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Design and Simulation of a Fractal Micro-Transformer

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ABSTRACT
Due to advancement in smart technologies, the issues like renewable energy integrations into the existing power systems, reduced weight and size of power equipments is required**.** In this regard, this work is focused on the study and design of fractal type micro-transformer for day-to-day applications. An air core transformer is designed using finite element modeling. The obtained results showed far better implementation parameters in comparison to the macro transformers.
Keywords - Finite element modeling, micro-transformer, 2D simulation, energy conversion, magnetic field.

I. INTRODUCTION

Coils and transformers are basic components in electronic devices. Integrating transformers in electronic ICs is usually done with planar structures but the resulting efficiency is low. A lot of work has been done recently in order to overcome this drawback. Some processes have been studied both by realizing a thick integrated magnetic circuit and by realizing high thickness coils by copper electro-deposition [1–3]. Both techniques have shown good results.

In coming decades, new generations of electronic products such as mobile phones, notebooks, and e-paper will be developed with the primary goals of mobilization and miniaturization. New CMOS fabrication technology will be applied to fabricate the miniaturized IC of electronic products on silicon substrates, including on-chip micro-transformers. Several issues of on-chip micro-transformers have been investigated for many years [4]. Some researches focused on the material of the magnetic core and the geometry of the transformer [5]. Some papers discussed the parasitic effect of the conductive substrates. Transformer losses become dramatic at high frequencies and limit the performance of the transformers. Previous studies have discussed in detail the causes of transformer losses such as parasitic capacitance, ohmic loss, and substrate loss [6] [7]. Core loss from the solid magnetic core significantly affected the performance of the transformers. Transformers with magnetic core exhibit relatively high loss and compromised isolation at high frequencies due to degradation in magnetic core performances with the increase of frequency. Several ferrite core magnetic transformers have been reported by researchers. But it was estimated that the efficiency, operating frequency, and current limitation are the main challenges because of the magnetic saturation and eddy current losses in the ferrite magnetic core material at high frequencies. However, it is observed that the performance of the air core transformer is better than the magnetic core counterpart at high frequencies due to no lossy core material involved in air core transformers. The solutions for the solid magnetic core loss were proposed.

II. MATHEMATICAL ANALYSIS

The device presented in this paper is a two-winding transformer, with bonding wires as coils completed on the metallization layer, and a toroidal ferrite as a magnetic core. The low-frequency self-inductance of each winding *L* is estimated by the reluctance formula as [8].

$$L = \frac{\mu_0 \mu_1 n^2 A_c}{l_c}$$

where $\mu_0 = 4\pi \times 10^{-7}$ H/m is the free-space permeability, μ_1 is the core relative permeability, A_c is the cross-sectional area of the core, l_c is the mean magnetic path length, and n is the number of turns of the coil considered. The low frequency series resistance of the winding R can be expressed as $R = n(R_b + R_m)$, where R_b is the bonding wire resistance, and R_m is the printed circuit board (PCB) metal conductor resistance [9] [10]. Since in a real transformer not all flux produced by the primary winding is coupled to the secondary one, the mutual inductance L_{12} is defined by:

$$n_{12} = \frac{n_2}{n_1} = \left(\frac{L_{22}}{L_{11}}\right)^{\frac{1}{2}} \quad L_{12} = k\sqrt{L_{11}.L_{22}}$$

where k is the coupling coefficient which measures the magnetic coupling between the coils, and L_{11} and L_{22} are the self-inductances evaluated by (1) of primary and secondary windings, respectively. For the transformer we can define the turns ratio

$$n_{12} = \frac{n_2}{n_1} = \left(\frac{L_{22}}{L_{11}}\right)^{\frac{1}{2}}$$

where n_1 and n_2 are the number of turns of each side. The coupling coefficient k has to be taken into account in n_{12}, thus getting the effective turns ratio $n_e = k.n_{12}$. The minimum frequency f_{min} (Hz) at which the primary winding can operate without saturating the core, is estimated by applying a sinusoidal waveform voltage as follows

$$P_c = k_c f_{op}^a \left(10^4 B_m\right)^b V_c \quad f_{min} = \frac{V_{max}}{2\pi n_1 A_c B_s}$$

where V_{max} is the peak amplitude of the sinusoidal voltage, and B_s is the saturation magnetic flux density. At high frequencies the current density becomes non uniform due to eddy currents which cause skin effect. Hence, the transformer behavior can be considered in the low-frequency region only if the core skin depth is much greater than the core thickness.

