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Rethinking Basic Assumptions for Modeling Parasitic Capacitance in Inductors

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***Abstract*—This article rethinks the basic assumptions often used in analytically modeling parasitic capacitance in inductors. These assumptions are classified in two commonly-used physics-based analysis methods: the lumped capacitor network method and the energy conservation method. The lumped-capacitor network method is not the proper solution for calculating the equivalent parasitic capacitance in inductors at the first resonant frequency, but rather represents the equivalent parasitic capacitance above the last resonant frequency. The energy-conservation based method is shown to be more accurate and a reasonable solution to model the equivalent parasitic capacitance at the first resonant frequency. Multiple case studies of inductors are used for verifying the theory.**

***Index Terms*—Assumptions, inductors, modeling, parasitic capacitance.**

I. Introduction

THE PARASITIC parameters in passive components are of growing importance [1]–[7] due to the exponentially increasing use of wide band-gap devices in power electronic converters to operate at higher frequencies with faster switching transients [8]–[10]. Faster switching speed can result in larger currents due to the parasitic capacitance in inductors [11], which will cause extra losses in transistors [12] and EMI/EMC issues [1], [13], and therefore, limit the potential performance of high-frequency converters. In order to mitigate the effects of parasitic capacitance in magnetic components, it is important to properly model and analyze parasitic capacitance in inductors.

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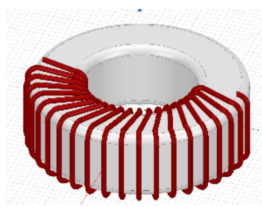
Physics-based modeling methods are widely used to analytically predict the parasitic capacitance of inductors [14], [15] since the value can be calculated from geometric values and material properties [16]–[18]. As opposed to finite-element-based (FEA-based) modeling, physics-based modeling more readily produces guidelines for designing and improving components.

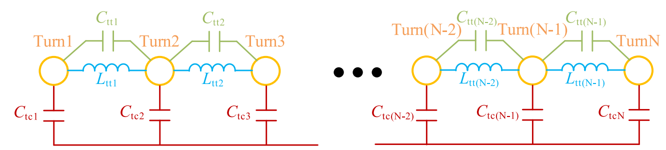
Generally, there are two state-of-the-art physics-based modeling methods that can provide the explicit equations of the equivalent capacitance at the first resonant frequency: 1) the lumped capacitor network method [14], [19]–[21] and 2) energy conservation method [15]–[18], [22]–[24]. Both methods represent the inductors with an equivalent circuit constructed from multiple inductors and capacitors, with resistance usually neglected. However, two different assumptions are further used in these two modeling methods for simplifying the physics-based models of parasitic capacitance at the first resonant frequency in inductors.

In the lumped capacitor network method [14], [19]–[21], the original equivalent circuit is simplified to a purely capacitive network, where elementary inductors are completely neglected since this method assumes that the impedance of elementary inductors is negligibly high at the first resonant frequency. In the energy-conservation based method [15]–[18], [22]–[24], the effects of elementary inductors are considered by the voltage drop between turns, where the voltage drop is assumed to be distributed linearly at each turn. Then, the equivalent capacitance between the two terminals of inductors is calculated by deriving the total energy in the electric field between the turns and matching it to the energy stored in the equivalent capacitance.

As mentioned, although both the lumped capacitor network method and energy conservation method have been widely used in calculating the equivalent capacitance of inductors at the first resonant frequency, the similarities and differences of these two methods are only partially elaborated. For example, [14] indicates that the lumped capacitor network method is only suitable for inductors with simple structure, i.e., the single-layer inductor with ferrite core or air core since the pi-circuit transformation used is only applicable in the equivalent circuit with a simple geometrical structure. However, the description is still not accurate and comprehensive. Most importantly, the key limitation of the lumped-capacitor method is still not revealed in prior publications.



(a)



(b)

Fig. 1. Toroid inductor. (a) 3-D model. (b) 2-D equivalent circuit representation with neglected mutual inductive couplings and capacitive couplings between nonadjacent turns.

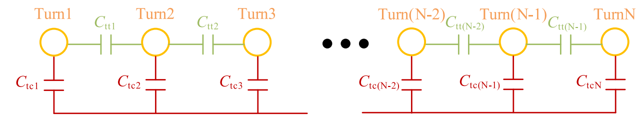


Fig. 2. Simplified equivalent circuit using the lumped capacitor network method [11].

