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Investigation of polymer bonded magnetic materials for power conversion

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***Abstract* - Polymer bonded magnetic materials offers many advantages compared to the conventional type of magnetic materials including shape, physical property and cost. This is a new type materials will form a new era of power conversion and is also a new area of research. Until today, no research has been reported on use of polymer bonded magnetic materials. This research studies the method of fabricating a micro-powder filled magnetic polymer composite, its magnetic property and electric property. The paper also describes the application in high frequency power conversion. A phase-sifted converter using self-resonance which is especially useful for transformer constructed from the low permeability material was used to examine the core. A flyback converter is also used to confirm the use as a coupled inductor. Measured characteristics of the materials and the power conversion measurement data confirm the feasibility of the proposed materials.**

I. Introduction

The magnetic materials such as Ferrites are mixed compounds of ferromagnetic oxides (Fe_2O_3) with several oxides of bivalent metals such as NiO MnO and ZnO. They are famous for their low loss characteristics and high frequency operation. Powder iron such as Molydbenum Permalloy Powder (MPP) are also mixed with Nickel and Iron. They are very popular for power conversion. One of the applications is the power converter which uses magnetic materials to construct inductors and transformers. The loss for the magnetic device usually accounts for 30-40% of the total loss of the converter. The design of the magnetic device also depends on the permeability, loss factor and size and shaper of the materials.

Conventional type of magnetic material suffers from a number of disadvantages including limited size, brittle, high loss and high cost. One of the typical problems is that for application in high power conversion such as more than 20kW system [1], the transformer or inductor required is getting very difficult to obtain because of the mechanism of formation of Ferrites or powder iron is very difficult and expensive. The Polymer-bonded magnetic material is composed of polymer matrices and magnetic powders which can be produced by traditional polymer processing methods. Hence, it offers significant advantages over the conventional counterparts. One of the important advantages is the ease of moulding such as injection moulding which can save on manufacturing costs and quality control.

The loss can be divided into conductor loss and core loss. The conductor (winding) loss is the resistive loss due to the current passed through the winding and they will also increase dramatically as the frequency increases because of the current distribution in the conductor at high frequency. Ref [2] reported a detailed analysis on the calculation of conductor loss which both eddy current and proximity effect are considered. The core loss of magnetic materials is usually caused by the hysteresis, eddy loss and residue loss. The hysteresis loss and eddy loss can be decreased by using power iron core for high frequency application.

This paper is to present the investigation a polymer bonded magnetic material techniques for use in power conversion. The proposed materials will form a new concept of power conversion and will offer many advantages. This includes the polymer bonded magnetic material can be moulded into any shape which is impossible to be obtained by ferrites or powder iron which requires a special tool to press. Hence the proposed material presents flexibility. The characteristic presented includes thermal stability, environmental deterioration, mechanical property, magnetic and electrical property and its use in electrical circuit. In addition, because the polymer is a high non-conductive materials, it therefore decreases the eddy current in the materials and therefore it is expected that the loss is low.

In fact, recently there are many developments reported by using polymer-bonded magnetic material in various application. The synthesis and processing method has also been improved recently [3-4]. This paper also presents the application of this magnetic material as a transformer for DC/DC power conversion. The converter topology chosen for this study is the phase-shifted converter [5-8] which has been used in the past for superconductor-winding made transformer and has been proved to be very successful. The measured characteristics of the B-H and its procedure for the application of the core into self-resonance DC/DC converter is described.

II. FABRICATION OF MAGNETIC COMPOSITE

The magnetic composite was fabricated by filling the metal powders into the epoxy resin. The base material was prepared mainly by an epoxy resin and two monomers. They are 4,4-isopropylidenediphend epichlorohydrin resin and alkyl glycidyl ether and poly-acrylate ether. The cross-linking agent (hardener) of the epoxy resin contains diethylenetriamine and 2-hydroxyethydiethylenetriamine. One part of the hardener was mixed with five parts of epoxy resin. Then, the mixture of 20 grams was moulded and cured at room temperature for 30 minutes until solidification.

The filler of the composite materials were micro cobalt particles (spherical, diameter < 18μm) and micro nickel

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particles (spherical, diameter < 4μm). Their surfaces were treated by titanic coupling agent (1.5% weight of filler) to enhance dispersing the micro particles and increasing the bond strengthen between particles and resin.

