

Analysis of Test Methods for Measurement of Leakage and Magnetising Inductances in Integrated Transformers

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Abstract

The attention in integrated transformers has increased recently. The operation of the converters with integrated transformers depends on their components' value significantly. Therefore, a sensitivity analysis is provided to find the most precise measurement method for characterization of integrated transformers, especially when they have different primary and secondary leakage inductances. The theoretical analysis is verified by simulation and experimental results.

Introduction

The pulse-width-modulated converters, such as boost converter, cannot provide high efficiency at high switching frequency due to high switching losses. However, resonant converters can provide high efficiency and power density since they benefit from soft switching capability and magnetic integration [1-6].

The attention in integrated transformers has increased in recent years and they have been developed to be used in many resonant converters for different applications [7-9]. The integrated transformers usually have a high leakage inductance either in the primary or secondary side or in both sides. This leakage inductance may be used as the series inductor of the converters in which there is an inductor in series with the isolated transformer [10, 11]. For example, the schematic of the LLC resonant converter while it has three separate magnetic components, including series (L_S) and parallel (L_P) inductors and transformer, is shown in Fig. 1(a). As shown, the series and parallel inductors of the LLC converter can be integrated into the transformer to reduce the number of passive components. In other words, as presented in Fig. 1(b), the magnetising inductance (L_m) of the transformer can be used as the parallel inductor and the leakage inductance (L_{lk}) of the transformer can be used as the series inductor to enhance the power density and efficiency of the converter [12].

The operation of the resonant converters highly depends on their resonant components. Therefore, the leakage and magnetising inductances of the integrated transformers need to be quantified precisely to guarantee the proper operation of the converter [13-15].

A lot of research has been done on the calculation and measurement of the leakage and magnetising inductances of the transformers in recent years [16, 17]. The standard test approach has been largely used to characterize a transformer. This method uses open-circuit and short-circuit tests and assumes that the leakage inductances of the primary and secondary windings are identical and very small compared to the magnetising inductance [18]. This method may be used for the characterization of the integrated transformers with similar primary and secondary leakage inductances, e.g., shunt-inserted integrated planar transformers. However, in some topologies of the integrated transformers, not only the

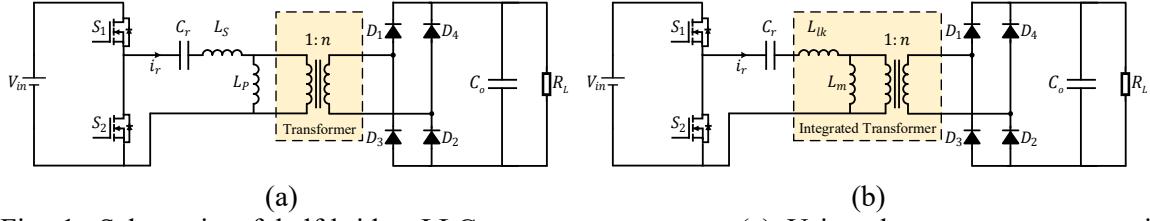


Fig. 1: Schematic of half-bridge LLC resonant converter. (a) Using three separate magnetic components. (b) Using an integrated transformer.

primary and secondary leakage inductances may not be identical but also the leakage inductance has a noticeable value in comparison with the magnetising inductance.

This issue with the standard test method can be addressed by adding a third test. In this approach, named as extended test method, the primary and secondary leakage inductances can be measured separately even when they have high and different values. This method is effective for transformers with low resistance, e.g., low-frequency transformers. However, this approach may not be precise for high-frequency integrated transformers since there is significant resistance in the windings of the transformer [18].

The series-coupling test is introduced to overcome the issue of high resistance of the windings [19]. The inductances measured in the series-coupling tests are the algebraic addition and subtraction of inductances and are independent of the winding resistances and parallel paths, facilitating direct measurement by the LCR meter. However, this approach can be very sensitive to measurement errors.

