Modelling of High Frequency Converter Transformer with Floating Active Inductor

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***Abstract*—As number of digital electronics and power electronics based devices has risen recently, the fields of application for high frequency transformers have been increased. Aircraft industry, solar converters, electric drives, medical imaging systems and similar applications contain high frequency transformer operations. To express proper operation of transformers, equivalent circuit based analysis is conducted for typical transformers in which circuit parameters obtained. Rather than a conventional equivalent circuit analysis, a delicate analysis based on novel floating active inductor employed equivalent circuit is proposed for modelling of high frequency transformer characteristics. In this study, high frequency operated 2500 W 311 V/200 V transformer is investigated for frequency spectrum between 20 kHz and 200 kHz. Measured characteristics of investigated transformer are compared with the characteristics of proposed equivalent circuit. Proposed floating active inductor is designed with MOSFETs and can be tuned for wide frequency spectrum adaptively. In addition, proposed equivalent circuit is capable of modelling various high frequency transformers for different frequency values.**

***Index Terms*—High-frequency transformers; Active inductors; Transconductance; Equivalent circuits.**

I. INTRODUCTION

It is very common way to model transformers with their equivalent circuits based on their losses. Iron losses and copper losses are the key signatures for determining shunt admittances and the series impedances related with core and windings [1], [2]. For higher frequencies flux penetration into the core of the transformer is limited [3]. Besides varying frequency values of the input source, end up with different inductance values in the equivalent circuit in which modification of the equivalent circuit is mandatory. Another shortcoming is the single equivalent circuit representation for specific condition where rated values of the transformer are chosen as the inputs for the short circuit and open circuit tests. To overcome these bottlenecks an adaptive equivalent circuit for high frequency transformers or high frequency operated conventional transformers is proposed.

High frequency transformers are frequently employed in solar converters, electric drives, medical imaging systems, the aircraft industry, power conversion applications [4]–[8] etc. Although there are several applications for modelling high frequency transformer [9], [10], there is not any such similar study, which enables VDTA, based active inductor on high frequency transformer modelling.

In this study, 311 V/200 V 2500 W 100 kHz high frequency full bridge converter transformer is investigated for real case scenario. The tests are conducted for frequencies between 20 kHz and 200 kHz where overloading in terms of excessed frequency is additionally analysed. At the higher frequencies, iron losses on the core are accelerated due to increased variations of magnetic fluxes where shunt inductances are dominant in the equivalent circuit. For this purpose, simplified equivalent circuit is derived by open circuit tests for different frequency values [1]. In addition, stray capacitances for high frequency transformer are introduced in various studies however; their effects are displayed under resonance conditions [11]. According to the tests for different frequency values, different inductances are necessity in terms of equivalent circuit. As a novel approach, proposed active inductor is employed for simulating core inductances in the equivalent circuit.

Several floating active inductor circuits employing different active elements such as electronically controllable current conveyor (ECCC) [12], current differencing transconductance amplifier (CDTA) [13], dual-output differential difference current conveyor (DO-DDCC) [14], voltage differencing transconductance amplifiers (VDTA) [15], Z-copy current follower transconductance amplifier (ZC-CFTA) [16], Z-copy voltage differencing transconductance amplifier (ZC-VDTA) [17], operational transconductance amplifier (OTA) [18] have been investigated in the literature. In this study, VDTA based floating active inductor circuit is employed for modelling of high frequency converter transformer, which is proposed by Yesil [19]. The key characteristics of the floating active inductor circuit has been verified by using SPICE simulation with TSMC CMOS 0.18 μm process parameters. Based on high frequency characteristics of proposed active inductor, it

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is employed to model investigated transformer since operation bandwidth of the inductor is quite satisfying.

This paper can be summarized as follows. In Section II, the test setup for high frequency transformer and equivalent circuit are explained. In Section III the floating active inductor is introduced. In Section IV, the test results and spice simulation results are provided for comparison purposes. Finally, in Section V, the conclusion is given.

II. Test Setup

The test setup contains high frequency 311 V/200 V 2500 W 100 kHz full bridge converter transformer, a signal generator and a high speed oscilloscope. In order to obtain high frequency sinusoidal, a signal generator with 20 V_{pp} amplitude output is applied from the HV side (311 V) of the transformer where LV side is open circuited. In order to investigate transformer characteristics while excessive frequency sinusoidal signals are applied transformer is operated lower voltages than the ratings. The test setup is given in Fig. 1.

