Michaud, 2020; Bird et al., 2013).

The interdependencies between core size, wire type, and interleaving winding, which complicates the design process, must be addressed in high-frequency transformer designs. The skin effect and proximity effect of high-frequency eddy currents greatly affect the loss of winding power (Bu et al., 2023; Liu et al., 2023; Tabei et al., 2020; Liu et al., 2018). This frequency-dependent effect changes the current density distribution over the cross-section of the winding conductors and increases the AC resistance. At high frequencies, the current is inclined to be concentrated on the conductor's surface, so that leakage energy is stored in a small cross-sectional area. The leakage inductance decreases at higher frequencies because the total current remains unchanged (Chen, 2019). Thus, accurate leakage inductance prediction will be very helpful in designing power electronic devices.

The interleaved winding technique is widely used in several high-frequency transformer applications because it can reduce the leakage inductance value in the transformer. The interleaved winding technique is a winding method in which each turn/coil is placed as close as possible to another winding with the opposite current. Many studies have analyzed the leakage inductance in planar transformers with EE-type cores (Park et al., 2023; Dang et al., 2022; Guo et al., 2022; Ann et al., 2020; Chen, 2019; Zhao et al., 2017; Das et al., 2017; Ouyang et al., 2015; Barrios et al., 2014). However, few studies have analyzed interleaved windings in toroidal cores. Comparative analyses from previous studies (Ali et al., 2021; Nia et al., 2019) indicate that toroidal cores offer significant advantages over other core types for high-frequency and high-power applications. This superiority is attributed to the circular flux path in toroidal cores, which enables more efficient and effective magnetic flux distribution compared with the more complex flux paths found in EE and U cores. (Amirbande and Vahedi, 2020) analyzed the leakage inductance in toroidal transformers with a non-interleaved winding configuration. The problem is the high level of leakage inductance produced. This leakage inductance can interfere with circuits in power converter applications by storing energy within the transformer, potentially causing voltage spikes in the circuit.

This study proposes a leakage inductance reduction method using 1-layer interleaved winding techniques on a toroidal transformer. This study examines the nonlinear distribution of magnetic field strength at high frequencies and evaluates the magnetic field variation across the conductor thickness for different winding arrangements to better understand the impact of these arrangements on the transformer's performance characteristics. Furthermore, a mathematical model is developed to quantify the leakage inductance reduction, providing new insights into optimization techniques for high-frequency transformer design. The leakage inductance is then considered using the stored leakage energy. Leakage inductance is a measure of the magnetic energy that is not coupled between a transformer's primary and secondary windings. It is calculated on the basis of the stored leakage energy, which is the energy associated with the magnetic field outside the core. Analysis and verification were conducted using FEA simulation. FEA simulation is used in this study because it provides a detailed analysis of the magnetic field distribution and leakage inductance in complex geometries, such as toroidal cores. Unlike analytical methods, FEA can capture nonlinearities and variations across the conductor thickness, making it a powerful tool for simulating multiple winding arrangements and predicting high-frequency behavior.

2. Methods

2.1. Leakage Inductance Modeling

In high-frequency transformers, the magnetic flux produced by the primary winding is not totally connected to the secondary winding. The unconnected magnetic flux is wasted in the volume between the winding and the magnetic core. The coupling coefficient becomes less than one; thus, the magnetization inductance is smaller than the primary or secondary inductance (Liu et al., 2023).

The magnetic flux created by the primary coil of the transformer cannot be fully linked with the secondary coil because the windings are not fully linked. Some flux will escape from the core and return through the air. The leakage magnetic flux stores energy, which is reflected in the form of leakage inductance during transformer operation, thereby affecting the output power quality. If the leakage flux energy is equivalent to the concentrated leakage inductance, the leakage inductance of the transformer can be determined by the leakage magnetic field energy stored between the windings. The leakage inductance (L_σ) with leakage magnetic flux energy is expressed using equation (1) as follows:

$$L_\sigma = \frac{2W_s}{I^2} = \frac{2}{I^2}\int_V \frac{H\cdot B}{2}\,dV = \frac{\mu_0}{I^2}\int_V |H|^2 dV \tag{1}$$