The power loss of the device P_C is calculated by evaluating the power dissipation in the core due to eddy currents and hysteresis losses [5] [6], and is expressed as:

$$P_c = k_c f_{op}^a \left(10^4 B_m\right)^b V_c$$

where f_{op} is the operating frequency, B_m is the amplitude of the AC component of the magnetic flux density, $V_c = A_c \cdot l_c$ is the core volume, and k_c, a, and are constants for the core material.

III. METHODOLOGY

The proposed micro-transformer has been designed in a FEM based Comsol Multiphysics software. A 2D designed has been modeled and simulated and is shown in Fig. 1. The design is on the basis of fractal transformer as the primary coil design is repeating itself periodically. The advantage of this kind of design is that, this will induce stray fields thereby reducing coupling between the primary and secondary windings of the transformer. Also, there is a a very small gap between the two coils. Air core has been selected for this work. Since the dimensions of the gaps are much smaller than those of the frame, many mesh elements will be required for an accurate model. The designed configuration is almost symmetric. The input applied voltage selected for simulation is 230 V, 50 Hz.

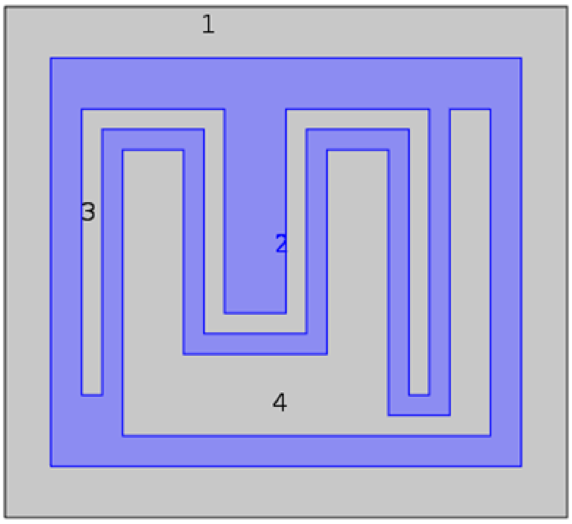

Fig 1: 2D schematic layout of the micro-transformer.

The parasitic capacitance exists due to transformer's lateral and vertical dimensions. The self inductance of the primary and secondary coils of the transformer depends upon the lateral dimensions. The trench under the coils gradually decreases the parasitic capacitance between the coils and the substrate. Also, this trench helps in diminishing the eddy current losses in the substrate that further helps in improving the quality factor. To avoid high resistance in the transformer it is necessary to increase the thickness of the coil. Therefore, highly conductive material has been selected as coil.

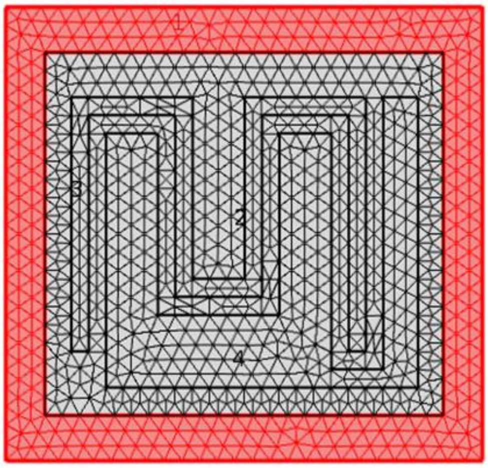

Fig 2: Schematic layout of the meshed device.

Fine meshing is applied to compensate the computational load and is shown in Fig. 2. The inner side of the core frame is manually restricted to a finer element size in order to avoid inverted elements. For rest of the geometry, low resolution is selected for a fast and stable convergence of the solution without the need of a tedious model optimization process.

IV. RESULTS AND DISCUSSIONS

Transient simulations of 2D with electrical analysis is selected and studied under stationary frequency domain. The simulation of the proposed model is performed on a high end computational machine with 2.8 GHz processing speed and 4 GB RAM. The electric displacement on the surface is shown in Fig. 3 while the average magnetic energy density is shown in Fig. 4. The maximum electric displacement obtained while simulating the micro-transformer as 2 x 10^{-11} C/m^2 and the maximum magnetic energy density obtained is 100 J/m^3.

