Design of Liquid Core Transformer for Hybrid Electric Vehicles

Vilas V. Sarwadnya [1], Mrs. Rajashree V. Sarwadnya [2], Shambhunath G. Kahalekar[3]
[1,2,3]SGGSIET, Nanded Maharahtra
(E-mail: vsarwadnya@yahoo.co.in)

***Abstract*—** In the modern era, high power handling capacity and higher power density are prime necessities for technology requirements of new DC/DC and AC/DC power supplies. In this regard, the primary objective of the power supply researcher/engineer is to build energy efficient, high power density converters by reducing the losses and increasing the switching frequency of converters. Operating the converter circuits at higher switching frequencies reduces the size of the passive components such as transformers, inductors, and capacitors, which results in a compact size, weight, and increased power density of the converter.

The EV (Electric Vehicles) and HEV (Hybrid Electric Vehicles) are gaining higher importance in day today life. The stringent environment concern is making inefficient vehicles obsolete. The solar energy is an abundant source for the energy leading towards green technology. The role of inductors in reducing harmonics is vital one and hence to improve its performance in HF is area of research since decades. The paper describes design of a liquid core type planar transformer for its possible usage in the hybrid electric vehicles. Comparison of different planar structures is given for analysis purpose.

***Keywords*—**DC-DC converters, High frequency components, Hybrid Vehicles, SMPS, Planar transformer

I. INTRODUCTION

In recent year, electric vehicles are the most preferred mode of conveyance. It has main part as AC-DC bidirectional converters. Such vehicles have main constraints of transformer size, volume and weight. High frequency is generally used in order to reduce the size and weight of the various components [1]. Due to improved performance of switching devices (SiC, GaN MOSFETs) the switching frequency can well be increased in converters [2]. But the components such as inductors and transformers need suitable magnetic materials. The utility of ferrites such as MnZn, NiZn is restricted to a few MHz only. Thus the absence of magnetic materials in MHz range is a gap which has restricted the progress [3]. Fig. 1 shows the identified gaps for new magnetic materials.

Use of micro-machined inductors, which is a costly approach, has limitations [4]. The heat dissipation from such microstructures is also an important factor [5]. The liquid cooled inductor is a better alternative in reducing the temperature gradients. Higher permeability liquid will help to improve the performance by dissipating heat and reducing the overall weight with cheaper option [6].The research on AC-DC converters with single phase single stage [7], single stage three phase [8] and ZVS (Zero voltage Switching) [9] inverters has been done extensively.

The work describes new high performance structures suitable for the production of the high frequency inductors and transformers. Use of higher frequency reduces the size of the transformers and inductors. But increased frequency increases core and copper losses. Hence proper magnetic materials are needed. The frequency presently being used is in the kHz range. Ferrite cores (e.g. Mn-Zn, Ni-Zn) are used in a variety of shapes and sizes in the electromagnetic devices and are commercialized up to kHz range only. The core for high frequency transformer can be of torroid, E type, EC type, PQ type and POT type.

Research leading to fabricate planar structures has started about 1960 [10-14]. The planar PCB winding structure has advantages over winding as good repeatability, lesser size, less skin effect, less leakage inductance, suitable for mass production. Different core sizes are available in the market [16]. Fabrication of POT core transformer has been studied in the literature [17]. In order to overcome the limitation of high frequency cores above 10 MHz, coreless transformers (air core) have been investigated for the higher frequency ranges [18]. Planar PCB transformers without core materials (air core) may have various advantages [19] such as operating frequency will have no upper frequency limitation, no magnetic saturation and core losses, high power density, easy to manufacture low profile transformers, avoiding manual winding and bobbin and small size, thermal stability, higher energy efficiency, thus providing a cost effective solution [20-21]. But poor coupling between the windings and low shielding may affect the performance. Liquid core transformer can be the best choice. Use of magnetic fluids (also called ferrofluids) could be made as a core for the transformer. Ferrofluid consists of suspensions of magnetic nanoparticles stabilized by surfactants in carrier liquid viz. transformer oil.

