International Journal of Technology v(i) pp-pp (YYYY)
Received Month Year / Revised Month Year / Accepted Month Year

International Journal of Technology

http://ijtech.eng.ui.ac.id

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

Dody Yunus Putra Siregar[1], Wijono[1*], Muhammad Aziz Muslim[1]

[1]*Departement of Electrical Engineering, Universitas Brawijaya, Jl. MT. Haryono 167 , Malang, 65145, Indonesia*

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 designing power electronic devices. This paper provides an analysis of high-frequency leakage inductance in toroidal transformers. Leakage inductance reduction is carried out by implementing an interleaved winding arrangement. Interleaved winding is a winding method where the primary winding and secondary winding are positioned side by side in each 1 winding. The leakage magnetic field strength distribution is also analyzed in several winding arrangements using Finite Element Analysis (FEA) simulation. The effect of leakage inductance on high frequency is also discussed. The frequency effect shows the difference in the leakage magnetic energy curves between conventional windings 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%. 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 dc current sources (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 pulse width modulation (PWM) converters and resonant, soft-switching converters. PWM converters are widely utilized due to their high efficiency, straightforward control mechanisms, and minimalistic topology that requires fewer components. Nonetheless, PWM converters face considerable power losses when operating at high switching frequencies (Attia and Suan, 2024; Andreas *et al*., 2018). One type of dc-dc converter for high power is a phase-shift full bridge converter that uses a high-frequency transformer as one of its components (Lim *et al*., 2019). The main disadvantages of dc-dc

*Corresponding author's email: wijono@ub.ac.id, Tel.: +62-341-554166; Fax: +62-341-551430
doi: 10.14716/ijtech.v0i0.0000

converters are losses from rectification, ringing, and voltage and current spikes due to resonance between parasitic capacitance and leakage inductance (Poongothai and Vasudevan, 2018). These weaknesses are a concern in the design of components that produce parasitic elements. Parasitic parameters such as leakage inductance and parasitic capacitance have a particular affect on the potency and capability of power electronic devices. It is principal to estimate the leakage inductance 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. (Attaullah *et al*., 2022; Noah *et al*., 2020). Therefore, high leakage inductance is disadvantageous as it causes unwanted power flow circulation in the converter, which ultimately lowers its efficiency and dissipates active power. However, it can also somewhat increase the soft-switching zone (Attaullah *et al*., 2022; Noah *et al*., 2020).

Leakage inductance is a small parasitic element in a transformer that occurs due to unacceptable flux connection between one coil and another coil. Leakage inductance in transformers is the main cause of excessive voltage spikes and ringing waveforms in flyback converters (Storus and Simonelli, 2019). Resulting in additional component voltage and increased electromagnetic interference (EMI). The current flow is interrupted and the energy stored in the leakage inductance will cause a voltage spike in the mosfet when the switch is turned off (Storus and Simonelli, 2019). The energy will oscillate between the leakage inductance and capacitance in the switching devices, causing the characteristic ringing observed in the waveform. Likewise, due to electromagnetic interferences (EMI), switching losses increase so that system efficiency decreases (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 boost electromagnetic interference (EMI) and can create electrostatic connections with other circuit components (Attaullah *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 dimensions of the transformer. Although, as the frequency increases, the parasitic components become significant, making it essential to accurately calculate parasitic parameters to attain optimal performance in resonant converters. Leakage inductance in transformers can also cause interference in the control system (Rahman *et al*., 2022; Rothmund *et al*., 2018). Different core shapes and winding arrangements can produce different leakage inductance characteristics as well (Ali *et al*., 2021; Nia *et al*., 2019). Reference (Poongothai and Vasudevan, 2019) shows the differences in leakage inductance values from several winding configurations. Therefore, understanding the parasitic parameters of various transformer geometries and their applications is essential to optimize these parasitic parameters (Michaud, 2020; Bird *et al*., 2013).

High frequency transformer designs need to solve the interdependencies between core size, wire type, and interleaving winding, which complicates the design process. The loss of winding power is greatly affected by the skin effect and proximity effect of high frequency eddy currents (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, current be incline to concentrated on the surface of the conductor, so that leakage energy is stored in a small cross-sectional area. Since the total current remains unchanged, the leakage inductance decreases at higher frequencies (Chen, 2019). Thus, accurate prediction of leakage inductance will be very helpful in designing power electronic devices.