where H is the magnetic field strength, B is the magnetic intensity, W_s is the leakage magnetic field energy, μ_0 is the vacuum permeability, I is the excitation current, and V is the transformer volume. Because the strength of the magnetic field is closely related to the leakage inductance, as expressed in Equation (1), the relative location between the primary and secondary windings is important in designing a transformer. To reduce leakage inductance, one important way is to distribute the magnetic field evenly throughout the transformer. Thus, an interleaved winding arrangement is adopted in the optimization process of this toroidal transformer to reduce the leakage inductance. The leakage inductance of each section can be expressed in a conventional two-layer winding based on references (Liu et al., 2023; Dang et al., 2022; Baktash and Vahedi, 2014; Hernandez et al., 2011). This study modifies the 2-layer toroidal transformer winding modeling (Bu et al., 2023) into 1-layer winding. The total of leakage inductance calculations in 1-layer conventional or interleaved windings can be expressed in equation (2):

$$L_{\sigma,total} = L_{\sigma}{'}\, w_p \tag{2}$$

where w_p is total of winding portion in interleaved winding arrangements and $L_{\sigma}{'}$ is the leakage inductance in each 1 winding portion of the transformer volume, which can be expressed in equation (3):

$$L'_{\sigma} = L_{\sigma,1}{'} + L_{\sigma,2}{'} + 2L_{\sigma,3}{'} + 2L_{\sigma,4}{'} + 2L_{\sigma,5}{'} \tag{3}$$

where $L'_{\sigma,i}$ (i is 1, 2, 3, 4, 5) shows the leakage inductance in each part i, and each part contains a primary winding, secondary winding, and insulation layer, as shown in Figure 1. Each region can be expressed in the equation (3)-(7):

$$L_{\sigma,1}{'} = \frac{\left(\frac{N}{w_p}\right)^2 \mu_0 h}{2\pi}\left[\left(\frac{R_{m1}}{R_1^2}\right)\left(\frac{\sinh(2\gamma a)-2\gamma a}{4\gamma\,\sinh^2(\gamma a)}\right)\right] \tag{4}$$

$$L_{\sigma,2}{'} = \frac{\left(\frac{N}{w_p}\right)^2 \mu_0 h}{2\pi}\left[\left(\frac{R_{m3}}{R_4^2}\right)\left(\frac{\sinh(2\gamma a)-2\gamma a}{4\gamma\,\sinh^2(\gamma a)}\right)\right] \tag{5}$$

$$L_{\sigma,3}{'} = \frac{\left(\frac{N}{w_p}\right)^2 \mu_0}{2\pi}\left[\left(\frac{R_{mh}R_o-R_{mh}R_i}{R_iR_o}\right)\left(\frac{\sinh(2\gamma a)-2\gamma a}{4\gamma\,\sinh^2(\gamma a)}\right)\right] \tag{6}$$

$$L_{\sigma,4}{'} = \frac{\left(\frac{N}{w_p}\right)^2 \mu_0}{4}\left[\left(\frac{R_{m1}}{R_1^2}\right)\left(\frac{\sinh^2(\gamma a)-\gamma^2 a^2}{4\gamma^2\,\sinh^2(\gamma a)}\right)\right] \tag{7}$$

$$L_{\sigma,5}{'} = \frac{\left(\frac{N}{w_p}\right)^2 \mu_0}{4}\left[\left(\frac{R_{m3}}{R_4^2}\right)\left(\frac{\gamma a\,\sinh(2\gamma a)-\sinh^2(\gamma a)-\gamma^2 a^2}{4\gamma^2\,\sinh^2(\gamma a)}\right)\right] \tag{8}$$

where a, R_{m1}, R_{m3}, R_1, R_4, R_o, and R_i are dimensions as shown in Figure 1, h is the core height, and μ_0 is the vacuum permeability. N is the number of primary (N_p) and secondary (N_s) turns expressed as equation (9). R_{mh} is the mean radius of the core and can be expressed in equation (10):