The attention in integrated transformers increases daily and new topologies of the integrated transformers have been proposed with different primary and secondary leakage inductances for utilization in unidirectional and bidirectional resonant converters. As pointed out earlier too, the inaccurate quantifying of the leakage and magnetising inductances can affect the converter operation, optimization, efficiency, modelling and control system. The methods of transformer characterization were introduced in the 1990s and they have not been proposed for the recently introduced integrated transformers, and investigation of their accuracy for characterization of the new integrated transformers is a gap in the literature. Therefore, in this paper, different methods of transformer characterization are investigated to find the most accurate method for characterization of the integrated transformers.

A set of six common transformer tests are considered for the transformer characterization and a measurement analysis is provided for the different combination of this set when three of the tests is only taken. In addition, the sensitivity of the different combinations to measurement errors is investigated. The most accurate combination is finally proposed, and its accuracy is confirmed by finite element analysis and experimental implementation.

Integrated transformer modelling

Fig. 2(a) shows the modelling of a lossless transformer. As shown, the relationship between the voltages and currents of the transformer may be obtained as (1) [12, 20].

$$\begin{bmatrix} v_P \\ v_S \end{bmatrix} = \begin{bmatrix} L_{PP} & L_{PS} \\ L_{SP} & L_{SS} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_P \\ i_S \end{bmatrix} \quad (1)$$

where \$L_{PP}\$ and \$L_{SS}\$ are primary and secondary self-inductances and \$L_{PS}\$ and \$L_{SP}\$ are mutual inductances and \$i_P\$ and \$i_S\$ are primary and secondary currents, respectively.

In Fig. 2(b), another modelling for a lossless transformer is presented which is based on primary magnetising inductance, \$L_{m_p}\$, primary, \$L_{lk_p}\$, and secondary, \$L_{lk_s}\$, leakage inductances and transformer turns ratio, \$n\$. The relationship between the voltages and currents of this model may be obtained by (2).



Fig. 2: Transformer models. (a) Based on self and mutual inductances. (b) Based on magnetising and leakage inductances.

$$\begin{bmatrix} v_p \\ v_s \end{bmatrix} = \begin{bmatrix} L_{lk_p} + L_{m_p} & \frac{N_S}{N_P} L_{m_p} \\ \frac{N_S}{N_P} L_m & L_{lk_s} + \frac{N_S^2}{N_P^2} L_{m_p} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_p \\ i_s \end{bmatrix} \quad (2)$$

where \$N_P\$ and \$N_S\$ are the primary and secondary turns numbers, respectively and the turns ratio, \$n\$, is equal to \$\frac{N_S}{N_P}\$. The primary magnetising inductance may be obtained by (3).

$$L_{m_p} = \frac{N_p}{N_S} L_{PS} \quad (3)$$

The mutual inductance may be defined by (4).

$$L_{PS} = \frac{N_S}{I_p} \phi_{PS} \quad (4)$$

where \$\phi_{PS}\$ is the mutual flux produced by the magnetic field of the current in the primary winding that links with the secondary winding and \$I_p\$ is the RMS of primary current. From (3) and (4), the primary magnetising inductance may be obtained as (5).

$$L_{m_p} = \frac{N_p}{I_p} \phi_{PS} \quad (5)$$

From (5), the primary magnetising inductance of a transformer can be obtained after the calculation of the mutual flux of its windings. The primary self-inductance can be obtained by (6).

$$L_{PP} = \frac{N_p^2}{\mathcal{R}_{T_p}} \quad (6)$$

where \$\mathcal{R}_{T_p}\$ is the core reluctance (evaluated from the primary side). The primary leakage inductance may be calculated by (7) [12, 20].

$$L_{lk_p} = L_{PP} - L_{m_p} \quad (7)$$

From a similar approach, the secondary leakage inductance can be obtained by (8).