The interleaved winding technique is widely used in several high frequency transformers applications, because it is a method that can reduce the leakage inductance value in the transformer. The interleaved winding technique is a winding method where each turn/coil is placed as close as possible to another winding with the opposite current. Many studies have analyzed the determination of leakage inductance in planar transformers with EE type cores (Park *et al.*, 2023; Dang *et al.*, 2022; Guo *et al.*, 2022; Chen, 2019; Zhao *et al.*, 2017; Das *et al.*, 2017; Barios *et al.*, 2015; Ouyang *et al.*, 2015). However, few of the studies have discussed the analysis of 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 for high-frequency and high-power applications over other core types. This superiority is attributed to the circular flux path in toroidal cores, which enables more efficient and effective magnetic flux distribution compared to the more complex flux paths found in EE and U cores. (Amirbande and Vahedi, 2020) analyzed leakage inductance in toroidal transformers with a non-interleaved winding configuration. The problem is a 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 paper offers a leakage inductance reduction method using 1-layer interleaved winding techniques on a toroidal transformer. The 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 reduction in leakage inductance, 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 the primary and secondary windings of a transformer. It is calculated based on the stored leakage energy, which is the energy associated with the magnetic field outside the core. Analysis and verification were carried out using Finite Element Analysis (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 Modelling

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

Since the windings are not fully linked, the magnetic flux created by the primary coil of the transformer cannot be fully linked with the secondary coil. Some flux will escape from the core and return through the air. The leakage magnetic flux will store energy, which is reflected in the form of leakage inductance during transformer operation, thereby affecting the quality of the output power. If the leakage flux energy is equivalent to the concentrated leakage inductance, the transformer leakage inductance can be determined by the leakage magnetic field energy stored between the windings. Calculating 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 volume of transformers. Because the strength of the magnetic field is closely related to leakage inductance as expressed in equation (1), so the relative location between the primary and secondary windings is important in designing a transformer. To reduce leakage inductance, distributing the magnetic field evenly throughout the transformer is one important way. Thus, in the optimization process of this toroidal transformer, an interleaved winding arrangement is adopted to reduce the leakage inductance. Based on reference (Liu *et al.*, 2023; Dang *et al.*, 2022; Baktash and Vahedi, 2014; Hernandez *et al.*, 2011), the leakage inductance of each section can be expressed in a conventional 2-layer winding. This research modifies the 2-layer toroidal transformer winding modelling (Bu *et al.*, 2023) into 1-layer winding. Modified 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):

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

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

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

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

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

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 core and can be expressed in equation (10):

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

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

γ is the characteristic root of Helmholtz equation and can be expressed in equation (10):

$$\gamma = \frac{(1+j)}{\delta} \tag{10}$$

$$\delta = \sqrt{\frac{1}{2\pi f \mu_0 \sigma}} \tag{11}$$

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

To calculate the total leakage inductance across all winding portions, it must be multiplied by how many winding portions (w_p) there are in the interleaved winding arrangement. Then the total leakage inductance can be expressed by substituting expressions (4)-(8) into equations (2). Finally, the total leakage inductance can be expressed in equation (12):