$$N = N_p + N_s \tag{9}$$

$$R_{mh} = \frac{(R_i + R_o)}{2} \tag{10}$$

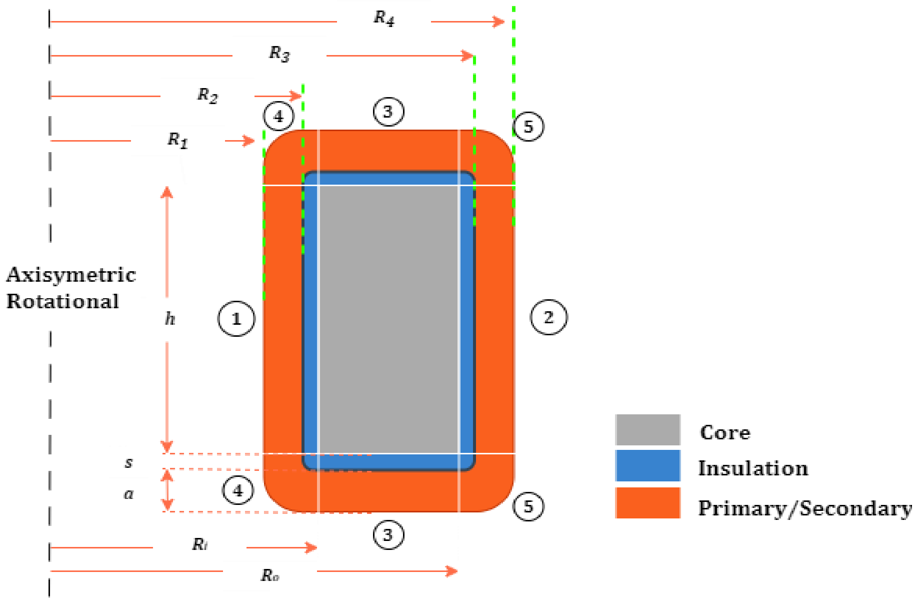

Figure 1 2D axisymmetric rotational view of toroidal transformers

γ is the characteristic root of the Helmholtz equation and can be expressed in equation (11):

$$\gamma = \frac{(1+j)}{\delta} \tag{11}$$

$$\delta = \sqrt{\frac{1}{2\pi f \mu_0 \sigma}} \tag{12}$$

where δ is the skin depth, f is the frequency, and σ is the conductivity of the conductor.

To calculate the total leakage inductance, multiply the leakage inductance per portion by the number of winding portions (w_p) in the interleaved winding arrangement. Then, the total leakage inductance can be expressed by substituting expressions (4)-(8) into Eq. (2). Finally, the total leakage inductance can be expressed in equation (13):

$$L_{\sigma,total} = \frac{L_\sigma{}'}{w_p} \tag{13}$$

2.1.1. High-frequency effects

At high frequencies, the current tends to flow primarily along the plane of the conductor, effectively decreasing the area of the conductor's cross-section where leakage energy occurs. This implies that the leakage inductance decreases as the frequency increases. As shown in Supplementary Figure S1, the current is no longer distributed consistently in the conductor at high frequency due to eddy current effects (Bu et al., 2023). The area under the magnetomotive force (MMF) curve is smaller at high frequencies than at low frequencies, indicating that the stored leakage energy is reduced at higher frequencies. Since the leakage energy decreases at high frequencies, the leakage inductance also decreases, as defined in equation (1).

2.2. Research Method

Figure 2 shows the reduction process, where the parameter to be reduced is the high leakage inductance in the conventional winding arrangement.

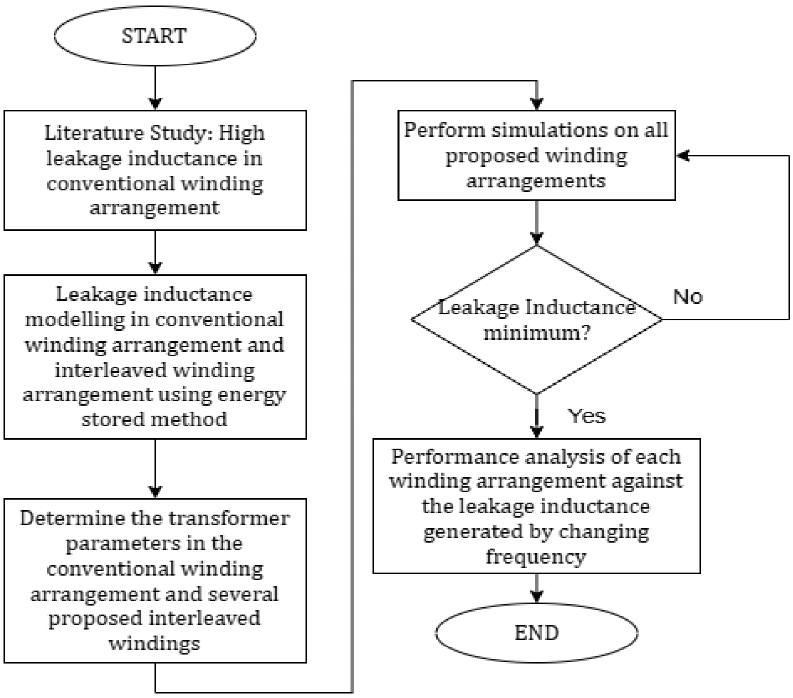

Figure 2 Research flowchart illustrating the methodology of this study

Transformer design is required before the leakage inductance is reduced. Determining transformer design parameters is necessary to facilitate initial design planning, so that research objectives can be achieved. The main purpose of this research is to reduce the leakage inductance as much as possible by simply changing the winding arrangement. The reduction target is described in Equation (14) as follows:

