INTEGRATION OF HEAT PIPES INTO COAXIAL TRANSFORMERS UTILIZING COAXIAL CONDUCTORS

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Abstract. Magnetic component design has received much attention over the last few decades specifically with their application in high frequency power converters. Conventional indirect cooling methods for these components involve air and oil as transport mechanisms for the thermal energy. The insertion of thermally conductive layers and heat pipes into transformers has also been reported. This paper is aimed at the integration of heat pipes into coaxial transformers by using the conductors, already present for electrical functionality, as the heat pipe material. The concept is investigated experimentally by constructing a physical transformer.

Key Words. Heat pipes; coaxial transformers; coaxial conductors.

1. INTRODUCTION

Magnetic components will always be some of the most important parts of high frequency power conversion. Not only do they impact on the size and weight of the converter but they have to be carefully designed and constructed to minimize parasitics and thermal issues [1],[2],[3].

Air and oil are vehicles commonly used to transport thermal energy from the heat source to the ambient [4]. One of the advantages of planar magnetic structures is the increased surface area through which heat can be extracted from the device [5]. Thermally conductive layers may also be inserted between cores to extract heat as reported in [6].

Magnetic components such as transformers and inductors all experience the problem that heat is generated throughout the component by conductors and magnetic materials. This heat has to propagate to the surface of the component through various layers of material of which not all are good thermal conductors.

Ferrite material losses usually decrease slightly with an increase in the operating temperature [7] but conductor and insulator materials need to be cooled for best performance. The component temperature thus has to be kept at an optimal value if the optimal efficiency is to be maintained.

Heat pipes seem like a good solution to this problem because they can be inserted into the component to remove heat more effectively. They should be positioned carefully in the structure and the pipe should preferably not be made of an electrically conductive material since proximity effects may cause losses in the heat pipe itself. This paper is aimed at the integration of heat pipes into coaxial transformers. The electrical conductors are assigned a dual function. Apart from conducting electricity some of the conductors are also converted into heat pipes. The concept is investigated experimentally by constructing a single heat pipe as well as a physical transformer and the results are reported in the experimental section.

The construction of the conventional coaxial transformer is discussed in the next section with the proposed changes that will enable the integration of heat pipes into the transformer. In section 3 heat pipe operation is explained and a single heat pipe experiment devised as a preliminary investigation into the proposed idea.

2. COAXIAL TRANSFORMERS

2.1 Background

The ease with which the leakage and capacitance of coaxial conductors may be calculated attracted the attention of transformer designers and it seems that at least the leakage inductance can be calculated accurately for some arrangements of the conductors [8], [9].

Conventional coaxial transformers such as shown in figure 1 are restricted to having one secondary winding. Efforts have been made to increase the number of secondary conductors by using concentric conductors [8], and split conductors [10], [11], [12]. These techniques pose several manufacturing problems with interconnections, which are not discussed in this paper but they limit the possible number of secondary conductors. The current distribution in split conductors is not ideal with detrimental consequences on the efficiency of the transformer.

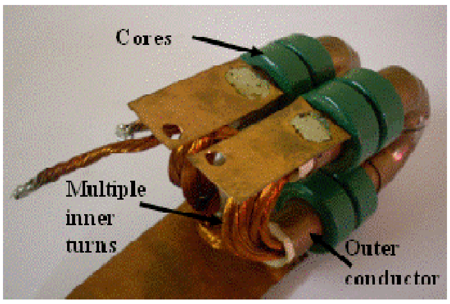


Fig. 1. Conventional coaxial transformer

This matter will not be discussed further in this paper but needs to be investigated further.

The use of several smaller secondary conductors, each with one or two primary windings threaded through each of them to form a coaxial conductor is proposed in [10]. These secondary conductors, made of copper tubing, are arranged in a particular pattern in a rectangular core window and the end connections are made with a braided conductor to reduce the added leakage inductance due to end effects. The authors of [10] also discuss the multiple concentric conductors and split conductor methods discussed earlier. Losses due to proximity effect and the conductor arrangement chosen are however not discussed. The interconnections are made via a soldered pcb-method at both ends of the structure. The reduction in leakage inductance is illustrated by comparing it to a conventional EE-core reference transformer [10].

2.2 Proposed Idea

In this work the idea of using coaxial conductors in the construction of coaxial transformers is adopted with the difference that the coaxial conductors are constructed by using copper tubing for both the inner and outer conductors resulting in the same effect of reduced leakage inductance and conductor losses. The contribution of this work is toward the integration of heat pipes into the transformer with minimal addition of copper. The inner tubing of the coaxial conductors is extended somewhat and radiator fins are added to the construction.

3. HEAT PIPES

3.1 Background

The operation of heat pipes is discussed briefly in this section. A single heat pipe experiment is used to obtain some idea of the possible cooling effects.