$$L_{\sigma,total} = \frac{L_{\sigma}'}{w_p} \tag{12}$$

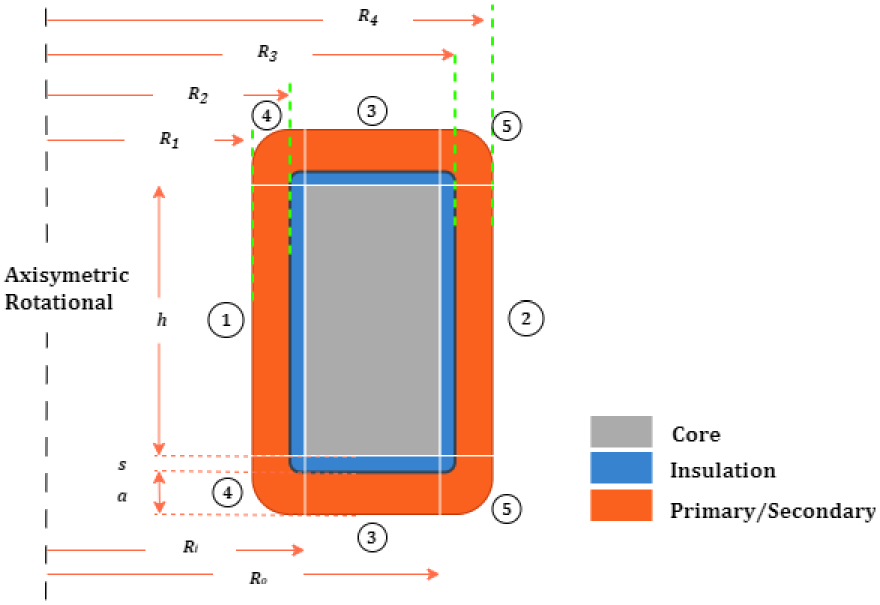

Figure 1 2D axisymmetric rotational view of toroidal transformers

2.1.1. High Frequency Effects

At high frequencies, 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 leakage inductance decreases as frequency increases. The current is no longer distributed consistently in the conductor at high frequency due to eddy current effects, as shown in Figure 2 (Bu *et al.*, 2023). At high frequency, the area under the magnetomotive force (MMF) curve is smaller than at low frequency, indicating that the stored leakage energy is reduced at higher frequency. Since the leakage energy decreases at high frequency it can also be said that the leakage inductance decreases as defined in equation (1).

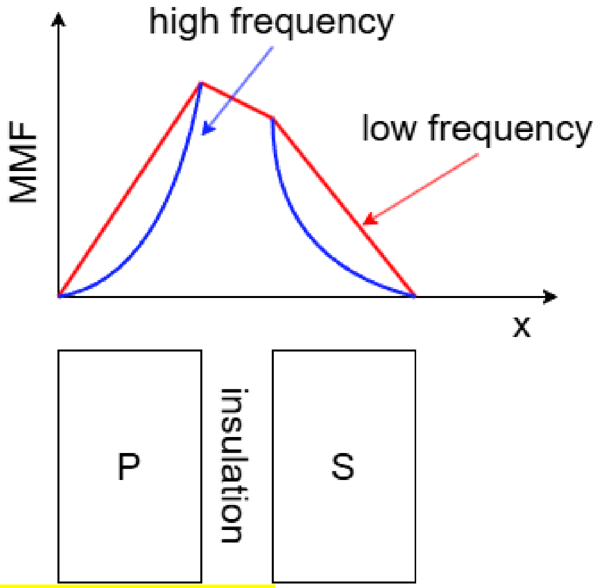

Figure 2 MMF variations at high frequency

2.2. Research Method

The reduction process carried out is shown in Figure 3, where the parameter to be reduced is the high leakage inductance in the conventional winding arrangement.

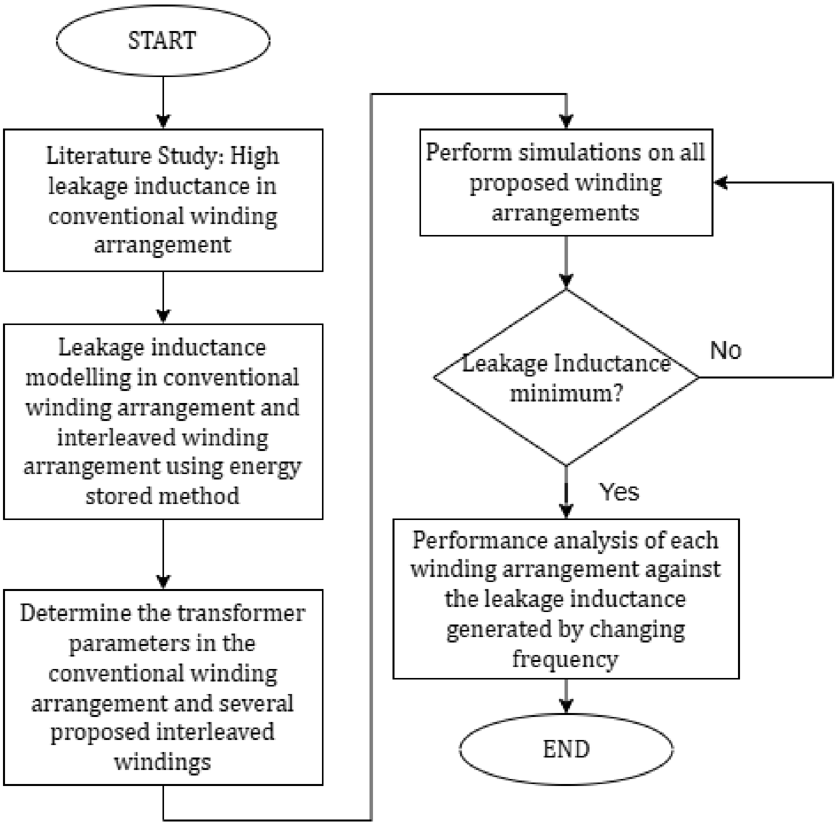

Figure 3 Research Flowchart

Transformer design is required before reduction the leakage inductance. Determining parameters in transformer design is necessary to facilitate initial design planning, so that research objectives can be achieved. The main purpose of this research is to decrease the leakage inductance as low as possible by simply changing the winding arrangement. The reduction target is formulated in equation (13) as follows:

$$f(w_p) = min\{L_\sigma\} \tag{13}$$

where L_σ is the leakage inductance in the transformer, w_p is defined as the winding portion, whereas in conventional windings, there is only one winding portion. The number of winding portions (w_p) must not exceed the number of primary or secondary windings (whichever is less). Reducing leakage inductance must be done by distributing the primary and secondary windings evenly throughout the transformer window, so that the distribution of the magnetic field 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 will be placed next to each other. Table 1 shows summary of the transformer parameter that will be used in this research. Core dimensions and materials are obtained from manufacturing specification T60004-L2130-W630. The core material does not influence the results, as equations (1)–(12) do not involve the permeability of the transformer core material. Therefore, this parameter is not critical in determining the outcome. Although it is stated that magnetic core materials have different characteristics (Djuhana *et al.*, 2021). The number of turns is assumed to be 30 for each primary and secondary winding to fill the transformer core. The excitation current is assumed to be 1 A to simplify the analysis (Chen, 2019)

Table 1 Parameter of the Transformers

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 is used and the total number of windings is 60. Figure 4 (a) depicts the winding arrangement, namely conventional winding, the number of winding portion 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 4. The type-a interleaved winding arrangement has a total of $w_p = 2$, where each winding portion has 15 primary windings 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. Interleaved winding arrangement type-d 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, namely 60 turns (30 primary and 30 secondary).

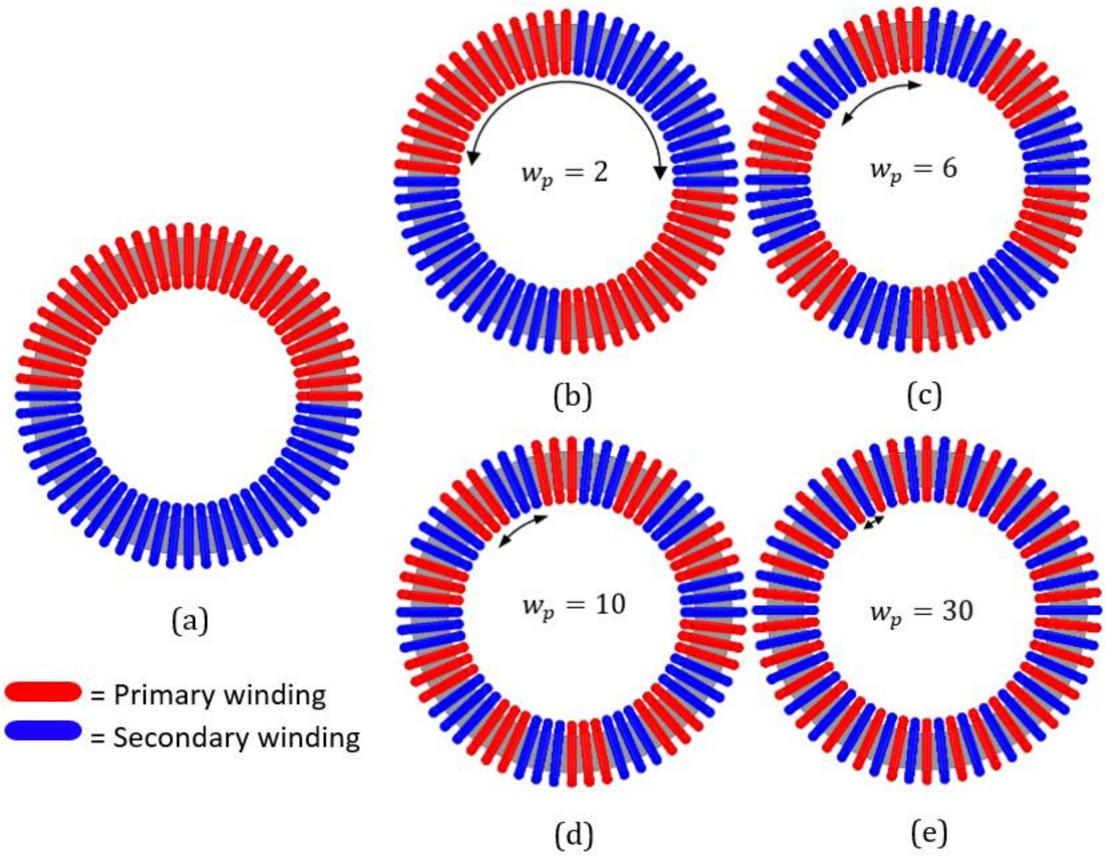

Figure 4 (a) Conventional winding arrangements ($w_p = 1$); Interleaved winding arrangements (b) $w_p = 2$; (c) $w_p = 6$; (d) $w_p = 10$; and (e) $w_p = 30$

The verification process begins by creating a 3D design of the toroidal transformer using the specifications provided in Table 1. The winding arrangement is simplified into a ring configuration to streamline the design process. 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 for the calculation of leakage inductance using the stored energy method, as described in equation (1). Finally, the models of all winding arrangements, as shown in Figures 4, are simulated using the Eddy Current Solver in Ansys Maxwell 3D.