$$f(w_p) = min\{L_\sigma\} \tag{14}$$

where L_σ is the leakage inductance in the transformer, w_p is defined as the winding portion, whereas there is only one winding portion in conventional windings. The number of winding portions (w_p) must not exceed the number of primary or secondary windings. The leakage inductance must be reduced by evenly distributing the primary and secondary windings throughout the transformer window, so that the magnetic field distribution in the transformer volume can be even and high leakage energy can be reduced (Park et al., 2023; Dang et al., 2022; Guo et al., 2022; Chen, 2019). Thus, the interleaved winding method is adopted to optimize the leakage inductance parameters in transformers, where each primary and secondary winding is placed next to each other. Table 1 summarizes the transformer parameters used in this research. The core dimensions and materials were obtained from the manufacturing specification T60004-L2130-W630. The core material does not influence the results, as Equations (1)–(12) do not involve the transformer core material's permeability. Therefore, this parameter is not critical for determining the outcome. Magnetic core materials have different characteristics (Djuhana et al., 2021). For each primary and secondary winding to fill the transformer core, the number of turns is assumed to be 30. To simplify the analysis, the excitation current is assumed to be 1 A (Chen, 2019).

Table 1 Summary of the key transformer characteristics considered in the research

Parameter	Value/Type
Winding ratio	1: 1
Number of primary windings	30
Number of secondary windings	30
Wire diameter	4 mm
Core material	Nanocrystalline
Outer diameter	130 mm
Inner diameter	100 mm
Core height	25 mm
Insulation Core	2 mm

To simplify the analysis of the magnetomotive force (MMF) generated by the winding, a winding ratio of 1:1 was used, and the total number of windings was 60. Figure 3 (a) depicts the winding arrangement, namely conventional winding, where the number of winding portions is only 1 where each part of the winding has 30 primary windings and a secondary winding with another 30 windings. This paper uses 4 winding arrangements, as shown in Figure 3. The type-a interleaved winding arrangement has a total of $w_p = 2$, where each winding portion has 15 primary and 15 secondary windings. The type-b interleaved winding arrangement has a total of $w_p = 6$, where each winding portion has 5 primary windings and 5 secondary windings. The type-c interleaved winding arrangement has a total of $w_p = 10$, where each winding portion has 3 primary windings and 3 secondary windings. Type-d interleaved winding arrangement has a total of $w_p = 30$, where each winding portion has 1 primary winding and 1 secondary winding. w_p indicates how many parts are interleaved in the winding arrangement. All variations of the arrangement still have the same total number of turns, i.e., 60 turns (30 primary and 30 secondary).

The verification process begins with the creation of a 3D design of the toroidal transformer using the specifications provided in Table 1. To streamline the design process, the winding arrangement is simplified into a ring configuration. Next, the current direction between the primary and secondary windings is set in opposite directions to cancel out the magnetizing current in the transformer core (Baktash and Vahedi, 2014). This setup allows the leakage inductance to be calculated using the stored energy method, as described in equation (1). Finally, the models of all winding arrangements, as shown in Figure 3, are simulated using the Eddy Current Solver in Ansys Maxwell 3D.