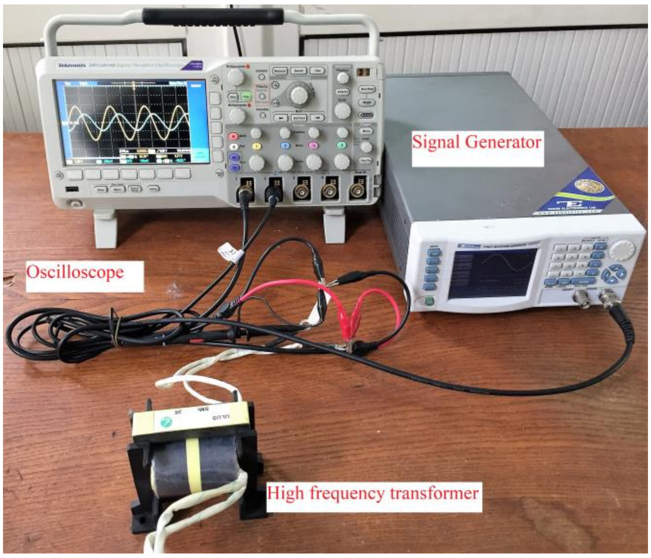

Fig. 1. Test setup.

The equivalent circuit is based on core admittances (especially inductor) where flux penetrations are bounded under high frequency conditions [1]. During the tests magnetizing inductances, phase angles and input currents are obtained for different frequency values. The simplified equivalent circuit for proposed setup under high frequency conditions is given in Fig. 2 [1].

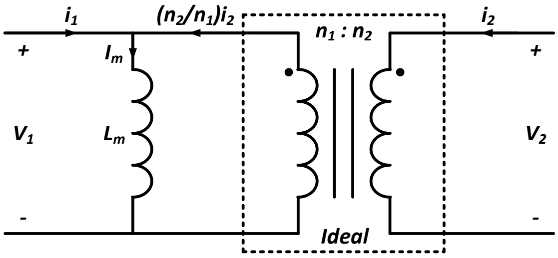

Fig. 2. High frequency transformer simplified model.

In the equivalent circuit L_M is the magnetizing inductance based on transformer's core characteristics where the ideal transformer is employed for electrical isolation purposes. In the test procedure primary voltage (v_1) and current (i_1) is recorded via oscilloscope while the secondary is open circuited.

III. Floating Active Inductor

The floating active inductor circuit for modelling high frequency transformer is realized with VDTA. The terminal relationships of an ideal VDTA can be characterized by

$$\begin{bmatrix} I_Z \\ I_{X+} \\ I_{X-} \end{bmatrix} = \begin{bmatrix} g_{m1} & -g_{m1} & 0 \\ 0 & 0 & g_{m2} \\ 0 & 0 & -g_{m2} \end{bmatrix} \begin{bmatrix} V_{VP} \\ V_{VN} \\ V_Z \end{bmatrix}. \tag{1}$$

The g_ms are transconductance values of the VDTA model. The circuit symbol and the CMOS realization of the VDTA are shown in Fig. 3. The VDTA circuit is implemented with improved floating current sources as shown in Fig. 3(b) [19].

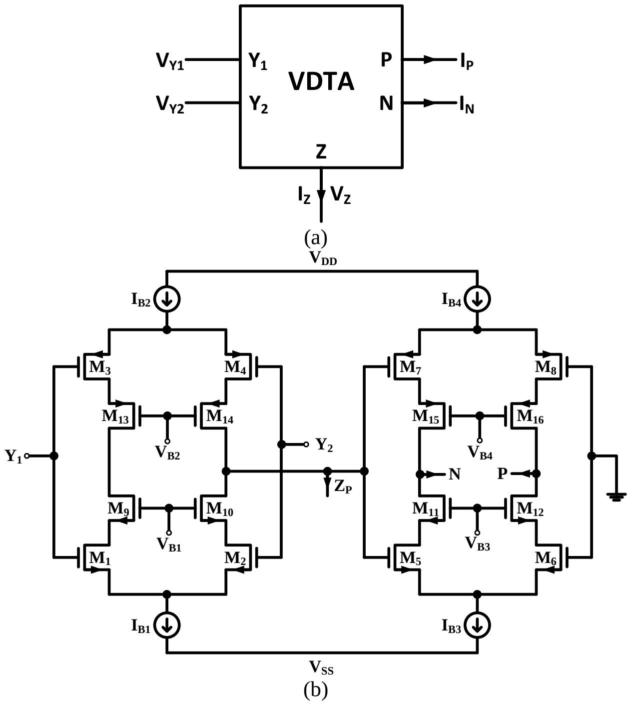

Fig. 3. Circuit symbol (a); CMOS realization of the VDTA (b).

The VDTA based floating active inductor configuration is given in Fig. 4. The simulations are performed with LTSPICE program using TSMC CMOS 0.18 μm process parameters. The aspect ratios of the transistors are given in Table I. Supply voltages are taken as $V_{DD} = -V_{SS} = 0.9$ V where $I_{B1} = I_{B2} = I_{B3} = I_{B4} = 10$ μA biasing currents and $V_{b1} = V_{b3} = -V_{b2} = -V_{b4} = 0.2$ V voltages for bias are used.