Heat pipes are sealed tubes of copper or aluminium containing a small amount of solvent. Vertical heat pipes are ideal for removing heat from localised heat sources. If the temperatures are high enough, the solvent vapourises at the heat source and the vapour acts as a vehicle to transport the heat energy away vertically to a position where the heat is removed directly or via a radiator, which in turn may be cooled through natural convection or through forced cooling with for instance a fan [13]. As soon as the heat is removed the vapour turns to liquid again and simply runs back down to the bottom where heat is absorbed again and the process is repeated. If the heat pipe has to be installed horizontally, a wick or capillary structure may be used to transport the liquid phase of the solvent back to the heat source. This however reduces the efficiency of the heat pipe because the wick inevitably also reduces the flow of the vapour through the heat pipe. Figure 2 shows a photograph of a commercial heat pipe.

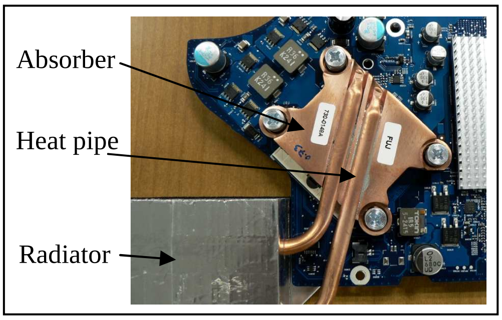
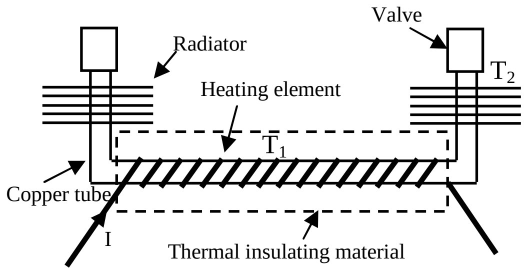


Fig. 2: Commercial heat pipe

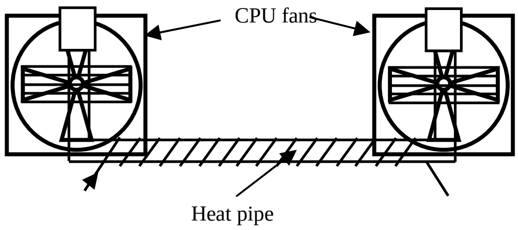
3.2 Single heat pipe experiment

Figure 3 shows a diagram of an experimental setup used to do preliminary tests and a photograph of this experimental setup is shown in figure 4.

A single horizontal copper tube is fitted with a vertical section on each side. A few radiator fins and a valve are mounted on the vertical sections. The valves are convenient for experimental purposes can be omitted once the heat pipes have been optimized. A heating element is installed as indicated and represents a distributed heat source. Two



a. Heat pipe



b. Heat pipe with fans

Fig. 3: Single heat pipe experiment

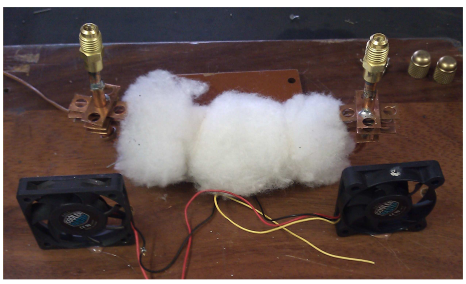


Fig. 4. Photograph of heat pipe experiment

thermocouples are inserted in positions indicated by T_1 and T_2 and the heating element is thermally isolated using an appropriate material. The first part of the experiment involves the heating of the pipe without any solvent in the heat pipe and the CPU-fans aligned with the radiators are switched off. The temperatures are recorded together with the ambient temperature as soon as they reach steady state values. The fans are then switched on and the cooling effect recorded. Some solvent (acetone) is now sealed into the pipe using the valves and the experiment is repeated first without and then with the fans switched on.

Figure 5 shows the results of the experiments graphically. The ambient temperature remained more or less constant at 25^0C for the duration of the whole experiment and the power dissipated in the element is 7W.

It is clear from the results that the temperature of the heat pipe at the centre of the pipe reduces if the fans are switched on without any solvent in the pipe. This is to be expected because a higher temperature gradient is created by cooling the radiator. The temperature in the centre of the heat pipe however drops considerably when a solvent is added because the vapour transports the heat energy much faster than the copper medium itself. The inner temperature drops to a temperature slightly higher than the boiling point of the solvent (57^0C for acetone). This is to be expected since the increase in pressure in the heat pipe will cause the boiling point to increase. This temperature is a mere 38% of the initial temperature of the pipe without any acetone in it and with no fans cooling the radiators.