In this article, the basic simplifying assumptions used in the lumped capacitor network and the energy conservation methods are reviewed. Then, a significant contradiction between the lumped capacitor network method and the energy conservation method is identified. Then, three theoretical comparisons of these two methods at the circuit-level are elaborated and validated in LTspice, where the limitations are addressed. The comparisons show that the lumped capacitor network method is improper for calculating the total equivalent capacitance at the first resonant frequency of inductors, while the energy conservation method is the proper solution. This article also validates this conclusion with experimental measurements of the parasitic capacitance of multiple prototype inductors.

II. Problem Formulation

A single-layer toroid inductor with a ferrite core is used as an example in this section, though we emphasize that the conclusions apply to a broader class of components. Fig. 1(a) shows the 3-D structure of the toroid-inductor, where multiple turns of conductors are constructed as the winding. The high-frequency equivalent circuit of the exampled toroid-inductor is given in Fig. 1(b), where the resistance is neglected as usual.

The high-frequency equivalent circuit of the toroid inductor is based on the following three assumptions.

1) Each turn can be simplified as a 2-D element, i.e., a circular conductor running into the page. Therefore, the capacitive coupling between two adjacent turns is simplified as a single capacitor C_{tt}. The capacitive couplings between each turn and core are simplified as the single capacitor C_{tc}. Between two adjacent turns, there is an elementary inductor L_{tt}.
2) The complicated coupling among all the turns is neglected in favor of a simplified model with a series inductance between each turn. Similarly, the capacitive coupling between nonadjacent turns is also neglected. Losses are also neglected.
3) The core is assumed as a perfect conductor, as is commonly done. Even high-resistivity cores often have relatively high permittivity [25], which has a similar effect when modeling electric field distributions.

The rationality of these three assumptions has been deeply elaborated in [11]–[21]. They are important for obtaining explicit expressions of parasitic capacitance in inductors (or transformers) by making the analytic problem tractable. Both the lumped capacitor network method and the energy conservation method are based on the three above assumptions, with different new assumptions further introduced for simplifying the modeling and calculations, which will be elaborated in the following sections.

A. Lumped Capacitor Network Method

In [14] and [19]–[21], the lumped capacitor network method has been used for solving the explicit expression of total equivalent capacitance between Turn1 and Turn N.

The additional assumption made in the lumped capacitor network method is to neglect elementary turn-to-turn inductance shown as $L_{\mathrm{tt}1}$–$L_{\mathrm{tt}(N\text{-}1)}$. The lumped capacitor network method argues that the impedances of elementary turn-to-turn inductances $L_{\mathrm{tt}1}$–$L_{\mathrm{tt}(N\text{-}1)}$ are very high at the first resonant frequency, and therefore could be considered as open circuits. This assumption should immediately appear improbable as the first resonance is by nature a magnetic–electric interaction.

Thus, the equivalent circuit is shown in Fig. 1(b) is simplified to a purely capacitive network [14], as shown in Fig. 2. By using the delta-to-star transformation, the total equivalent capacitance $C_{\mathrm{total}}(N)$ of the inductor with a different number N of turns can be calculated [19], which is given here as follows:

$$C_{total}(2) = C_{\mathrm{tt}} + \frac{C_{\mathrm{tc}}}{2}$$
$$C_{total}(3) = \frac{C_{\mathrm{tt}}}{2} + \frac{C_{\mathrm{tc}}}{2}$$
$$C_{total}(N) = \frac{C_{total}(N-2)\times\frac{C_{\mathrm{tt}}}{2}}{C_{total}(N-2)+\frac{C_{\mathrm{tt}}}{2}} + \frac{C_{\mathrm{tc}}}{2}, \text{if} N > 3. \quad (1)$$

According to (1), if $N > 3$, $C_{\mathrm{total}}(N)$ is an iterative sequence. The authors in [14] and [19]–[21] found that the iterative sequence is convergent if N is large enough, which is given as an analytical equation as follows:

$$C_{total}(\infty) = \frac{C_{\mathrm{tt}}}{4}\left(\alpha + \sqrt{\alpha^2+4\alpha}\right), \alpha = \frac{C_{\mathrm{tc}}}{C_{\mathrm{tt}}}. \quad (2)$$

For example, if $\alpha = 2$ (approximately the case if the turn-to-turn and turn-to-core spacing are set by wire insulation), then

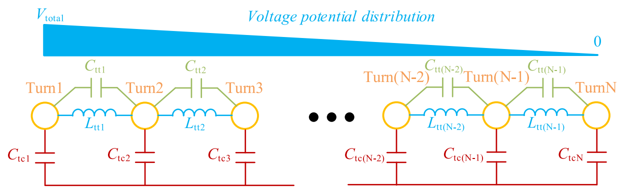


Fig. 3. Simplified equivalent circuit using the energy conservation method.