3. Results and Discussion

This section details the simulation results to verify the proposed method. The simulations were conducted using Ansys Maxwell 3D software, which is employed to analyze magnetic fields with non-uniform static frequency domains. The purpose of this paper is to reduce the leakage inductance that occurs in conventional windings by simply changing the winding arrangement technique. This section will show the changes in the winding arrangement in the toroidal core that can affect the leakage magnetic field, so that the optimal leakage inductance can be achieved.

To carry out an analysis of the distribution of the magnetic field along the windings in a toroidal transformer, it is carried out on the determined cutting line in Figure 5. Figure 5 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 6 shows the distribution of magnetomotive force (MMF) along the cut line defined in Figure 5. At low frequency, the MMF is linearly distributed in the conductor. However, as the frequency increases, the skin effect causes the current density to become irregular across the conductor cross-section, with most of the current concentrated at the conductor surface. Proximity effect occurs in conventional windings which causes current to tend to flow towards the outermost layers of the winding. At high frequency, the leaked magnetic energy forms a "concave shape", especially when there are many turns in 1 winding portion, as shown in the previous reference in Figure 2. The high frequency of 10 kHz contributes to a substantial increase in the leakage magnetic field intensity between the primary and secondary windings as shown in Figure 6. However, in interleaved windings type-d, 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 7.

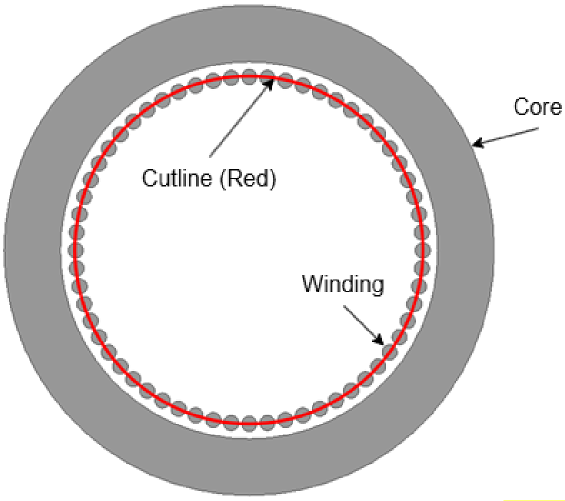

Figure 5 Determined cutline across the conductors on the primary and secondary windings

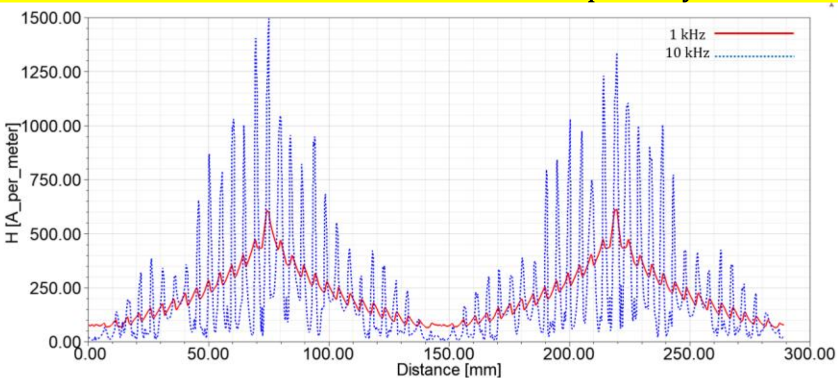

Figure 6 MMF distribution across the defined cutline according to Figure 5 on the conventional winding arrangement