This experiment was repeated several times with different amounts of solvent and even with two different solvents. The amount of solvent added in proportion to the volume of the heat pipe and the boiling point of the solvent are two very important parameters. The vapour phase transports the heat and the flow of vapour should not be inhibited. Care should also be taken that the inner and radiator temperatures allow for the existence of both the vapour and liquid phases of the solvent. If the radiator temperature is higher than the boiling point of the solvent, the vapour will not return to liquid and too little solvent in the liquid phase will be available for effective removal of the heat from the walls of the tube.

A quantity equal to 5 to 10% of the tube capacity seems to yield good results in this case but further research into the optimal design of these specific heat pipes is necessary. Some manufactures also draw a vacuum in the tubes before inserting the solvent to lower its boiling point but this technique is not used here.

3.3 Experiment with heat pipes integrated into coaxial transformer

Several factors have to be considered carefully as heat pipes are usually used in applications where heat has to be removed from a specific location to where a radiator can best be installed. In case of the coaxial transformer the heat source is distributed as heat is generated in the cores and conductor material throughout the length of the transformer. In order to avoid using a wick as in the single heat pipe experiment, the heat pipes have to be put horizontally at this point in time.

Figure 6 shows a schematic of the coaxial transformer construction being used for experimental purposes and a photograph of the experimental setup appears in figure 7.

A 4:1 turn ratio transformer is constructed. Only the one side of the transformer is fitted with heat pipes so that a comparison may be made between the temperatures measured on this side of the transformer and the side that has no heat pipes. In this way

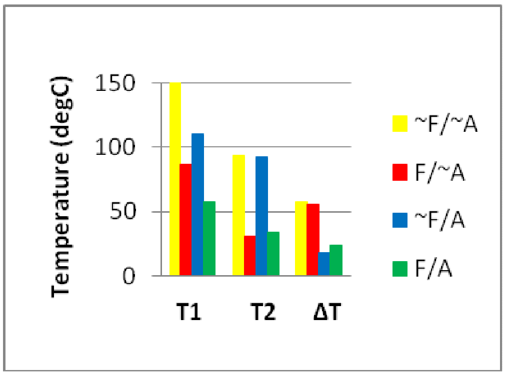


Fig. 5. Graphical representation of single heat pipe results

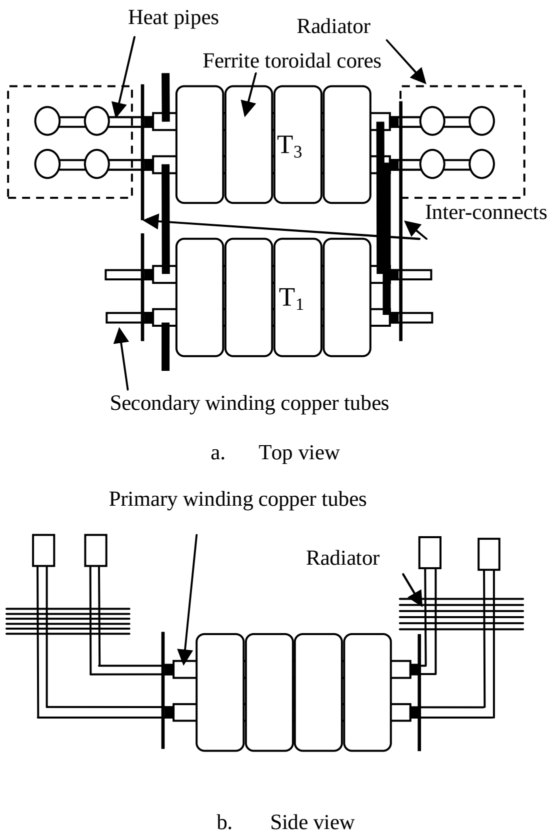


Fig.6. Coaxial transformer cooled on one side

parameters such as the ambient temperature and the primary and secondary current for all the windings will be the same for the two sides of the transformer. It is possible that thermal energy may flow between the two sides of the transformer through the interconnecting conductors but although the effect is visible in the experimental results it is not studied in this paper.

The heat pipes are created by extending the inner copper tubes of the coaxial conductors and bending them up vertically. The valves are again mounted for experimental purposes only. The radiator fins short-circuit the four inner conductors and therefore the inner conductors are interconnected to form a single secondary winding in this application and the outer tubes of the coaxial conductors are interconnected to form the four turn primary winding. The intension is not that current actually flows through the radiator fins. The interconnections meant for the purpose of conducting the secondary current, indicated on the sketch, should carry most of the secondary current. The radiator fins may also be constructed in such a way that they do not short-circuit the conductors.