The structure of the titanic coupling agent is:

$$\begin{array}{l} \quad CH_3 \\ \quad \;| \\ CH_3CH\text{—}O\text{—}Ti\text{—}[OOCR]_3 \end{array}$$

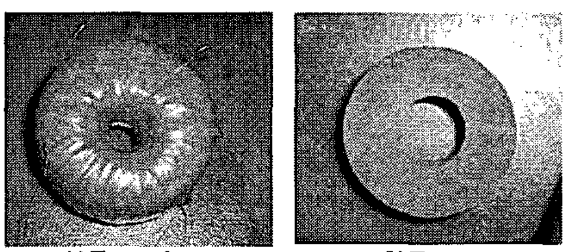
where R is $C_{15}H_{32}$.

The composition of the magnetic core is 0 to 32 grams of cobalt micro-powder and 10 grams of nickel micro-powder with 62.5%w/w filler ratio.

In order to avoid the formation of air bubbles, the blending process of the fillers and the resin should be done in vacuum. Otherwise, the composite will become porous and the electromagnetic property will be deteriorated.

III. The Polymer Bonded Magnetic Core

The polymer bonded magnetic component is constructed to a toroid with outer and inner diameters to be 3.7cm and 1.6cm respectively. The height is 1.6cm. The weight of the core is only 20- 35g. Fig 1 shows the core and the transformer wounded by 500 turns of winding. It can be seen that the core is very similar to other ferrite or powder iron. The strength of the core is also very high but not brittle as the ferrite and power iron.



(a) The transformer (b) The core

Fig 1 Photos of the Polymer-bonded core and its transformer

The characteristic was measured at 400Hz is shown in Fig 2. Fig 2a shows the core's B-H characteristics with 500 turns wound on the core for the measurement of the characteristics. It is found that the core has difficulty to saturate and even the H-field is increased to 40kA/m, the B-field only increases to 0.18T. It can be seen that the material has a low relative permeability of 3.6. The hysteresis loss is $725J/m^3$. For the other composition, the loss varies between 500 to $40J/m^3$ for the peak B-field swings up to ±0.2T.

The low permeability allows the self-resonant transformer [5] to be used for power conversion. The low permeability also has a better confinement of the leakage field than that of an air-core. This type of transformer can be constructed by using low permeability materials. During the self-resonant condition, the apparent magnetizing current is decreased and hence the high efficiency can still be maintained.

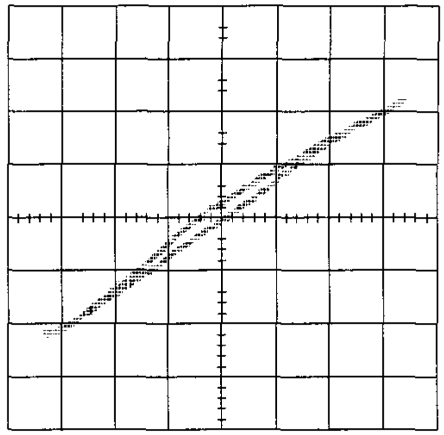


Fig 2 Measured B-H loop of the new material #10 (y: 0.08T/div, x: $11600Am^{-1}$/div)

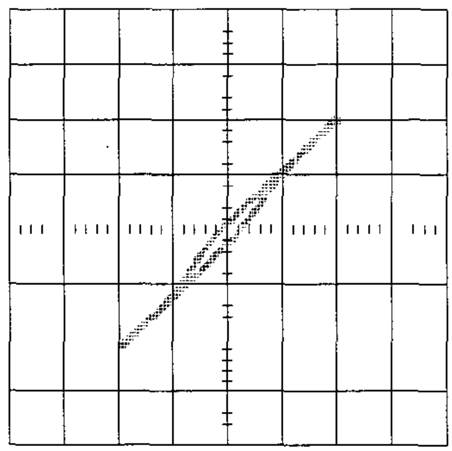


Fig 2b Measured B-H loop of the new material #8 (y: 0.09T/div, x: $22.4kAm^{-1}$/div)