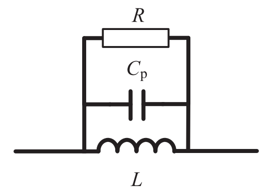


Fig. 4. Equivalent circuit for inductors before the first resonant frequency.

the total capacitance between Turn1 and Turn N is convergent to $1.366C_{tt}$ when N is larger than about 10 [19]–[21]. Thus, the lumped capacitor network method predicts that the equivalent capacitance does not vary with the number of turns N so long as N is large enough.

B. Energy Conservation Method

The energy conservation method has also been used for calculating the explicit expressions of parasitic capacitance in inductors [15]–[18], [22]–[24], using a different assumption compared to the lumped capacitor network method.

The energy conservation method assumes that the voltage potential is linearly distributed along the winding ($V_{turn} = V_{total}/(N-1)$) due to magnetic coupling between the turns. The elementary inductors are not considered as open-circuit elements in this method. Since the core is floating, the voltage potential on the core is assumed to be $V_{total}/2$ according to [1], [3], and [24].

For the equivalent circuit illustrated in Fig. 3, the total parasitic capacitance between Turn 1 and Turn N can be obtained as (3), based on the energy conservation law introduced in [15]

$$C_{total}(N) = \sum_{n=1}^{N}\left(\frac{(N-n)V_{total}}{N-1} - \frac{V_{total}}{2}\right)^2 \frac{C_{tc}}{V_{total}^2} + \sum_{n=1}^{N-1}\left(\frac{V_{total}}{N-1}\right)^2 \frac{C_{tt}}{V_{total}^2}. \quad (3)$$

Since the voltage potential is discrete in (3), the sum sequence is used to represent the total equivalent capacitance. In the limit of many turns, the sum can be approximated as an integral and $C_{total}(N)$ can be presented as (4)

$$\begin{aligned} C_{total}(N) &= \tfrac{NC_{tc}}{12} + \tfrac{C_{tt}}{N-1} \\ C_{total}(\infty) &= \infty. \end{aligned} \quad (4)$$

Thus, the total parasitic capacitance is unbounded as N grows. This stands in contrast to the lumped capacitor network method, which predicts that capacitance converges as N increases.

C. Contradictions

Although both methods are aiming to analytically calculate the total equivalent capacitance of inductors at the first resonant frequency, the results and conclusions of (2) and (4) are totally different, especially as N becomes large.

The lumped capacitor network method claims that the total equivalent capacitance of the inductor will be convergent with increasing the number of turns, where the energy conservation method claims that the total equivalent capacitance of inductor will continue to grow with increasing number of turns. Therefore, one or both methods are improper in solving the total equivalent capacitance of the equivalent circuit at the first resonant frequency.

The difference comes from the lumped capacitor network assumption that the elementary inductors can be considered as open circuits versus the energy conservation method's assumption of linear voltage distribution across turns owing to magnetic coupling. In a way, each model makes the opposite assumption–the lumped capacitor model assumes that magnetic effects are irrelevant, while the energy-conservation approach assumes that the voltage distribution between turns is entirely determined by magnetic effects.

We will show that neither assumption is entirely accurate, though the energy-conservation approach is much more accurate and can be considered a reasonable solution for calculating the parasitic capacitance and predicting the first resonant frequency.

III. Evaluation of Model Assumptions

As mentioned, the lumped capacitor network method appears improbable as it ignores magnetic effects while the first resonant frequency is, by definition, a magnetic-electric interaction. This section will prove that it is improper to consider the elementary inductors as open circuits around the first resonant frequency of inductors. We will further show that the energy conservation method reasonably predicts the equivalent parasitic capacitance around and below the first resonant frequency. In order to prove it, multiple circuit simulations are applied in LTspice.

A. Impedance Measurement Evaluations

First, the original equivalent circuit shown in Fig. 1(b) is established in LTspice, where the parameters are $L_{tt} = 1$ mH, $C_{tt} = 5$ pF, $C_{tc} = 10$ pF, and $N = 10$. The impedance of the original equivalent circuit, which includes every interturn inductance, turn-to-turn capacitance, and turn-to-core capacitance, is measured and shown as the yellow curve in Fig. 4. Meanwhile, with the known value of C_{tt}, C_{tc}, and N, the calculated total equivalent capacitance of the network is calculated as 6.9 pF using the lumped capacitor network method, and as 10.8 pF using the energy conservation method. Therefore, for the behaviors of inductors before the first resonant frequency, they could be represented by the equivalent circuit shown in Fig. 4. C_p is the total equivalent capacitance that needs to be modeled.