$$L_{lk_s} = L_{SS} - L_{m_s} \quad (8)$$

where \$L_{m_s}\$ is the secondary magnetising inductance and it may be obtained by (9).

$$L_{m_s} = \frac{N_S}{N_P} L_{SP} = \left(\frac{N_S}{N_P}\right)^2 L_{m_p} \quad (9)$$

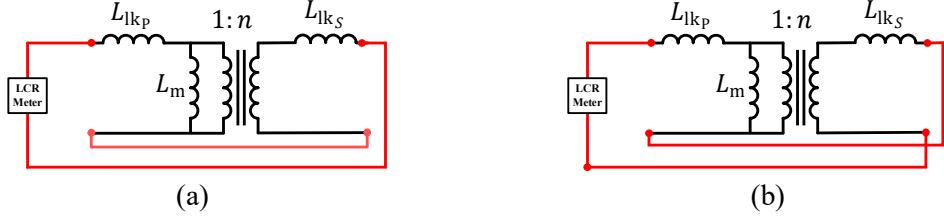


Fig. 3: Transformer test set-up. (a) Differentially-coupling. (b) Cumulative-coupling.

and the secondary self-inductance can be obtained by (10).

$$L_{SS} = \frac{N_S^2}{\mathcal{R}_{T_S}} \quad (10)$$

where \mathcal{R}_{T_S} is the core reluctance (evaluated from the secondary side).

Measurement tests

In general, there are six well-known transformer tests that can be used for the characterization of a transformer. Different transformer characterization approaches usually use either two or three of these tests to characterize a transformer [16-19]. These transformer tests are presented as follows.

Test A: The transformer configuration of this test is presented in Fig. 3(a). As shown, a common current goes through the positive terminal of the primary winding and then into the negative terminal of the secondary winding. According to Fig. 3(a), the differential-coupling inductance, L_D , measured by the LCR meter can be given as (11).

$$L_D = L_{lk_p} + (1 - n)L_{m_p} - n(1 - n)L_{m_p} + L_{lk_s} \quad (11)$$

Test B: The transformer configuration of this test is presented in Fig. 3(b). As shown, a common current goes through the positive terminal of the primary winding and then into again the positive terminal of the secondary winding. According to Fig. 3(b), the cumulative-coupling inductance, L_C , measured by the LCR meter can be given as (12).

$$L_C = L_{lk_p} + (1 + n)L_{m_p} + n(1 + n)L_{m_p} + L_{lk_s} \quad (12)$$

Test C: The third test can be performed by measuring the inductance from the primary side while the secondary side is left open. According to Fig. 2(b), the open-circuit inductance measured from the primary side can be given as (13).

$$L_{P_{SOC}} = L_{PP} = L_{lk_p} + L_{m_p} \quad (13)$$

Test D: The fourth test can be performed by measuring the inductance from the secondary side while the primary side is left open. According to Fig. 2(b), the open-circuit inductance measured from the secondary side can be given as (14).

$$L_{S_{POC}} = L_{SS} = L_{lk_s} + L_{m_s} = L_{lk_s} + n^2 L_{m_p} \quad (14)$$

Test E: The fifth test can be performed by measuring the inductance from the primary side while the secondary side is shorted. According to Fig. 2(b), the short-circuit inductance measured from the primary side can be given as (15).

$$L_{P_{SSC}} = L_{lk_p} + \frac{L_{m_p} L_{lk_s}}{n^2 L_{m_p} + L_{lk_s}} \quad (15)$$

Table I: Different combinations for transformer characterization

| Combination | Equations | Combination | Equations |
|-------------|------------------|-------------|------------------|
| ABC | (11), (12), (13) | BCD | (12), (13), (14) |
| ABD | (11), (12), (14) | BCE | (12), (13), (15) |
| ABE | (11), (12), (15) | BCF | (12), (13), (16) |
| ABF | (11), (12), (16) | BDE | (12), (14), (15) |
| ACD | (11), (13), (14) | BDF | (12), (14), (16) |
| ACE | (11), (13), (15) | BEF | (12), (15), (16) |
| ACF | (11), (13), (16) | CDE | (13), (14), (15) |
| ADE | (11), (14), (15) | CDF | (13), (14), (16) |
| ADF | (11), (14), (16) | CEF | (13), (15), (16) |
| AEF | (11), (15), (16) | DEF | (14), (15), (16) |