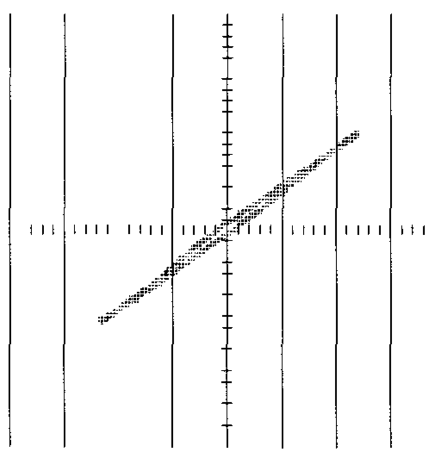


Fig 2c Measured B-H loop of the new material #7 (y: 0.06T/div, x: $13.3kAm^{-1}$/div)

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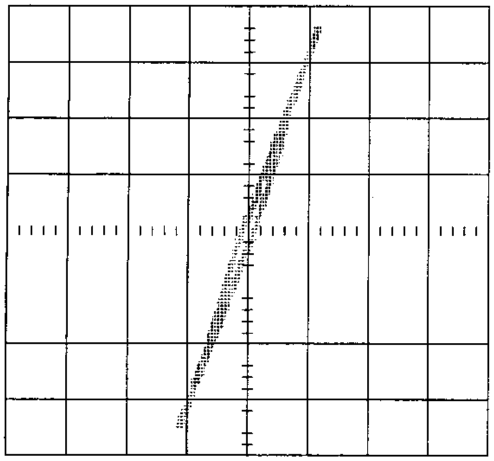

Fig 2d Measured B-H loop of the new material #5
(y: 0.0116T/div, x: 17kAm^{-1}/div)

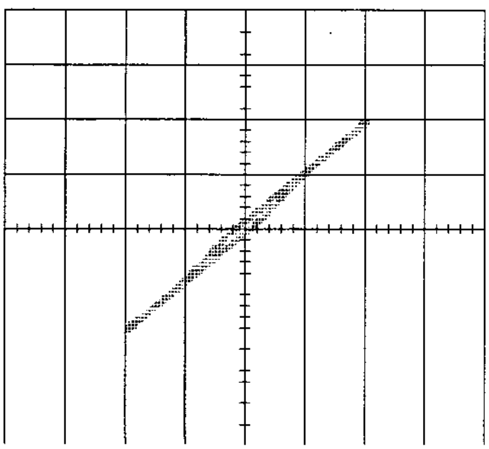

Fig 2e Measured B-H loop of the new material #2
(y: 0.053T/div, x: 24.5kAm^{-1}/div)

Fig 2b-e shows the core with other compositions. The B-H slope appears to be less. The relative permeabilities of different compositions are tabulated in Table I.

TABLE I
MEASURED PERMEABILITY OF THE CORE WITH THEIR CORRESPONDING COMPOSITION

Number #	Co-Ni composition	μ_r
10	32g + 10g	3.65
8	25g +10g	3.20
7	20g +10g	2.71
5	16g+10g	1.73
2	12g+10g	1.63

IV. CHARACTERISTICS OF THE POLYMER BONDED TRANSFORMER

The above core #7 is then used to construct a transformer. The transformer is a 1:1 turns ratio with 50 turns on each side. The leakage inductance and magnetising inductance against frequency were measured to examine its possibility to be used as a high frequency transformer. The measured leakage inductance and magnetising inductance of the transformer are 3.5μH and 17.2μH as the frequency is varied between 80kHz to 120kHz respectively. As the inductances are constant over a wide frequency of operation, the next step is to use the transformer to develop a self-resonance device for the power conversion [6]. The proposed operation frequency of the power converter using the polymer bonded magnetic transformer is 100kHz. Therefore a resonant capacitor C_r is selected to be 147nF and is connected in parallel with the primary winding of the transformer. The impedance and its corresponding phase of the transformer are examined and are shown in Fig 3 and 4.

It can be seen that the self-resonance impedance during the impedance around 300Ω and hence the impedance seen by the converter will therefore be high around these operation frequencies. There is a small error between the measured and calculated resonance frequencies and is due to the component tolerance. Based on the self-resonance converter theory [6-7], it is possible to design a converter to work at this frequency for power conversion.