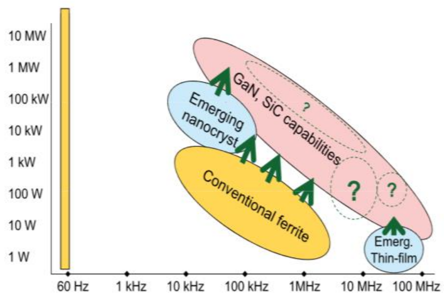

Fig.1 Courtesy Charles R.Sullivan ,Daniel V.Harburg and Jizhang Qui.,” Integrating Magnetics For On Chip Power: A perspective”- IEEE Transactions on Power Electronics, Vol.28 No.9,september 2013

II – PROPOSED LIQUID CORE TYPE PLANAR TRANSFORMER

The multilayer PCB having eight layers with four conductors in each layer is considered as shown in Fig, 2. The windings are nothing but copper tracks having track height of 35 µm and width of 0.5 mm with 1 mm spacing in horizontal as well as in vertical. There are four tracks in each layer and total 32 rectangular shaped conductors. These conductors are distributed equally in the lower and upper halves of the pot core. Fig. 3 shows the magnetization curve for the ferrofluid under consideration. As depicted in Fig. 4 (a) and (b), 16 conductors are connected in series. Thus there are two coils each having the 16-16 conductors. These coils can be treated as coupled inductors or a transformer. The air gap is 1.2 mm. FR4 material has been used for the PCB.

III. MATHEMATICAL MODEL

Static analysis of the planar structure could be carried out using the magnetic and electric fields formulation to find the currents and the magnetic fields. At steady state, magnetic field associated with the coils is given by the following equations:

The windings

$$\nabla\times(\mu_0^{-1}\mu_r^{\ -1}\nabla\times A) = J^e e_\varphi,\ A = A_\varphi e_\varphi \qquad (1)$$

The ferrite part of the core and ceramic wafers

$$\nabla \times (\mu_0^{\ -1}\mu_r^{\ -1}\nabla \times A) = 0 \qquad (2)$$

The nanofluid core

$$\nabla \times (\mu_0^{-1}\ \nabla \times A - M) = 0 \qquad (3)$$

where, A [T·m] is the magnetic vector potential, J_e [A/m^2] is the external electric current density, $\mu_0 = 4\pi\times10^{-7}$ H/m is the magnetic permeability of free space, and r is the relative permeability. The magnetization, M [A/m], is approximated by the analytic formula

$$M = \alpha \ \text{arctan}\ (\beta H) \qquad (4)$$

where, A is the magnetic vector potential, B is the magnetic flux density, H is the magnetic field strength and J is the current density, which can be solved simultaneously, or in a separate analysis.

Fig.2 Construction of the PCB Winding

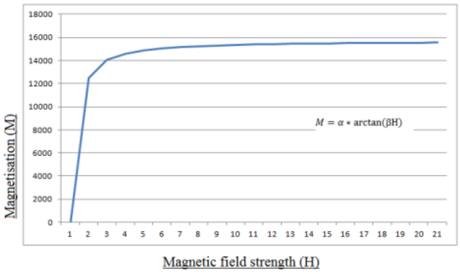

Fig.3 M-H curve for the ferrofluid.

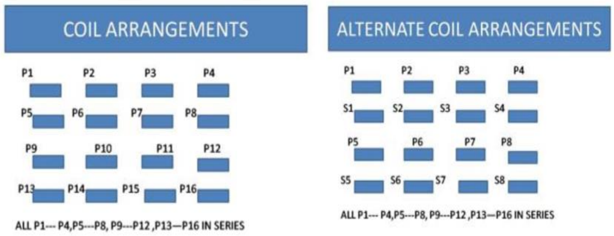

Fig.4 (a) and (b) Type 1 Series connected layers housed in upper half coil1and lower half coil2 of core separately TYPE2 Series connected layers housed in upper and lower half of core i.e. interleaved .

III. SIMULATION AND DISCUSSION

FEA simulation of the transformer was carried out considering 2D axi symmetric geometry as shown in Fig. 5. The Ni-Zn POT core type transformer was simulated in the absence and presence of ferrofluid as shown in the Fig. 5 (a) and (b). The structure of the transformer is same as that in TYPE 1 only gap is replaced by the transformer oil based Ni-Zn ferrofluid. (Primary winding resistance), R_s (secondary winding resistance), L_p (primary winding inductance), L_s (secondary winding inductance), M_{12} (Mutual Inductance between primary winding and secondary windings). Flux density, magnetic field strength at various locations in the structure have been simulated. Table I gives the comparison of the extracted parameters obtained after simulation. It is observed that the alternate coil arrangement of the transformer structure imparts more mutual inductance.