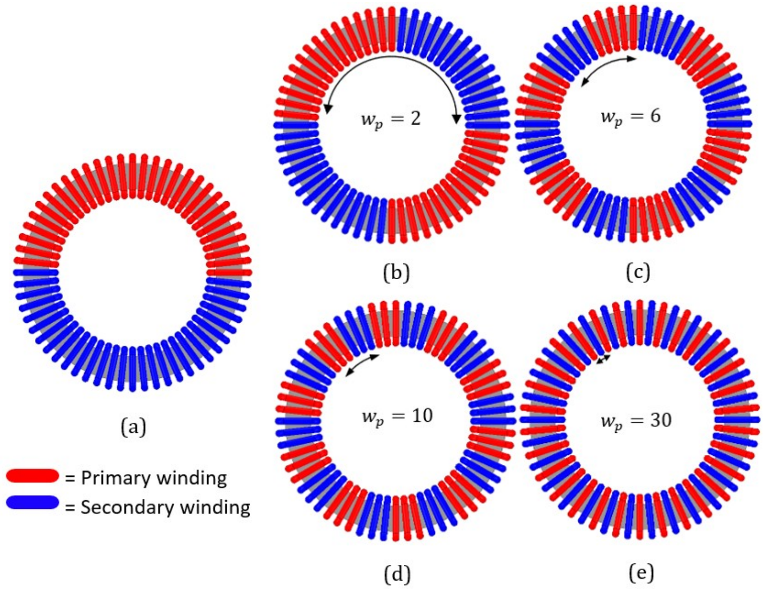

Figure 3 (a) Conventional winding arrangements ($w_p = 1$); Interleaved winding arrangements (b) $w_p = 2$; (c) $w_p = 6$; (d) $w_p = 10$; and (e) $w_p = 30$

3. Results and Discussion

This section details the simulation results used to verify the proposed method. The simulations were conducted using the Ansys Maxwell 3D software, which is employed to analyze magnetic fields with non-uniform static frequency domains. This study aims to reduce the leakage inductance that occurs in conventional windings by simply changing the winding arrangement technique. This section shows the changes in the winding arrangement in the toroidal core that can affect the leakage magnetic field, thereby achieving the optimal leakage inductance.

The distribution of the magnetic field along the windings in a toroidal transformer is analyzed on the determined cutting line as shown in Supplementary Figure S2. The Figure also shows a top view to facilitate the analysis of the magnetic field distribution because this study only uses 1 layer in the winding. Figure 4 shows the distribution of MMF along the cut line. The MMF is linearly distributed in the conductor at low frequency. However, the skin effect causes the current density to become irregular across the conductor cross-section as the frequency increases, with most of the current concentrated at the conductor surface. The proximity effect occurs in conventional windings, causing the current to flow toward the outermost layers of the winding. At high frequencies, the leaked magnetic energy forms a "concave shape", especially when there are many turns in 1 winding portion. The high frequency of 10 kHz substantially increases the leakage magnetic field intensity between the primary and secondary windings, as shown in Figure 4. However, in type-d interleaved windings, the high-frequency effects are not so visible because the proximity effect is much reduced but still has a concave shape on the winding curve, as shown in Figure 5.

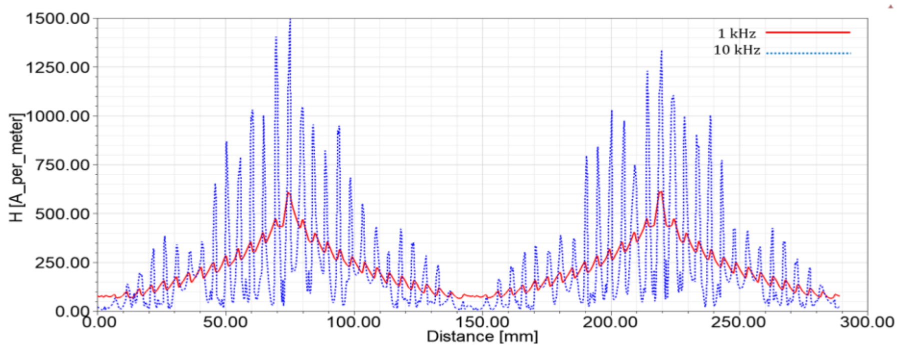

Figure 4 MMF distribution across the defined cutline on the conventional winding arrangement

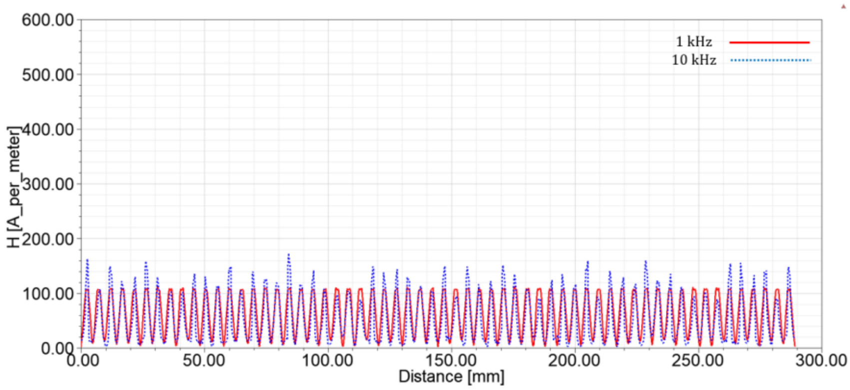

Figure 5 MMF distribution across the defined cutline on the type-d interleaved winding