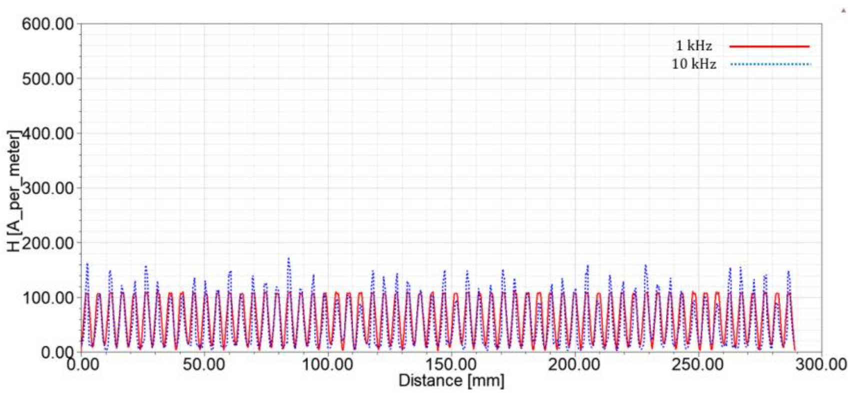

Figure 7 MMF distribution across the defined cutline according to Figure 5 on the type-d interleaved winding.

The area of the curve in the high frequency case appears to decrease, so the leakage flux will also decrease as the frequency increases. This causes the leakage inductance to decrease as the frequency increases, because equation (11) 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 outermost layer of the conductor. Therefore, the reduction in leakage inductance with enlarging frequency is more noticeable for transformers with fewer w_p. At high frequency, the leakage inductance value decreases as the frequency increases. 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%, while type-d shows a decrease of about 9.01%. The leakage inductance for the 5 different winding arrangements shown in Figure 4 is compared. 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

Leakage inductance decreases quite drastically with the number of winding portions, as shown in Figure 8 if applied to all w_p values in equation (12). The reduction in leakage inductance against the number of winding portions (number of interleaved turns) shows a negative exponential relationship in mathematics model as shown in equations (12). Evidently, interleaved winding can reduce leakage inductance as expected. Leakage inductance 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 around 98.90% and 98.94% where leakage inductance values of 0.58 μH and 0.53 μH for the type-d interleaved winding arrangement are achieved at 1 kHz and 100 kHz respectively. This shows good reduction in fully interleaved winding (type-d) compared to conventional, type-a, type-b, and type-c winding arrangements. This can be interpreted that 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 is known to have relatively high leakage inductance (Baktash and Vahedi, 2014). An example of this conventional winding configuration is shown in Figure 4(a). Unlike the 1:1 ratio commonly used in interleaved windings, the study by Bakhtash and Vahedi did not adopt this approach. This research aims to reduce the leakage inductance of the model proposed by (Baktash and Vahedi, 2014), yielding a significant reduction in leakage inductance. Furthermore, a study conducted by (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 percentage reduction between the EE core and the toroidal core 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 toroidal and EE cores, particularly in terms of their dimensions and winding arrangements. Therefore, the toroidal core is highly recommended for power applications where low parasitic parameters are essential.

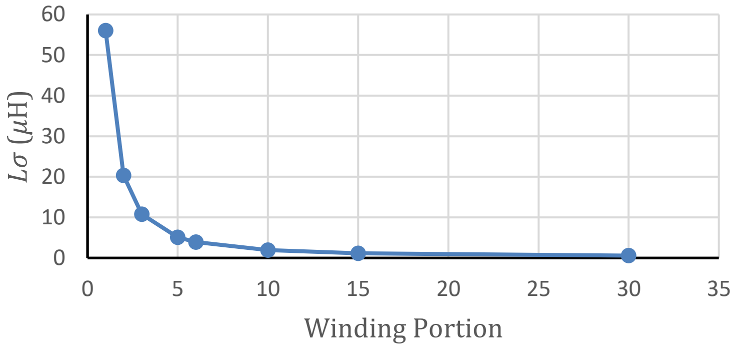

Figure 8 Leakage inductance vs winding portions

Figure 9 indicates a comparison of leakage inductance between the conventional winding arrangement and the type-d interleaved winding arrangement. The proximity effect occurs in conventional winding arrangements which causes the leakage magnetic field to be pushed towards the outermost layer of the conductor. Therefore, the effect of frequency in reducing leakage inductance is more apparent in transformers with conventional windings. This is evidenced by the marked difference in the curves between Figure 6 and Figure 7. The skin effect and proximity effect are closely related to skin depth, which is expressed in equation (11). As the frequency is increased, the leakage inductance value drops with increasing frequency due to the skin effect as seen in Figure 2. It is observable in Table II, the leakage inductance in the conventional winding with frequency of 1kHz and 100kHz shows a decrease of about 10.71%, while the type-d shows a decrease of about 9.01%. Even high frequency effects also show significant differences in conventional windings and optimal designs (interleaved windings). The characteristics of the curve can be used to analyze the resonance frequency of the converter. However, additional analysis is needed on the winding losses because the higher the frequency, the higher the winding losses due to the eddy current effect.