Test F: The sixth test can be performed by measuring the inductance from the secondary side while the primary side is shorted. According to Fig. 2(b), the short-circuit inductance measured from the secondary side can be given as (16).

$$L_{S_{PSC}} = L_{lk_S} + \frac{n^2 L_{m_P} L_{lk_P}}{L_{m_P} + L_{lk_P}} \quad (16)$$

Transformer characterization methods

The standard open- and short-circuit (SOS) approach (test C and test E) can be used to find leakage and magnetising inductance of a transformer. In this approach, it is assumed that the primary and secondary leakage inductances are identical and winding resistance is negligible. Therefore, this approach cannot be accurate when the primary and secondary leakage inductances are different and there is high winding resistance.

The limitation of SOS can be addressed by having a third test. This approach, which is named as extended open- and short-circuit (EOS) method, uses tests C, D and E to characterize a transformer. Even though the primary and secondary leakage inductances can be different in this approach, a large winding resistance relative to magnetising inductance can distort the measurement.

The series-coupling (SC) approach uses tests A, B and C to characterize a transformer. Since the inductances measured in the series-coupling tests are the algebraic addition and subtraction of inductances and are independent of winding resistances and parallel paths, this approach can be used for transformers with high winding resistance. However, this approach is very sensitive to measurement errors.

Amongst various transformer characterization methods, the SOS, EOS and SC approaches are very popular. These approaches have been developed to be used mainly for conventional transformers. Therefore, their performance for the characterization of integrated transformers needs to be investigated.

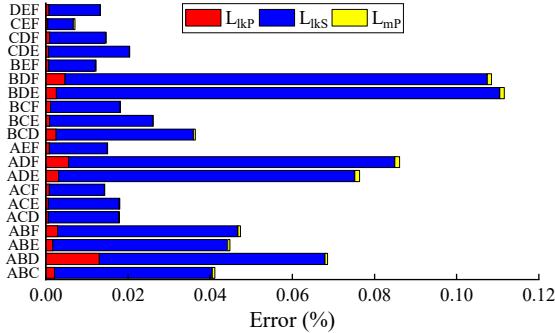


Fig. 4: The average of errors of the calculated inductances.

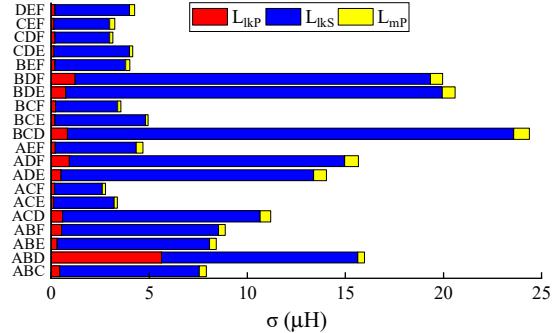


Fig. 5: The standard deviation of the calculated inductances.

The SOS test is not a good candidate for the characterization of the integrated transformers since the integrated transformers usually have different primary and secondary leakage inductances.

There are six tests and the number of combinations of them when a sample size of three is chosen is twenty and EOS and SC approaches are only two of these different combinations. The other eighteen combinations can also characterize a transformer. Hence, the other eighteen approaches need to be also investigated to find the best combination for the characterization of an integrated transformer.

Investigation of transformer characterization methods

As mentioned earlier, there are six common tests for a transformer and the number of combinations of them when a sample size of three is chosen is twenty. In this section, all twenty combinations are investigated and the best combination and the best way to characterize an integrated transformer is presented.