The area of the curve in the high-frequency case appears to decrease; thus, the leakage flux will also decrease as the frequency increases. This causes the leakage inductance to decrease as the frequency increases, because equation (12) explains that frequency is closely related to skin depth, which can affect the magnitude of the leakage inductance. Conventional winding arrangements have separate turns on the primary and secondary windings so that the proximity effect is more visible between windings with the same current direction and shows non-uniformity in each conductor. The magnetic field distribution is also concentrated in the conductor's outermost layer. Therefore, the reduction in leakage inductance with increasing frequency is more noticeable for transformers with fewer w_p. The leakage inductance value decreases as the frequency increases at high frequency. As shown in Table 2, the leakage inductance in conventional windings with frequencies of 1 kHz and 100 kHz shows a decrease of about 10.71%, type-a shows a decrease of about 14.7%, type-b shows a decrease of about 20.69%, type-c shows a decrease of about 20.95%, and type-d shows a decrease of about 9.01%. The leakage inductance for the 5 different winding arrangements is compared in Figure 3. Comparison of leakage inductance values for 5 winding arrangements at 1 kHz and 100 kHz is shown in Table 2.

Table 2 Comparison results of leakage inductance in several winding arrangements for 1 kHz and 10 kHz

Winding arrangement	Frequency	
	1 kHz	100 kHz
Conventional (wp = 1)	56.03 μH	50.03 μH
Interleaved Type-a (wp = 2)	20.38 μH	17.39 μH
Interleaved Type-b (wp = 6)	3.96 μH	3.14 μH
Interleaved Type-c (wp =10)	1.91 μH	1.51 μH
Interleaved Type-d (wp = 30)	0.58 μH	0.53 μH

The leakage inductance decreases quite drastically with the number of winding portions, as shown in Figure 6 if applied to all w_p values in equation (13) are applied. The leakage inductance reduction against the number of winding portions (number of interleaved turns) shows a negative exponential relationship in the mathematics model, as shown in Equation (13). As expected, interleaved winding can reduce leakage inductance as expected. Leakage inductances of 56.03 μH and 50.03 μH for the conventional winding configuration was obtained at 1 kHz and 100 kHz,, respectively. The reduction in leakage inductance in the fully interleaved winding configuration (type-d) is approximately 98.90% and 98.94%, respectively, where leakage inductance values of 0.58 μH and 0.53 μH for the type-d interleaved winding arrangement are achieved at 1 and 100 kHz, respectively. This shows good reduction in fully interleaved winding (type-d) compared with conventional, type-a, type-b, and type-c winding arrangements. Changes in the winding arrangement have a significant effect on the stored leakage energy. The interleaved winding method was applied to a conventional single-layer toroidal winding core, which has a relatively high leakage inductance (Baktash and Vahedi, 2014). Figure 3(a) shows an example of this conventional winding configuration. Unlike the 1:1 ratio commonly used in interleaved windings, Bakhtash and Vahedi did not adopt this approach. This study aims to reduce the leakage inductance of the model proposed by Baktash and Vahedi (2014), yielding a significant reduction in leakage inductance. Furthermore, Chen (2019) applied the interleaved method to an EE core, achieving a 91.07% reduction in leakage inductance compared to conventional windings. The difference in the percentage reduction between the EE and toroidal cores presents an interesting discussion, suggesting that interleaved winding may be more effective for toroidal cores. This effectiveness can be attributed to the distinct characteristics of the toroidal and EE cores, particularly in terms of their dimensions and winding arrangements. Therefore, the toroidal core is highly recommended for power applications requiring low parasitic parameters.