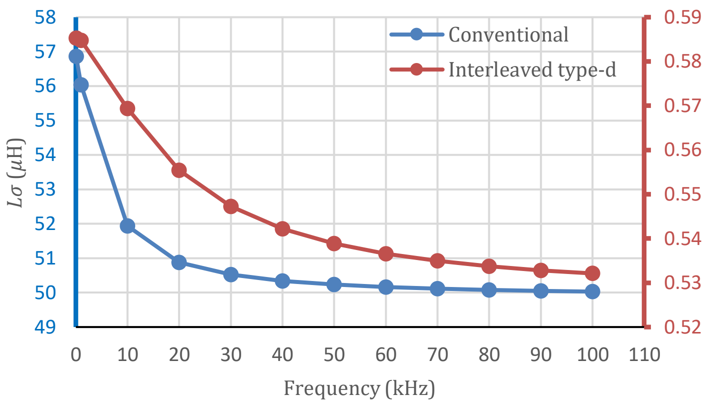

Figure 9 Comparison of simulation results between conventional and fully interleaved windings

Figure 10 and 11 shows the FEA simulation results on the distribution of leakage energy and the distribution of magnetic field strength for 5 different winding arrangements at 1 kHz. This shows that energy leakage is reduced drastically when the primary and secondary windings are positioned next to each other every 1 turn. The interleaved winding type-d is able to distribute the leakage magnetic field evenly in the transformer winding compared to the interleaved winding type-a, type-b, and type-c. The maximum mmf decreases when the winding arrangement with the highest winding portion. The interleaved winding arrangement divides the maximum leakage magnetic field into 60 points with approximately 100 A/m. This 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 mmf according to the number of winding portions in each interleaved winding. The difference in the curve area is also seen between the interleaved winding and the conventional winding. It can be seen that the reduction in leakage magnetic field in the interleaved winding arrangement indicates a reduction in leakage inductance because equation (1) states that the main factor in leakage inductance is only the leakage energy stored in the air and along the winding. The curve shape of conventional windings, type-a, type-b, and type-c looks non-linear (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 Figure 2 when the x-axis passes through the primary conductor area, insulation, and secondary conductor (Bu *et al.*, 2023). The characteristics of the curve and the distribution of MMF can be very useful in designing a transformer that requires low parasitic components. However, if designing about parasitic parameters, of course, we must analyze the parasitic capacitance as well for further work. Because parasitic capacitance is also one of the unwanted parasitic components in power electronics applications.