The different combination of six tests with a sample size of three is presented in Table I. Each combination is named according to the tests that are used in it. For example, the combination ABC uses tests A, B and C. The combination ABC is the same as the SC approach and the combination CDE is the same as the EOS approach. Therefore, the six transformer tests, presented earlier, can provide other eighteen combinations that can be used to characterize a transformer.

An air-gap is added to the integrated transformers to store more energy in their magnetising inductance and integrated transformers are developed to have high primary or/and secondary leakage inductances. An important application of the integrated transformers is in resonant converters. The operation of the resonant converters is very sensitive to their resonant components and inaccurate characterization of their transformer can affect the converter operation, optimization, efficiency, modelling and control system. Therefore, it is very important to characterize an integrated transformer precisely.

The measurement errors in the transformer tests are inevitable and these errors lead to the inaccurate characterization of a transformer. Therefore, in the first step of the investigation of the different combinations, the sensitivity of each combination to the measurement errors is investigated.

The sensitivity analysis has been done in MATLAB for a transformer with characteristics presented in Table II. In the first step, the ideal measurement for each test is calculated by substituting the values presented in Table II in (11)-(16). In the second step, 10000 random errors are applied to each measurement test by using “randn function” in MATLAB while the maximum error is 0.2%. Finally, the primary and secondary leakage inductances and magnetising inductance are calculated for each combination while there are 10000 random errors in each measurement.

The average of the calculated inductances with applying the 10000 random errors to the measurements is calculated for each combination and is presented in Fig. 4. The difference between the average of

Table II: Transformer characteristics

| Magnetising inductance (L_{mp}) | Primary leakage inductance (L_{lk_p}) | Secondary leakage inductance (L_{lk_s}) | Turns ratio (1: n) |
|-------------------------------------|---|---|-----------------------|
| 300 μ H | 120 μ H | 110 μ H | 1 : 5 |

Table III: The maximum error of the calculated inductances for each combination

| Combination | ABC | ABD | ABE | ABF | ACD | ACE | ACF | ADE | ADF | AEF | |
|-------------|------------|-------|--------------|-------------|------|------|-------------|-------------|-------------|-------------|------|
| Error (%) | L_{mp} | 0.386 | 0.386 | 0.38 | 0.38 | 0.61 | <u>0.17</u> | <u>0.18</u> | 0.69 | 0.74 | 0.34 |
| | L_{lk_p} | 1.518 | 19.24 | 1.00 | 1.75 | 1.80 | <u>0.39</u> | <u>0.54</u> | 1.65 | 3.02 | 0.72 |
| | L_{lk_s} | 25.15 | 38.19 | 27.3 | 28.1 | 34.0 | <u>11.2</u> | <u>9.04</u> | 45.4 | 49.5 | 15.6 |
| Combination | BCD | BCE | BCF | BDE | BDF | BEF | CDE | CDF | CEF | DEF | |
| Error (%) | L_{mp} | 0.787 | <u>0.169</u> | <u>0.18</u> | 0.68 | 0.64 | 0.23 | <u>0.18</u> | <u>0.17</u> | 0.28 | 0.26 |
| | L_{lk_p} | 2.631 | 0.580 | 0.71 | 2.37 | 3.89 | 0.65 | <u>0.48</u> | 0.61 | <u>0.54</u> | 0.68 |
| | L_{lk_s} | 77.59 | 16.88 | 11.7 | 67.6 | 63.9 | 13.7 | 13.4 | <u>9.78</u> | <u>10.6</u> | 14.4 |

errors of different combinations is negligible and there is no advantage for any combination when the average of errors is considered.