By paralleling $(N-1)L_{tt} = 9$ mH inductance to the calculated total equivalent capacitance, the equivalent circuit impedances

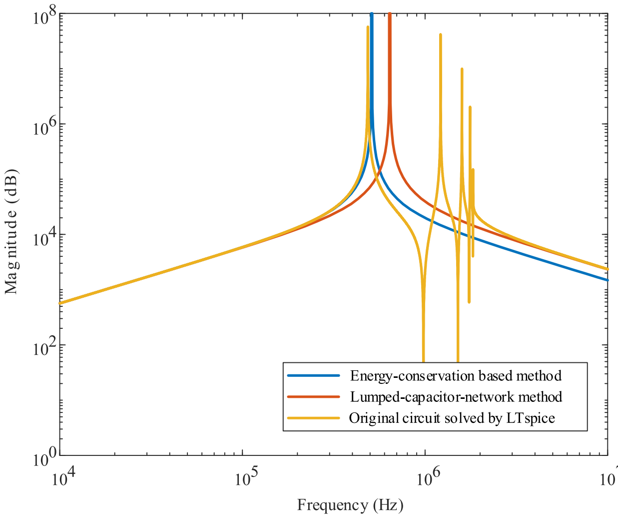


Fig. 5. Comparison of simulated impedance using LTspice and calculated impedance using energy conservation method and lumped capacitor network method ($N = 10$ is used in this case).

of each network are plotted in Fig. 5, which should be only valid before the second resonant frequency due to the common assumptions.

The measured impedance of the original circuit in LTspice, can also be fitted near the first resonant frequency with $L_{\mathrm{total}} = 9$ mH and $C_{\mathrm{total}} = 11.9$ pF. The lumped capacitor network method has the largest error of around 42%, for the equivalent capacitance at the first resonant frequency of the equivalent circuit shown in Fig. 1(b), where the energy conservation method has a smaller error of around 9%.

B. Voltage Potential Distribution Evaluations

Although the lumped capacitor network method shows huge error when predicting the total equivalent parasitic capacitance, it can match well with the measured impedance of the original equivalent circuit after the last resonant frequency. This makes sense, as the lumped-capacitor approach explicitly assumes that the frequency is high enough to ignore any magnetic impedances, where the frequency after the last resonant frequency point is high enough to consider the elementary turn-to-turn inductance L_{tt1}–$L_{\mathrm{tt}(N\text{-}1)}$ as completely open-circuits.

In order to further elaborate the comparisons, the individual voltage potentials versus frequencies of Turns 1–10 is simulated and compared using LTspice. The magnitude of ac perturbations is fixed at 1 V in LTspice. The simulated results of the original equivalent circuit and lumped capacitor network are shown in Fig. 6(a) and (b), respectively [the results for the energy conservation method are constant by assumption, in Fig. 6(c)].

The voltage potential distribution at each turn in the original equivalent circuit is not constant with respect to frequency. In lumped capacitor network method, the voltage potential is concentrated at the first and last turn, where the results for the energy conservation method are evenly distributed. By comparing the results at the first resonant frequency in Fig. 5, the voltage