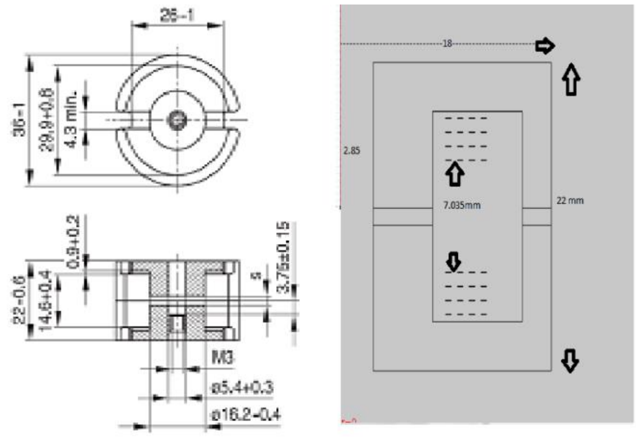

Fig.5(a) and (b) Constructional details of the pot Core. Simulation 2D-Axi conductors arrangement.

TABLE I : Comparison of the extracted parameters after simulation

Parameters	COMPARISON OF RESULTS FOR TWO COIL ARRANGEMENTS WITH			
	AIR FILLED GAP		FERROFLUID FILLED GAP	
	CONDUCTORS IN ONE HALF (TYPE 1)	ALTERNATE COIL ARRANGEMENT (TYPE 2)	CONDUCTORS IN ONE HALF (TYPE 1)	ALTERNATE COIL ARRANGEMENT (TYPE 2
Resistance of coil (R_{coil})	0.01206 Ω	0.00871 Ω	0.01368 Ω	0.01033 Ω
Inductance of coil (L_{coil})	2.0651 E-7 H	1.814 E-07 H	3.2259 E-7H	2.9744 E-7 H
Mutual inductance (M_{coil})	1.5466 E-7 H	1.79531 E-7 H	2.7057E-7 H	2.95524 E-7 H

CONCLUSION

The FEA tool provides information of the resistance, self inductance, mutual inductance between the two coils. Table I shows the increase in mutual inductance for the type 2 over type 1 coils. Also the presence of the ferro fluid increases the mutual inductance as compared to the air gap. This clearly indicates that the ferrofluid gap filled structure helps for better mutual coupling. Advantages of liquid type core (ferrofluid) are better cooling and insulating medium, better magnetic properties as compared to air.

REFERENCES

[1] William Gerard Hurley, W.H. Wolfie J.G. Breslin, “Optimized Transformer Design: Inclusive of High Frequency Effects”, IEEE Transactions on Power Electronics.Vol.13 No.4 July 1998.

[2] Sam Davis, “The Right Gate Driver Delivers the Right MOSFET Performance” Power Electronics Technology, 2000.

[3] Charles R. Sullivan D.V. Harberg, “Integrating Magnetics for On-Chip Power : A perspective”, IEEE Transactions on Power Electronics Vol.28 No. 9 September 2013.

[4] C. Marxgut J. Mulhetheler, “ Multi Objective Optimisation of Ultra –flat Magnetic Components with a PCB –Integrated core” , 8th International conference on Power electronics May 2011.

[5] Radhika Ambatipudi, H.B. Kotte, “ High Performance Planar Power Transformer with High Power Density in MHz Frequency Region for Next Generation Switch Mode Power Supplies”, International conference 2013.

[6] Hafiz Furkhan Ahmed, Honnyong Cha, “Wide Load Range Efficiency Improvement of a High-Power Density Bidirectional DC-DC Converter Using an MR Fluid –Gap Inductor”, IEEE Transactions On Industry Applications.

[7] F.Jauch,J.Biela” Single-phase single-stage bidirectional isolated ZVS ACDC converter with PFC Published in: Power Electronics and Motion Control Conference (EPE/PEMC), 2012

[8] A.Darwish,Derrick Holliday,s.Ahmed“Single stage three phase inverter based on cuk converters for PV applications”IEEE journal of emerging and selected topics in power electronics,Dec.2014

[9] C.M.Wang“ A novel soft switching single phase AC-DC-AC converter using new ZVS PWM strategy” IEEE Transactions on Power Electronics.Vol.22 No.5 Sept.2007.