The maximum error of the calculated inductances for each combination after applying the 10000 random errors to the measurements is presented in Table III, low errors are written in green and the lowest error for each inductance is underlined. As shown, the combination BCE has the lowest sensitivity to the measurement errors for magnetising inductance measurement and the combinations ACE, ACF, BCF, CDE and CDF have also lower sensitivity compared to others. The combination ACE has the lowest sensitivity to the measurement errors for the primary leakage inductance measurement and the combinations ACF, CDE and CEF have also lower sensitivity compared to others. The combination ACF has the lowest sensitivity to measurement errors for secondary leakage inductance measurement and the combinations ACE and CDF have also lower sensitivity compared to others. Therefore, from Table III, it can be concluded that the combination ACF may be the best combination in terms of sensitivity to the measurement errors. In addition, to obtain the most accurate answer, the magnetising inductance and primary and secondary leakage inductance can be obtained from the combinations BCE, ACE and ACF, respectively.

The standard deviation of the calculated inductances for each combination after applying the 10000 random errors to the measurements is presented in Fig. 5. As shown, the combination ACF has the lowest standard deviation and therefore has the lowest sensitivity in general. The combination CDF is the second rank, but it has higher sensitivity for every inductance compared to the combination ACF.

The histogram of the calculated inductances after applying the 10000 random errors to the measurements and after dividing by their precise value (presented in Table II) is shown for the combinations ABC (conventional SC), CDE (conventional EOS), and ACF in Fig. 6. As shown, in general, the calculated inductances from the combination ACF are closer to the right values and are less sensitive to measurement errors.

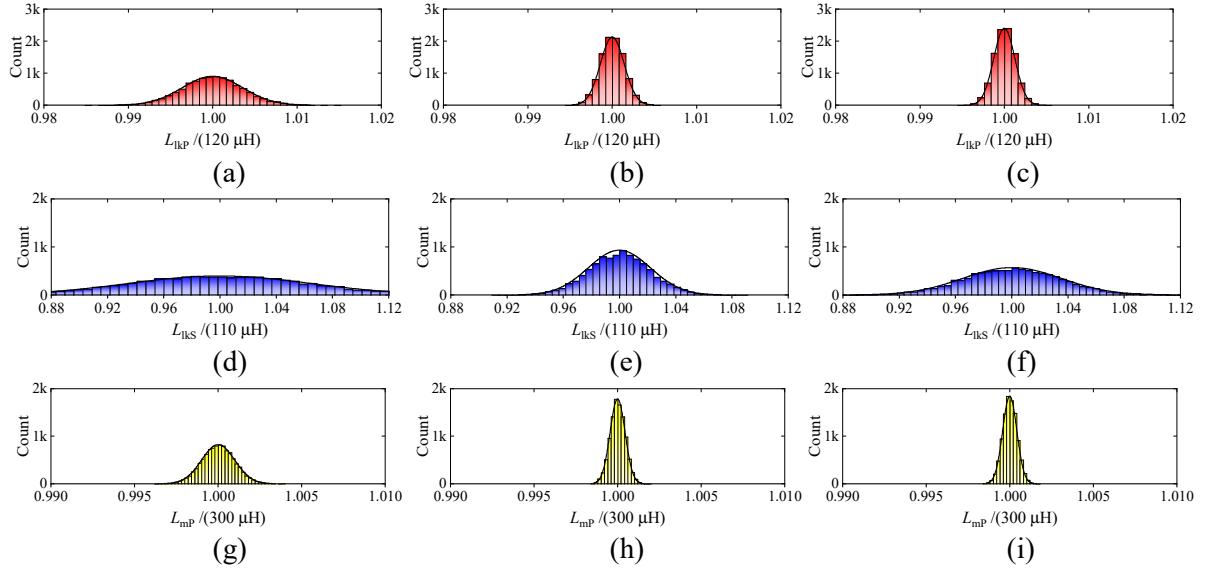


Fig. 6: The histogram of the calculated inductances. (a) L_{lk_p} from ABC. (b) L_{lk_p} from ACF. (c) L_{lk_p} from CDE. (d) L_{lk_s} from ABC. (e) L_{lk_s} from ACF. (f) L_{lk_s} from CDE. (g) L_{mp} from ABC. (h) L_{mp} from ACF. (i) L_{mp} from CDE.