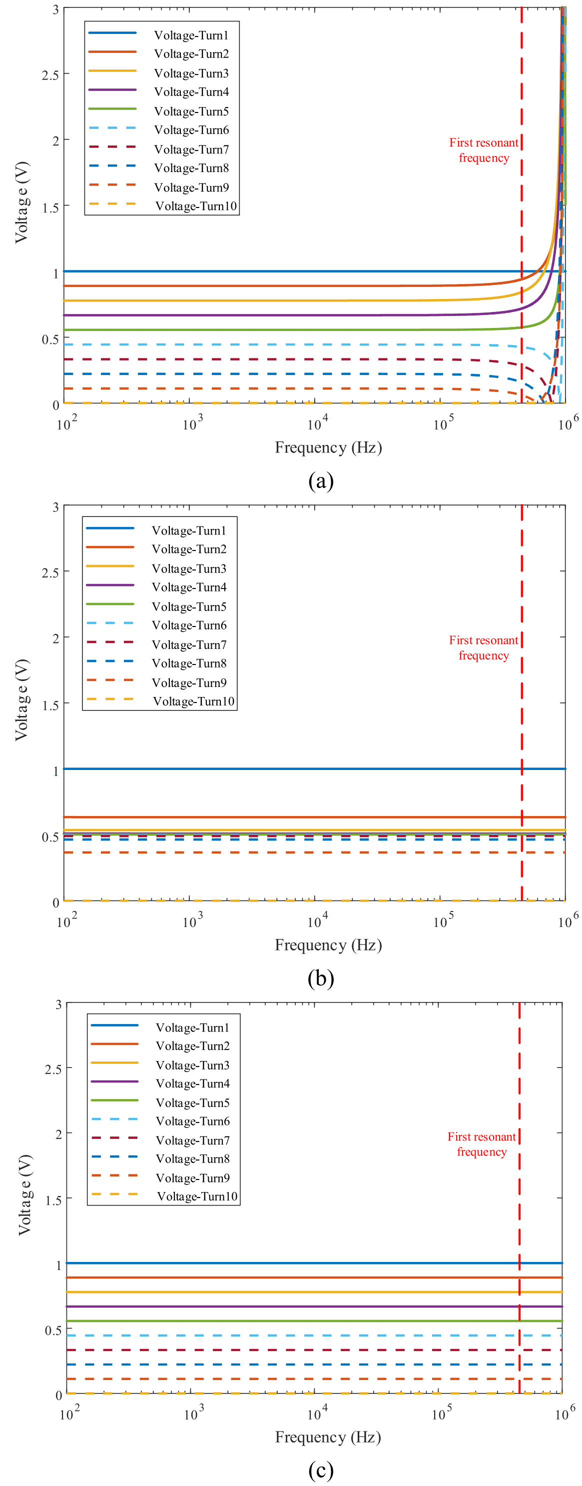


Fig. 6. Voltage potential distribution versus frequencies of Turns 1–10. (a) Original equivalent circuit (simulated by LTspice). (b) Lumped capacitor network method (simulated by LTspice). (c) Energy conservation method (according to assumption).

potential of the lumped capacitor network method has a huge difference compared to the original equivalent circuit, which means the assumption used in lumped capacitor network method fails to represent the actual voltage potential distribution. Although the voltage potential distribution is unevenly distributed at the first

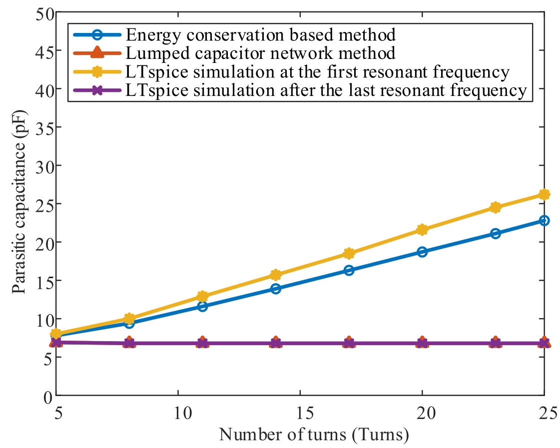


Fig. 7. Comparison of the calculated and simulated capacitance of the equivalent circuit with the different number of turns.

resonant frequency in the original equivalent circuit, it is still quite similar to the even voltage potential distribution, which means the assumption made in the energy conservation method is reasonable up to the first resonant frequency.

C. Equivalent Parasitic Capacitance Evaluations

In this section, the equivalent capacitances at the first resonant frequency are calculated using both methods with different numbers of turns and compared with the simulated value of the original equivalent circuit using LTspice, as shown in Fig. 7.

In Fig. 7, the number of turns in the inductor is varied from 5 to 25 turns. The parasitic capacitance of energy conservation method and LTspice simulation at the first resonant frequency shows a positive correlation with the number of turns. The errors between the energy conservation method and LTspice simulation at the first resonant frequency can be explained by the nonuniform voltage potential difference, which has been elaborated in previous sections. The lumped capacitor network method shows huge errors between the simulated capacitance at the first resonant frequency, and the errors become larger with an increased number of turns.

However, the calculated impedance using the lumped capacitor network method shows good agreements with the simulated equivalent capacitance after the last frequency, which still makes sense since the lumped capacitor network method assumed the frequency is high that the elementary turn-to-turn capacitance could be considered as open-circuits.

D. Summary

According to the evaluations presented in this section, the energy conservation method can predict the equivalent capacitance of network at the first resonant frequency, introducing some acceptable errors due to the actual nonlinear voltage potential distribution of winding. The lumped capacitor network method predicts the equivalent capacitance in the limit of high frequency, where previous research still used the method to calculate the equivalent capacitance of inductors at the first resonant frequency. Therefore, [14], [19]–[21] mis-state the valid frequency range of the lumped capacitor network method.