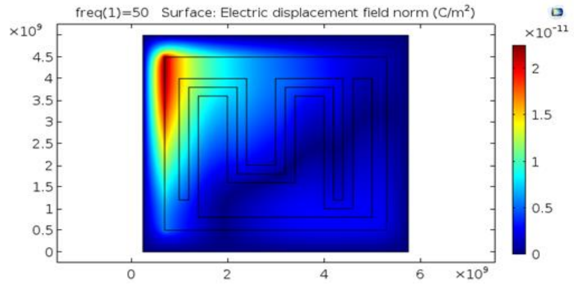

Fig 3: Electrical displacement obtained after simulating the micro-transformer.

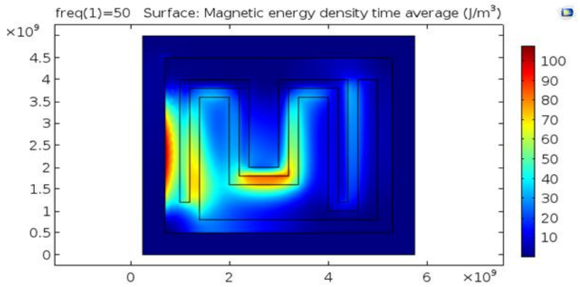

Fig 4: Magnetic energy density obtained after simulating the micro-transformer.

The results showed the proposed micro transformer acts as step transformer as the input voltage applied was 230 V ac but the voltage obtained at the secondary is 325 V. The graph obtained between the output voltage and the arc length is shown in Fig. 5. This may be due to larger surface area of the secondary coil in comparison to the primary coil.

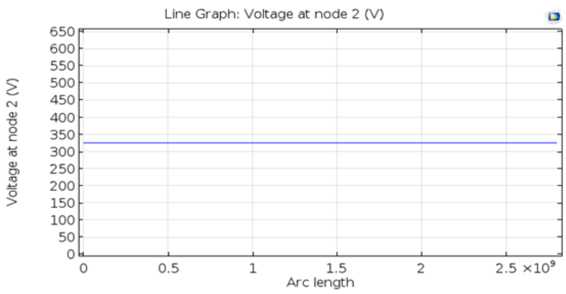

Fig 5: Output voltage obtained after simulating the micro-transformer.

Since the magnetic field exists within the transformer and hence causes losses also. However, the amount of losses in the proposed transformer is very small due to air core used.

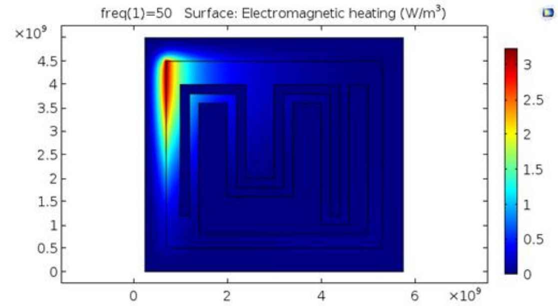

Fig 6: Electromagnetic heating inside micro-transformer due to electric and magnetic field.

Fig. 6 shows the losses obtained due to electromagnetic heating inside the micro-transformer and the maximum value comes out to be 3 W/m^3. Also, a high value of skin depth is always advantageous for a transformer and the value obtained during this simulation is 7 x 10^{11} Å and is shown in Fig 7.

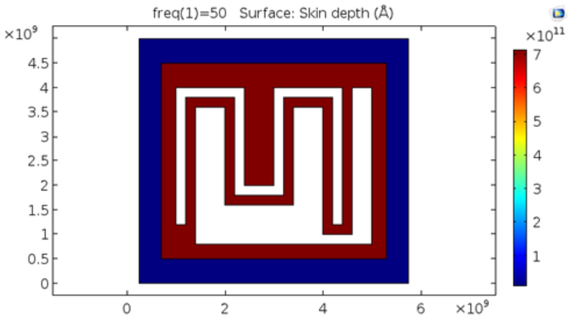

Fig 7: Skin depth inside micro-transformer due to electric and magnetic field.

V. CONCLUSION

In this paper, we have designed and analyzed a micro transformer for MEMS and VLSI technology. The proposed model is designed on a conducing substrate with air core. A very input and high impedance value exists within the design. It can be easily integrated with signal and power isolation capability thus reducing component count and improves system reliability and lifetime. The results showed a successful design implementation of a step-up micro transformer with precise but very small magnetic losses.

Focus of future work will be on improvement of the numerical stability of the models in order to extend their stable current amplitude and frequency ranges.

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