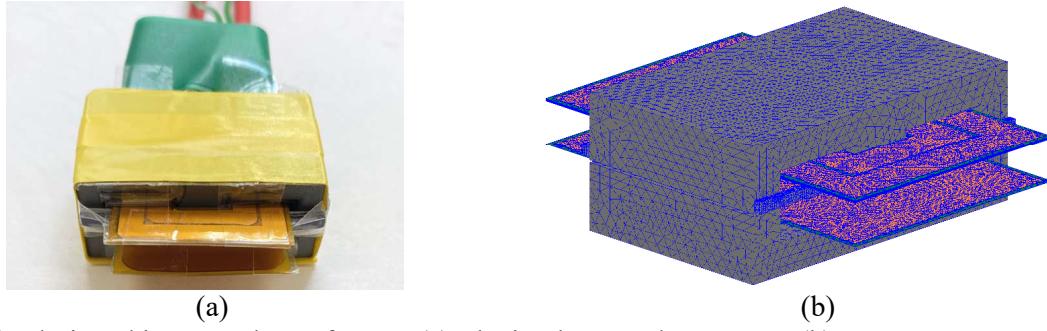


Fig. 7: The designed integrated transformer. (a) The implemented prototype. (b) FEA.

In summary, the combination ACF is less sensitive to measurement errors and can be used when primary and secondary leakage inductance are different. In addition, the combination ACF benefits from one of the series-coupling tests (measurement is independent of winding resistances). Therefore, the combination ACF is a suitable method to characterize the integrated transformers.

Experimental verification

To verify the theoretical analysis, an integrated transformer is implemented in the laboratory and simulated in Ansys Maxwell as presented in Figs. 7(a) and (b), respectively. The characteristic of the implemented integrated transformer is presented in Table IV. The topology of the chosen integrated transformer is similar to the topology presented in [10, 15]. This integrated transformer is based on a planar transformer in which a magnetic shunt is inserted between two E-cores. This integrated transformer is designed to be used in the LLC resonant converters and therefore it can provide high leakage inductance and can be designed for most of the required leakage inductance values.

The designed integrated transformer is characterized by finite-element analysis (FEA) and its primary and secondary leakage inductances and magnetising inductance are presented in Table IV. In addition, the implemented transformer is characterized by the combination ACF which is also presented in Table IV. As shown, the primary and secondary leakage inductances and magnetising inductance can be measured precisely by using the combination ACF.

Table IV: Transformer characteristics verification

| | Primary leakage inductance (L_{lk_p}) | Secondary leakage inductance (L_{lk_s}) | Magnetising inductance (L_{m_p}) |
|-------------|---|---|--------------------------------------|
| Designed | 8 μ H | 0.03 μ H | 28.5 μ H |
| FEA | 8.2 μ H | 0.04 μ H | 28.85 μ H |
| Measurement | 8.3 μ H | 0.05 μ H | 29.5 μ H |

Conclusion

The attention in integrated transformers has increased recently. The operation of the converters with integrated transformers depends on their components' value. However, the transformer characterization methods are introduced for the conventional transformers and may not be accurate if they apply to integrated transformers. In this paper, different transformer characterization methods are investigated. The advantages and disadvantages of different characterization approaches for the integrated transformer characterization are presented. The six well-known transformer tests that can be used to characterize a transformer are also presented. It is shown that the popular characterization methods such as EOS and SC use three of these tests. However, there are other eighteen combinations for these tests with a sample size of three. Therefore, to find the best combination to characterize an integrated transformer, all twenty combinations are investigated. It is shown that the best combination uses an open-circuit test, a short-circuit test and a series-coupling test and it is compared with the conventional EOS and SC approaches. In addition, the accuracy of the best combination is verified by finite-element analysis and experimental implementation.

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