TABLE I
GEOMETRICAL AND MATERIAL PARAMETERS OF PROTOTYPE A

Core size (Outer diameter/Inner diameter/Height)	50mm/ 30mm/ 20mm
Core material [27]	TDK N30
Mean length of per turn	68 mm
Number of turns	41 - 81
Average distance of the airgap between the winding and core (p_2)	0.1 – 0.3 mm
Average distance of the airgap between two adjacent turns (p_1)	0.1 mm
Diameter of conductor	0.6 mm
Diameter of cable includes coating	0.7 mm
Relative permittivity of the turn coating	3.7

IV. EXPERIMENTAL VERIFICATIONS

In order to verify the theory, three prototypes (inductors A, B, C) are researched by comparing the results of theoretical modeling methods and experimental measurements, where the parasitic capacitance of inductors is calculated and measured with the different number of turns.

The total equivalent capacitance of the inductors A–C under the different number of turns is theoretically calculated using the energy conservation method, where the voltage potential is assumed to be linearly distributed within the winding. The parasitic capacitance of the prototyping inductors A–C at the first resonant frequency is also measured using Keysight E4990 impedance analyzer and its adapter 16047E. The valid frequency range of the Keysight E4990 impedance analyzer is up to 120 MHz, and therefore it is not always possible to identify the equivalent parasitic capacitance after the last resonant frequency, due to the high-frequency limit. Therefore, only the equivalent capacitance of the inductor at the first resonant frequency is fitted by using the resonant method [24], according to the measured impedance.

The voltage potential distribution of inductors under different frequencies is not verified by experiments in this article, since the parasitic capacitance of probes and scopes can significantly influence the measured voltage distribution [26]. Therefore, the actual voltage potential distribution of inductors cannot be obtained using voltage probes directly.

A. Prototype A: R50mm/30mm/20mm N30 Toroid Inductor

Prototype A is constructed by a toroid core, using N30 core material from TDK [27]. The optimal frequency range of N30 material is below 0.4 MHz, where the measured frequency of the first resonant frequency should also be below 0.4 MHz for ensuring relatively constant permeability. Therefore, at least 51 turns are implemented in prototype A.

The rest parameters of Case A toroid inductor are listed in Table I, and the prototyping Case A is shown in Fig. 8. The

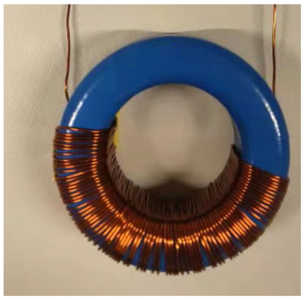


Fig. 8. Photograph of Prototype A: R50mm/30mm/20mm N30 toroid inductor.

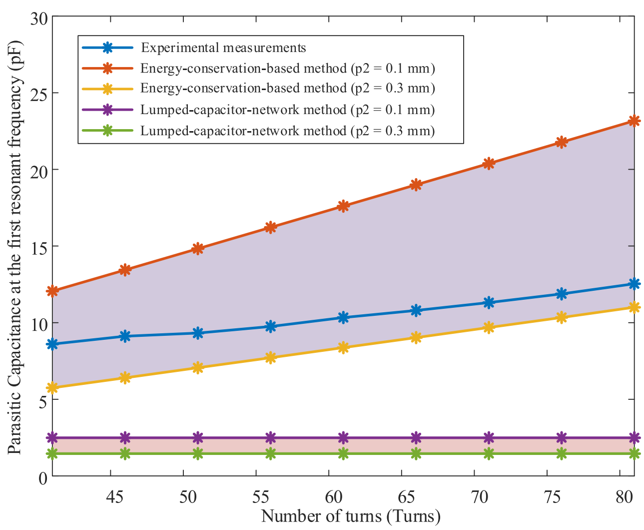


Fig. 9. Comparison among calculated equivalent capacitance (energy conservation method), calculated equivalent capacitance (lumped capacitor network method), and measured equivalent capacitance of Prototype A.

average distance between winding and core p_2 is highly relevant to predicting the parasitic capacitance of the inductor, and due to the bending ratio of copper, the value could be varied by the position of windings. In this case, the average distance is estimated from 0.1 to 0.3 mm according to the measurement by using a vernier caliper.

The calculations and measurements of parasitic capacitance at the first resonant frequency in Prototype A are shown in Fig. 9. The measured equivalent capacitance at the first resonant frequency versus the different number of turns is shown as the blue curve. The calculated capacitance versus the different number of turns is shown as a region of possibilities to account for the uncertainty in the average wire-to-core spacing p_2. The measured equivalent capacitance at the first resonant frequency increases when the number of turns is increased. The energy conservation method can predict the equivalent capacitance at the first resonant frequency, by introducing some uncertainties of geometrical errors. The calculated capacitance using lumped-capacitor modeling method shows huge errors (minimum 250%–600%) compared with the measured capacitance, especially when the number of turns is large.