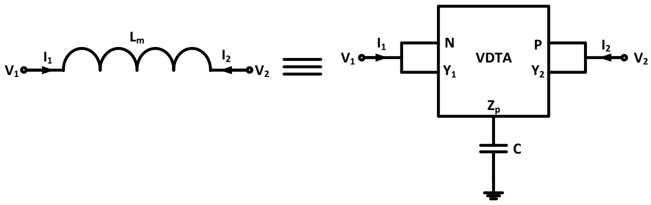

Fig. 4. VDTA based floating active inductor.

The proposed floating active inductor circuit is electronically tunable. Thus, different impedance values are obtained adaptively for modelling high frequency transformer characteristics by changing value of the capacitor C. The ideal and simulated magnitude response of the floating active inductor is shown in Fig. 5 for the inductance value of 0.82 mH which is empirically measured for proposed high frequency full bridge converter transformer.

TABLE I. ASPECT RATIOS OF THE TRANSISTORS.

Transistors	W (µm)	L (µm)
M_1, M_2, M_5, M_6	18	0.54
M_3, M_4, M_7, M_8	72	0.54
M_9, M_{10}, M_{11}, M_{12}	108	0.54
M_{13}, M_{14}, M_{15}, M_{16}	180	0.54

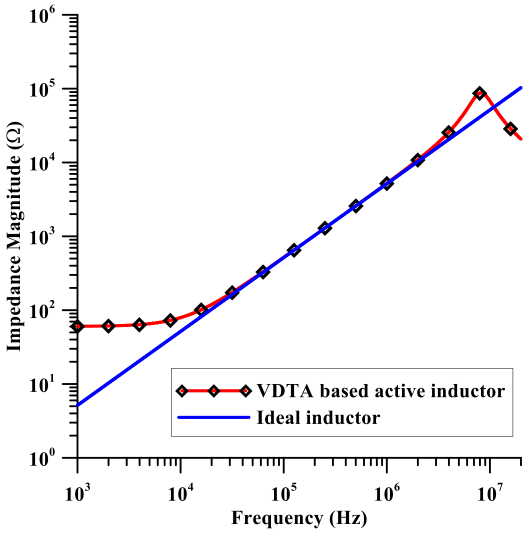

Fig. 5. Impedance variation of proposed VDTA based floating active inductor and ideal inductor for different frequencies.

It is obvious that the floating active inductor can be operated between 20 kHz and 2 GHz frequency range effectively. This region is not fixed region for the model; on the contrary, this region can be shifted to desired region by tuning VDTA for required frequencies.

IV. Results and Discussion

During the tests full bridge converter transformer is employed for different frequency values. Supply voltages (root mean square-RMS), phase differences, magnetizing currents and magnetizing inductances are measured and given in Table II.

Although test transformer is rated 100 kHz, tests are conducted up to 200 kHz for overload conditions. In order to verify reliability of the proposed model with floating active inductor, the SPICE model is investigated and related characteristics are observed under same conditions with transformer tests. SPICE model characteristics are given in Table III.

Magnetizing currents and phase angles are analysed for equivalent model capabilities under different frequencies. Both model and test transformer characteristics exhibit similar results except for 20 kHz frequency at which VDTA based active inductor displays slight difference with ideal inductor. The proposed model can be tuned for desired frequency values however; in this study, the initial value is chosen as 20 kHz to underline tuning characteristics of proposed SPICE model with VDTA based active inductor.

TABLE II. HIGH FREQUENCY TRANSFORMER CHARACTERISTICS.

Frequency (kHz)	Primary Voltage (V)	Phase Angle (Degree)	Magnetizing Current (mA)	Magnetizing Inductance (mH)
20,00	5,54	82,27	55,00	0,80
30,00	6,10	84,95	40,54	0,80
40,00	6,37	84,93	31,68	0,80
50,00	6,51	86,40	26,15	0,79
60,00	6,59	85,34	22,03	0,79
70,00	6,64	85,87	19,15	0,79
80,00	6,84	86,26	16,37	0,83
90,00	6,58	85,79	15,06	0,77
100,00	6,48	85,47	13,06	0,79
110,00	6,55	84,38	11,64	0,81
120,00	6,40	85,30	11,06	0,77
130,00	6,61	86,45	9,91	0,82
140,00	6,46	85,96	9,48	0,78
150,00	6,54	87,07	8,78	0,79
160,00	6,62	86,44	8,13	0,81
170,00	6,50	84,99	7,81	0,78
180,00	6,50	84,08	7,38	0,78
190,00	6,45	84,11	7,05	0,77
200,00	6,59	84,82	6,55	0,80

TABLE III. SPICE MODEL CHARACTERISTICS.