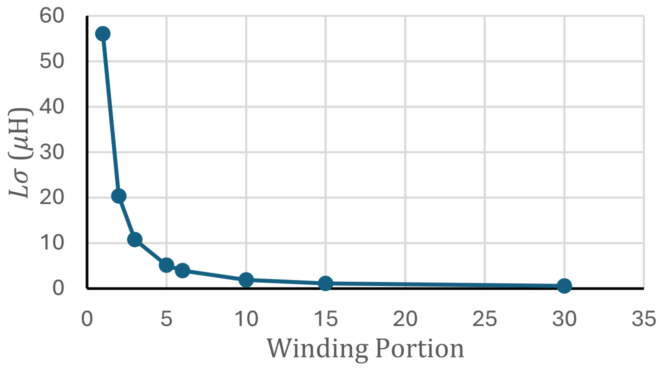

Figure 6 Leakage inductance vs. winding portions

Figure 7 shows a comparison of the leakage inductance between the conventional and type-d interleaved winding arrangements. The proximity effect occurs in conventional winding arrangements, which pushes the leakage magnetic field toward the conductor's outermost layer. Therefore, the effect of frequency in reducing leakage inductance is more obvious in transformers with conventional windings. This is evidenced by the marked difference in the curves between Figures 4 and 5. The skin effect and proximity effect are closely related to skin depth, which is expressed in equation (12). As the frequency increases, the leakage inductance value drops with increasing frequency due to the skin effect, as shown in Supplementary Figure S1. As shown in Table II, the leakage inductance in the conventional winding with frequencies of 1 and 100 kHz shows a decrease of about 10.71%, while the type-d winding shows a decrease of about 9.01%. Even high-frequency effects differ significantly between conventional windings and optimal designs (interleaved windings). The characteristics of the curve can be used to analyze the converter's resonance frequency. However, additional analysis is needed on the winding losses because the higher the frequency, the higher the winding losses due to the EC effect.

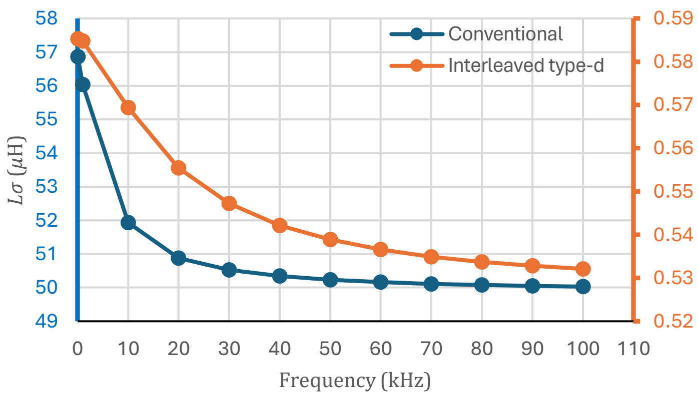

Figure 7 Comparison of the simulation results between conventional and fully interleaved windings

Figure 8 shows the FEA simulation results on the distribution of leakage energy and magnetic field strength for 5 different winding arrangements at 1 kHz. Additional results are provided in the Supplementary Figure S3. This shows that energy leakage is drastically reduced when the primary and secondary windings are positioned next to each other every 1 turn. The interleaved winding type-d can distribute the leakage magnetic field evenly in the transformer winding compared to the interleaved winding types-a, -b, and -c. The maximum imf decreases when the winding arrangement has the highest winding portion. The interleaved winding arrangement divides the maximum leakage magnetic field into 60 points with approximately 100 A/m.