TABLE II
Geometrical and Material Parameters of Prototype B

Core size (Outer diameter/Inner diameter/Height)	102mm/ 65.8mm/ 15mm
Core material [28]	TDK N87
Mean length of per turn	72 mm
Number of turns	66 - 148
Average distance of the airgap between the winding and core (p_2)	0.1 – 0.3 mm
Average distance of the airgap between two adjacent turns (p_1)	0.1 mm
Diameter of conductor	0.6 mm
Diameter of cable includes coating	0.7 mm
Relative permittivity of the turn coating	3.7

TABLE III
Geometrical and Material Parameters of Prototype C

Core size (Length/ Height/Width)	59mm/ 31mm/ 22mm
Core material [29]	TDK N97
Mean length of per turn	70.7 mm
Number of turns	30 - 63
Average distance of the airgap between the winding and core (p_2)	0 – 0.05 mm
Average distance of the airgap between two adjacent turns (p_1)	0.1 mm
Diameter of conductor	0.6 mm
Diameter of cable includes coating	0.7 mm
Relative permittivity of the turn coating	3.7

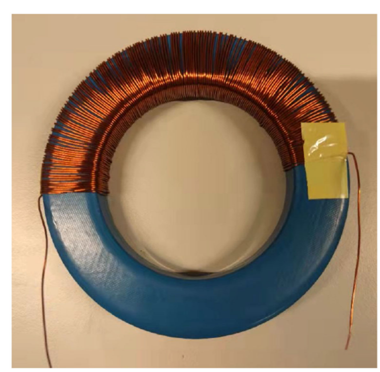


Fig. 10. Photograph of Prototype B: R102mm/65.8mm/15mm N87 toroid inductor.

B. Prototype B: R102mm/65.8mm/15mm N87 Toroid Inductor

Prototype B is constructed by a toroid core, using N87 material from TDK [28]. The parameters of the prototype are listed in Table II . In order to guarantee a constant permeability that the first resonant frequency of the inductor will be below the optimal frequency range (0.5 MHz), a minimum number of turns is selected as 66. The maximum number of turns is 148 in this case. The photograph of Prototype B is shown in Fig. 10.

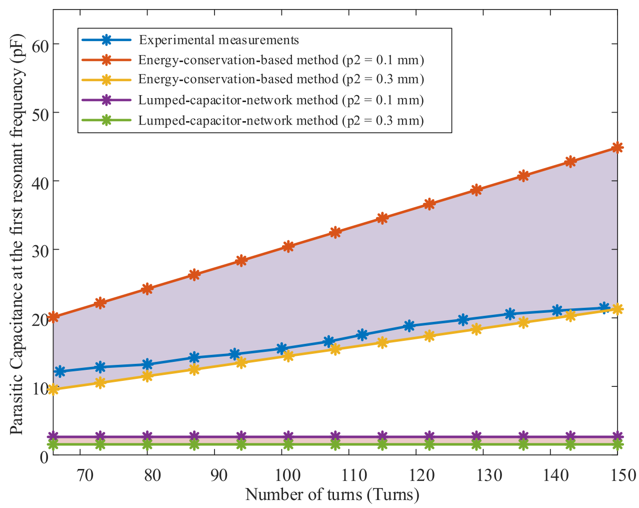


Fig. 11. Comparison among calculated equivalent capacitance (energy conservation method), calculated equivalent capacitance (lumped capacitor network method), and measured equivalent capacitance of Prototype B.

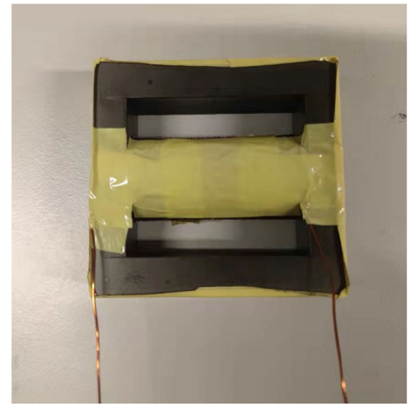


Fig. 12. Photograph of prototype C: ETD 59mm/31mm/22mm N97 E-core inductor.