[10]T. Yokohama et al., “A study on a design method for a planar transformer using sliced coils and amorphous foils”, IMET, 1991.

[11]K.K. Kawabe, H. Koyama, and K. Shirae, “Planar inductor,” IEEE Transactions on Magnetics. pp. 1804-1806, 1984.

[12]O. Oshiro et al., “A closed type planar inductor,” IEEE Transaction J Magn., Japan, 1987.

[13] O. Oshiro et al., “A wide frequency planar inductor,” IEEE Translation J. Magn., Japan, pp. 331-332, 1987.

[14] Oshiro et al., “A novel type planar inductor,” IEEE Translation J. Magn., Japan, pp. 3759-3761, 1989.

[15] Ferrites and Accessories TDK –EPCOS Handbook p.378.www.epcos.com [16] Magdalena Puskarczyk,Radosla Jez. Proceedings of the 2014 COMSOL Conference in Cambridge.The Design of Multilayer Planar Transformer for a DC/DC Converter with Resonant Inverter .

[17] S.Y. (Ron)Hui, Henry Shu-Hung Chung and S.C.Tang, “Coreless Printed Circuit Board (PCB) Transformers- Fundamental Characteristics and Application Potential”, IEEE Circuits and Systems Society Newsletter., vol. 11, No.3, Third Quarter 2000,ISSN 1049-3654,pp.3-15.

[18] Shu-Hung Chung, “Characterization of Coreless Printed Circuit Board (PCB) Transformers-A Fundamental Concept for Signal and Energy Transfer”, IEEE Transactions on Power Electronics., vol. 15, No.5, September, 2000.

[19] Radhika Ambatipudi, Hari Babu Kotte, and Kent Bertilsson, “Coreless Printed Circuit Board (PCB) Step-down Transformers for DC-DC Converter Applications”, Proceedings of World Academy of Science Engineering and Technology (WASET), Paris, France, October 2010, Issue. 70, pp. 380-389, ISSN 1307-6892.

[20] Radhika Ambatipudi, Hari Babu Kotte, Kent Bertilsson, “Comparison of Two Layered and Three Layered Coreless Printed Circuit Board (PCB) Step-down Transformers, Proceedings of 2010 3rd International Conference on Power Electronics and Intelligent Transportation System”, November 2010, Shenzhen, China Vol. IV, pp. 314 – 317, ISBN 978-14244-9162-9.

[21] Radhika Ambatipudi, Hari Babu Kotte and Kent Bertilsson, “Radiated Emissions of Multilayered Coreless Printed Circuit Board Step-Down Power Transformers in Switch Mode Power Supplies”, International Conference on Power Electronics”, ICPE 2011 - ECCE Asia, May 30 June 3, 2011, Jeju, Korea.

Vilas V. Sarwadnya Research scholar at SGGSIET Vishnupuri Nanded, Maharashtra works as HoD, Electrical Engg. in Govt. Polytechnic Arvi, Wardha, Maharashtra. His field of interest is High frequency magnetic components. He has attended different workshops in electrical Engg. He has worked as Coordinator for ISTE sponsored STTP on PLCs. Before joining the teaching, he has worked as GET in L&T,ECC India for two years. He has undergone training for six weeks in Bajaj LTD. and six weeks in TPS Parali. .S. INDIA. Simulation using FEA tools, HF systems and ferrofluids are the main areas of interest.

Dr. R. V. Sarwadnya received her B.E. and M.E. degree from Marathwada University, Aurangabad in the year 1988 and 1993 respectively. She received PhD degree from IIT Bombay, in the year 2008. Her area of interest is Biomedical Engineering, Embedded systems, MEMS. For last 30 years she has been working with SGGS Institute of Engineering & Technology as Associate Professor. She has worked as Coordinator for TEQIP and ISTE sponsored STTP on simulation of electrical components using COMSOL MULTIPHYSICS, Intellisuite. She is member of NPMASS program and established the NANOTECHNOLOGY centre (MEMS) at SGGSIET.

Dr. S. G. Kahalekar, Ex-Professor and Head of Instrumentation Engineering Department has written about 18 books in utilizing technology in day today life of Indian villages. He has worked in the Siemens India as Design Engineer prior to joining SGGSIET, Nanded for five years. He has completed his PhD from SRTMU, Nanded. He is recipient of different awards and prizes for his work in social as well as rural areas for transferring technology to root level.