The transformer secondary winding is short-circuited at the transformer terminals and the primary current

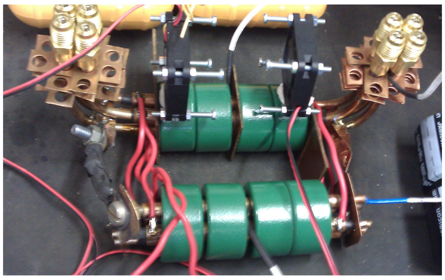


Fig. 7: Photograph of experimental setup

is supplied from a 100kHz H-bridge converter. The photograph in figure 7 shows the transformer. The converter is fed from a motor-generator set and the rms-current in the primary and secondary windings are 30A and 120A respectively. The harmonic content of this current waveform shown in figure 8 is expected to cause considerable conductor and core losses.

The same experimental procedure is followed as with the single heat pipe experiment. The heating effect on

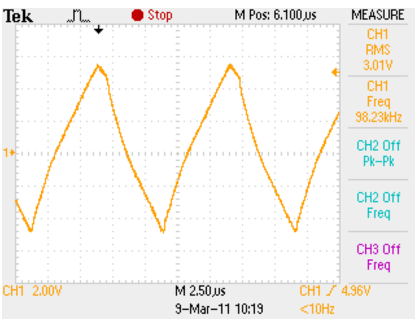


Fig. 8: Primary current waveform (10A/V)

both sides of the transformer is first of all studied with empty heat pipes and with the fans switched off. The fans will then be switched on and the temperatures measured after reaching steady state thermal conditions. These two experiments are then repeated with some solvents sealed off in the heat pipes.

The most important results of these experiments are presented graphically in figure 9 and are discussed briefly. Figure 9 shows the winding temperatures on the two sides of the transformer where T_1 is the temperature of the winding measured on the side of the transformer where no heat pipes are integrated into the winding and T_3 on the side with the integrated heat pipes. The two sets of data show the difference in winding temperatures with and without fans and acetone, similar to the results of the single heat pipe experiment, at an ambient temperature of 25^0C. Temperatures in the excess of 100^0C are measured on the winding without the integrated heat pipes if the fans on the other side of the transformer are not switched on.

The temperatures drop if either the fans are switched on or if acetone is added. The drop in temperature T_1 is attributed to the fact that the two sides of the transformer are not thermally disconnected from one another and the side without the heat pipes benefits from the cooling on the side of the heat pipes because heat flows through the interconnecting conductors.

The winding temperature on the side of the transformer with the integrated heat pipes drops from 102^0C to 68^0C when the fans are switched on with acetone in the heat pipes. This temperature is approximately 33% lower than the conductor

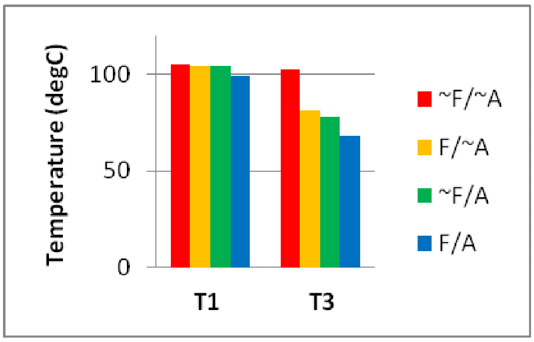


Fig. 9. Winding temperature

temperature measured on the side of the transformer where no heat pipes are integrated. In the single heat pipe experiment the temperature measured directly on the heat pipe dropped to a value slightly higher than the boiling point of the acetone. In case of the transformer this temperature is higher because it is measured on the outer tube of the coaxial conductor and one should keep in mind that not only are the primary and secondary windings separated by an insulation layer but they still both act as sources of heat.

4. CONCLUSION

Experimental results clearly show a promising solution to the problem of heat removal from transformers through integration of the heat pipes into the electrical conductors already present. The same technique may be applied to inductors. By manufacturing the windings using copper tube, the heat pipes can be integrated into the inductor in the same way as for the transformer.

A few aspects have to be investigated still:

- The distributed nature of the heat source in the transformer requires it to be mounted horizontally. This is an important consideration that will have to be kept in mind during application. The use of a capillary structure inside the heat pipes and the effect it has on the cooling still has to be investigated.
- Since all the conductors are constructed with copper tubes the number of interconnections required to be made afterward increases. This research group is presently investigating application of multi-tap, reconfigurable transformers in high frequency converters which benefits from this method of construction.
- In this experiment dedicated fans are used for the radiators. In the construction of a complete converter, utilizing forced cooling methods, efforts will be made to use the central fan for this purpose.
- The design of the heat pipes and radiators still need to be optimised in terms of the amount of solvent, the use of capillary structures etc. The possibility of using commercially manufactured heat pipes is also investigated as an option.
- The advantages of this cooling method will have to be weighed up against the added cost incurred by all of the above mentioned issues.

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