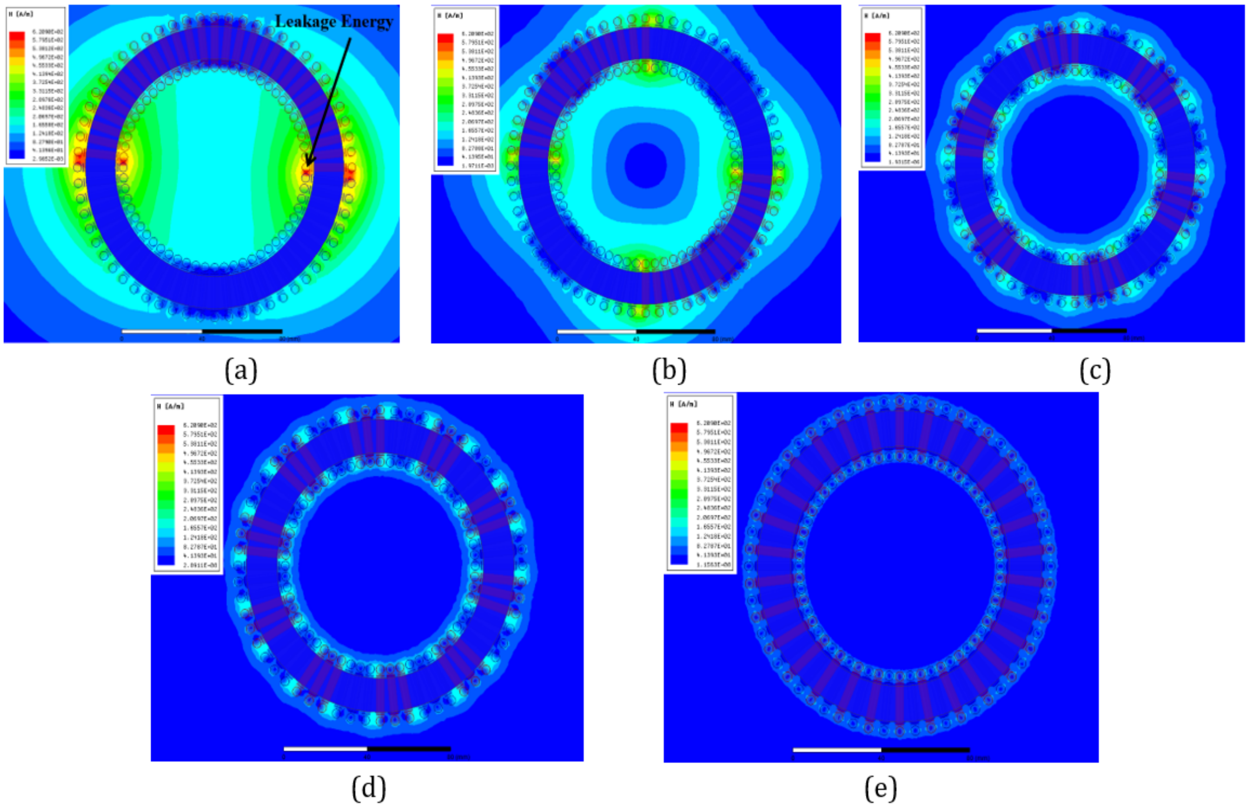

Figure 8 FEA simulation results on leakage magnetic energy distribution at 1 kHz, (a) conventional, (b) interleaved type-a, (c) interleaved type-b, (d) interleaved type-c, and (e) interleaved type-d

This arrangement is very different from the conventional winding arrangement which has 2 maximum leakage magnetic field points with a value of approximately 620 A/m. It can also be concluded that interleaved windings can divide the maximum imf according to the number of winding portions in each interleaved winding. The difference in the curve area is also observed between the interleaved and conventional windings. The reduction in the leakage magnetic field in the interleaved winding arrangement indicates a reduction in leakage inductance because equation (1) states that the leakage energy stored in the air and along the winding is the main factor in leakage inductance. The curve shape of conventional windings, type-a, type-b, and type-c, looks nonlinear (jagged). This is because the x-axis line passes through the insulation area, which causes the magnetic field to decrease. When passing through the conductor area, it tends to increase linearly. This phenomenon is similar to that shown in supplementary Figure S1 when the x-axis passes through the primary conductor area, insulation, and secondary conductor (Bu et al., 2023). The characteristics of the MMF curve and distribution can be very useful in designing a transformer that requires low parasitic components. However, if designing about parasitic parameters, we must analyze the parasitic capacitance as well for further work. Parasitic capacitance is also one of the unwanted parasitic components in power electronics applications.

4. Conclusions

This study successfully achieved a significant reduction in leakage inductance in high-frequency toroidal transformers through the interleaved winding technique. The interleaved winding configuration in the simulation minimized the leakage magnetic field between windings by positioning each primary and secondary winding adjacent to one another, thus lowering the leakage inductance. The interleaved winding arrangement, particularly the type-d arrangement, yielded a more even MMF distribution than conventional windings, which tend to concentrate MMF between primary and secondary windings. The simulation results indicate a reduction in leakage inductance of approximately 98.96% at 1 kHz and 98.94% at 1 and 100 kHz, respectively, demonstrating the efficacy of interleaved winding for high-frequency applications. Additionally, the study found a further decrease of about 10.71% in leakage inductance as the frequency increased from 1 to 100 kHz, attributed to the high-frequency skin and proximity effects, which limit current flow to the conductor’s surface and reduce the MMF and leakage energy within the conductor. These findings have practical implications for high-frequency, high-power applications, such as power converters, where reduced leakage inductance directly contributes to higher efficiency and reduced voltage spikes. Future research could explore different types of conductors, such as litz wire, to overcome the skin effect at high frequencies and conduct experimental verification to obtain actual results.

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Author Contributions

- Dody Yunus Putra Siregar : Conceptualization, methodology, analysis, data collection, visualization, and writing original draft.
- Wijono : Conceptualization, methodology, analysis, and supervision.
- Muhammad Aziz Muslim : Methodology, analysis, and supervision.

Conflict of Interest

The authors declare no conflicts of interest regarding this manuscript.

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