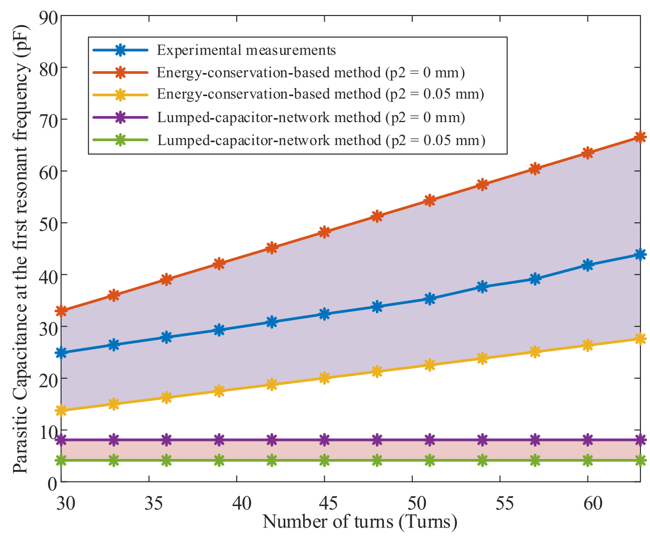


Fig. 13. Comparison among calculated equivalent capacitance (energy conservation method), calculated equivalent capacitance (lumped capacitor network method), and measured equivalent capacitance of Prototype C.

The calculations and measurements of parasitic capacitance at the first resonant frequency in Prototype B, versus the different number of turns, are compared in Fig. 11.

Using the lumped capacitor network method, the calculated capacitance is always a constant value versus the number of turns. However, the measured capacitance is increased when the number of turns becomes larger. The minimum error between lumped capacitor network method and measurement is between 500% and 1900%. According to Fig. 10, when p_2 is between 0.1 and 0.3 mm, the energy conservation method predicts the measured equivalent capacitance at the first resonant frequency. The calculated equivalent capacitance using the energy conservation method keeps increasing when the number of turns is larger, which is shown experimentally.

C. Prototype C: ETD 59mm/31mm/22mm N97 Inductor

The inductor in Prototype C is constructed by two E-type cores, using core material N97 from TDK [29]. Similar to before, the minimum turns are 30 for ensuring the first resonant frequency within the optimal frequency range. The parameters of the prototype are listed in Table III. The photograph of Prototype C is shown in Fig. 12. The calculations and measurement of parasitic capacitance at the first resonant frequency in Prototype C, versus the different number of turns, are compared in Fig. 13.

Similar to Prototype A and B, the calculated capacitance using lumped capacitor network method is always a constant value under the different number of turns, where the minimum error is calculated between 200% and 400%. The measured equivalent capacitance at the first resonant frequency in Prototype C could be predicted by using the energy conservation method, by estimating the average distance of the airgap between the winding and core from 0 and 0.05 mm. With a given value of the airgap distance between winding and core, the calculated capacitance at the first resonant frequency using the energy conservation method is increased when the number of turns is larger, which is aligned with the experimental measurements.

D. Summary

The experimental results show that equivalent capacitance should increase with a larger number of turns, as predicted by the energy conservation method and not by the lumped capacitor network method. Therefore, this experiment shows the prediction of the lumped-capacitor method, namely that capacitance should converge with increasing number of turns, is incorrect.

The equivalent parasitic capacitance at the first resonant frequency is sensitive to the distance of airgap between core and winding; therefore, this article introduces the range of the airgap distance and predicts the equivalent capacitance using a region. The experimental results for all three inductors always fell within the range predicted by the energy conservation method.

V. Conclusion

This article rethinks the methods of calculating the parasitic capacitance of inductors. Two methods are explained, and their assumptions are critiqued. According to technical comparisons, the misunderstanding concepts and limits of these two methods are classified.

1) The lumped capacitor network method assumes that only capacitive impedance is significant. Therefore it predicts the capacitance in the limit of high frequency and is improper to predict the equivalent capacitance at the first resonant frequency, which is the more usual case of interest.
2) The energy conservation method assumes that the voltage distribution between turns is uniform and is shown to be more proper for analytically calculating the parasitic capacitance at the first resonant frequency. However, the voltage potential distribution of winding is shown to be nonuniform at the first resonant frequency according to the LTspice simulations of the equivalent circuit, though by a relatively small amount, which can still introduce some errors in predictions.

The two modeling methods are compared by experiments using three prototypes. The lumped capacitor approach is confirmed to be inappropriate, while the errors of the energy conservation method are found to be tolerable based on both circuit simulations and experiments.

The conclusions are not limited to the applications of inductors, but can be extended to transformers since the physical concepts behind them are the same.

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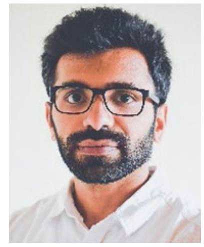

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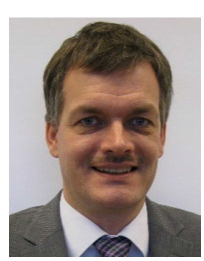

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