Frequency (kHz)	Primary Voltage (V)	Phase Angle (Degree)	Magnetizing Current (mA)	Magnetizing Inductance (mH)
20,00	5,54	68,00	51,10	0,80
30,00	6,10	74,90	39,00	0,80
40,00	6,37	78,52	30,96	0,80
50,00	6,51	80,66	25,33	0,79
60,00	6,59	82,24	21,44	0,79
70,00	6,64	80,16	18,40	0,79
80,00	6,84	81,38	16,64	0,83
90,00	6,58	82,28	14,20	0,77
100,00	6,48	83,00	12,50	0,79
110,00	6,55	83,58	11,42	0,81
120,00	6,40	84,00	10,29	0,77
130,00	6,61	84,46	9,77	0,82
140,00	6,46	84,80	8,83	0,78
150,00	6,54	85,08	8,30	0,79
160,00	6,62	85,33	7,86	0,81
170,00	6,50	85,54	7,21	0,78
180,00	6,50	85,71	6,80	0,78
190,00	6,45	85,87	6,37	0,77
200,00	6,59	86,00	6,16	0,80

In the model magnetizing current defines shunt magnetizing reactance and hence inductance of the core. The experimental and SPICE model magnetizing currents are given in Fig. 6. The phase difference of an operating transformer is distinctive characteristic where angle lags are observed. Inductive impedances in the equivalent model satisfies that the voltage leads current. Phase differences of supply voltage and measures input current for different frequencies are shown in Fig. 7.Except for intentionally chosen 20 kHz, the phase differences are quite similar (approximately 80 degrees–85 degrees) between voltage and current. Especially for rated frequency values (approximately 100 kHz), the phase differences are too close to compare.

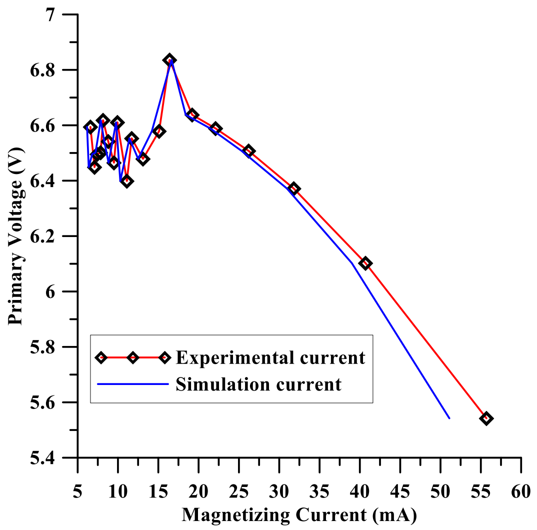

Fig. 6. Measured currents of proposed model and test transformer.

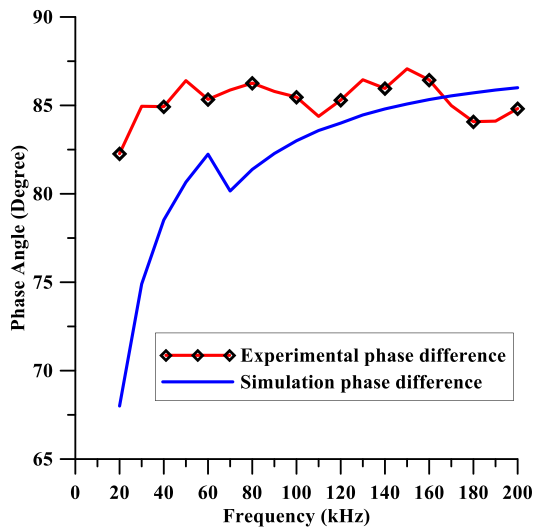

Fig. 7. Phase differences for different frequencies.

V. CONCLUSIONS

Increased frequencies in transformer applications accelerate frequency related core losses and hence magnetizing currents. It is challenging task to propose single equivalent model for high frequency transformers since varying system characteristics leads to different models for different inputs. For this purpose, an adaptive equivalent model for high frequency transformer applications in which magnetizing inductor is simulated with floating active inductor is proposed. VDTA based floating active inductor have satisfying characteristics such as increased bandwidth, electronically tunability and active element employed. As an active element based structure, VDTA promises semiconductor based electronic integration for modelling in high frequency applications especially for high frequency transformer. Besides, due to the tuning characteristics of proposed model it is plausible to simulate various inductor applications for higher frequencies. The proposed model is capable of simulating high frequency transformers where magnetizing inductance impedances (from 100 Ω to 100 kΩ based on frequency) and related losses are quite significant. Proposed model is capable of simulating high frequency transformer in terms of magnetizing inductances for wide frequency range from 20 kHz to 200 kHZ (which is adjustable). Various applications such as solar converters, electric drives, medical imaging systems, the aircraft industry, power applications require flexible transformer modelling where proposed model is quite effective.

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