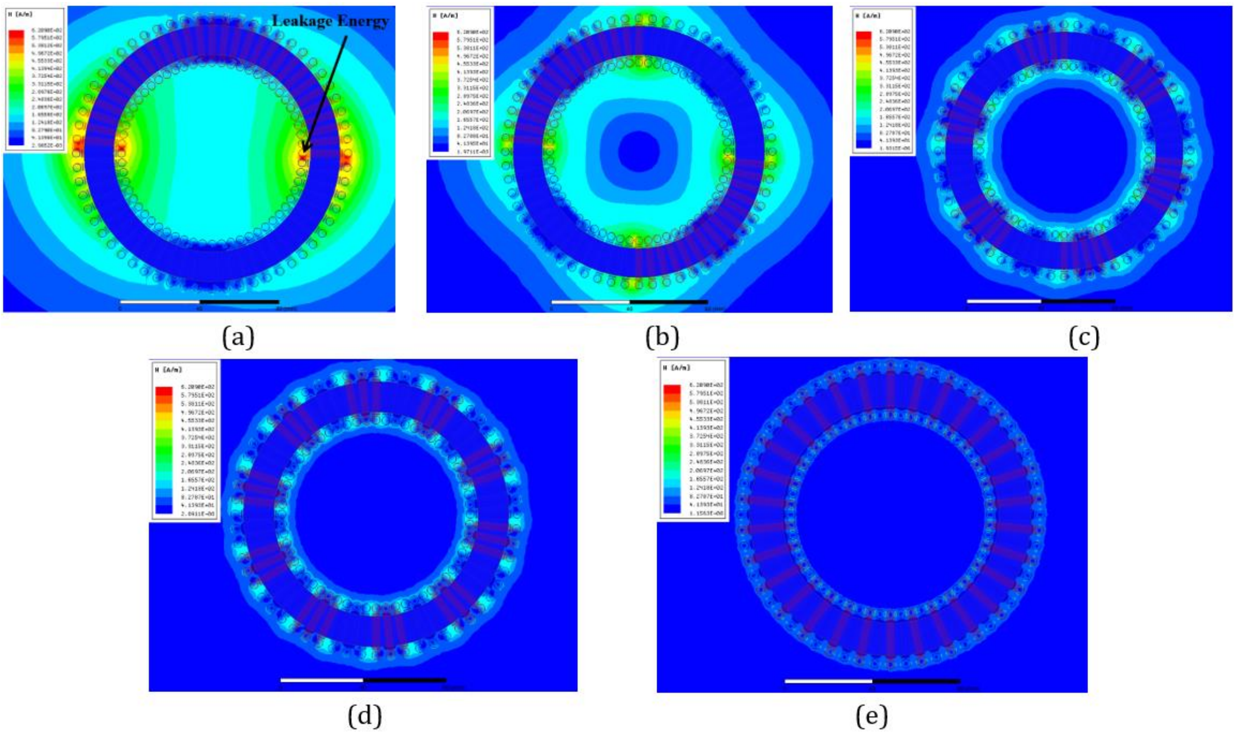

Figure 10 FEA simulation results on leakage magnetic energy distribution at 1 kHz, (a) conventional, (b) interleaved type-a, (c) interleaved type-b, (d) interleaved type-c, (e) interleaved type-d

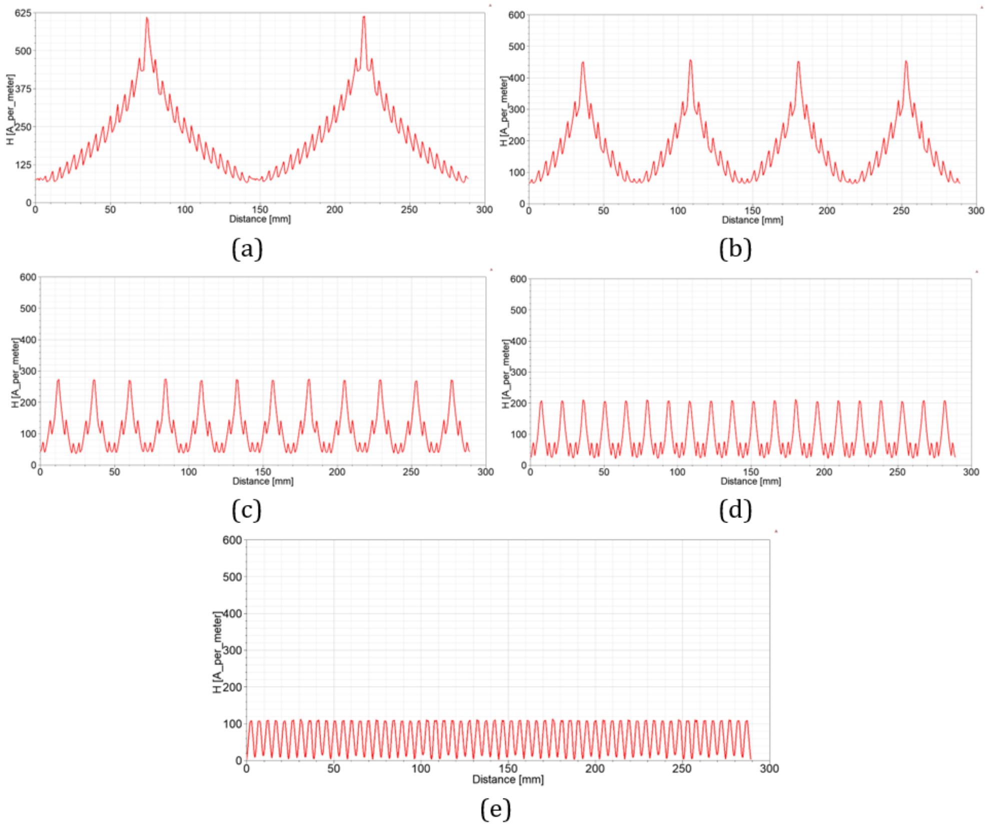

Figure 11 MMF distribution across the defined cutline according to Figure 7 (a) conventional, (b) interleaved type-a, (c) interleaved type-b, (d) interleaved type-c, (e) interleaved type-d

4. Conclusions

This study successfully achieved a significant reduction in leakage inductance in high-frequency toroidal transformers through the interleaved winding technique. By positioning each primary and secondary winding adjacent to one another, the interleaved winding configuration in the simulation minimized the leakage magnetic field between windings, thus lowering the leakage inductance. The interleaved winding arrangement, particularly the type-d arrangement, yielded a more even MMF distribution compared to 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 100 kHz, showcasing 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 kHz 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.

Acknowledgments

This paper is partially funded by the Indonesia Endowment Fund for Education (LPDP) under Project RISPRO No. PRJ-6/LPDP/LPDP.4/2022.

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