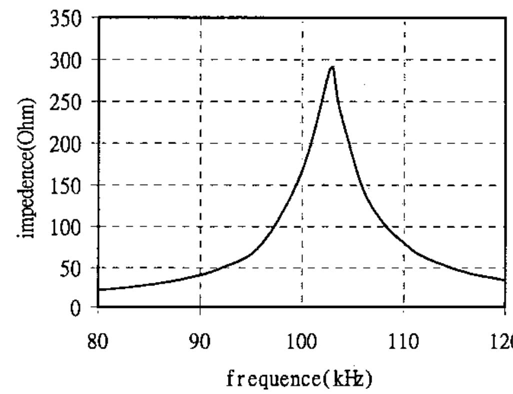

Fig 3. Resonant impedance of the transformer

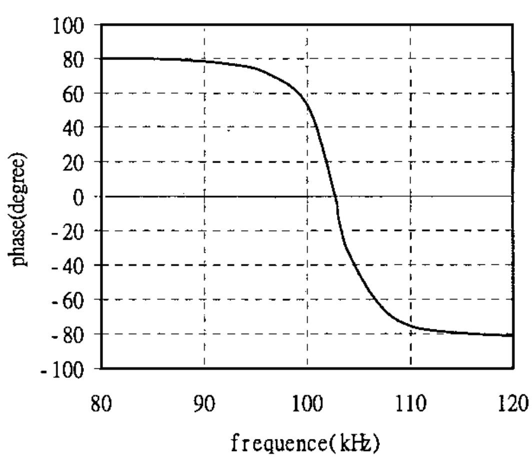

Fig 4 The phase angle of the resonant impedance of the transformer

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V. Application To A Phase-shift DC/DC Converter

A. *Description of the phase-shifted converter*

Fig 5 shows a DC/DC converter [6] using the proposed polymer bonded magnetic materials as a transformer. It can be seen that the DC/DC power conversion is performed by a self-resonant transformer which is constructed by the polymer bonded magnetic material. The converter is a conventional phase-shifted DC/DC type which consists of a inverter bridge to produce the high frequency ac voltage which is coupled through a transformer to the diode bridge. But the transformer core is just a polymer bonded magnetic material. Because of the low permeability of the transformer, it is difficult to use the transformer as the normal power conversion unless the transformer is operated at several MHz frequency. The concept used here is to exaggerate the stray winding capacitor such that an additional C_r is added in parallel with the primary winding. The previous section has confirmed that a 147nF capacitor can move the self-resonant frequency to around 100kHz. Therefore the same C_r is used and the converter operation frequency is set at 100kHz. This is the frequency close to the self-resonance frequency and is believed to have highest efficiency as shown by other publication [6]. The summary of parameters used in the circuit is shown in Table II.

TABLE II
List of Components of the Prototype Phase-SHIFTED CONVERTER with the Polymer-bonded Transformer

Components	Parameters	Remark
C_{in}	33μF	Smoothing
C_r	147 nF	External
L_{rk}	3.5μH	Internal
C_{out}	1μF	Smoothing
L_F	1mH	Smoothing
Q_1 - Q_4	IRF540	Switching
All Diodes	MBR10100	rectifiers

The transformer is constructed stranded wire in order to ensure the winding conduction loss is small. The electrical specification of the circuit under this test is shown in Table III. A low power prototype is chosen for this verification because the main purpose of the test is to ensure the transformer using a polymer-bonded material can be used as a power converter.

TABLE III
Electrical Specification of the Converter

Operation	Specification
Input voltage V_{in}	60V
Output voltage V_o	30-50V
Output power P_o	0-60W
Switching frequency f_s	100kHz

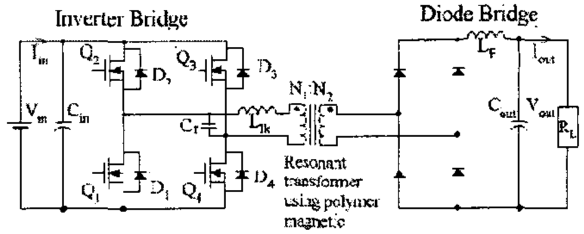
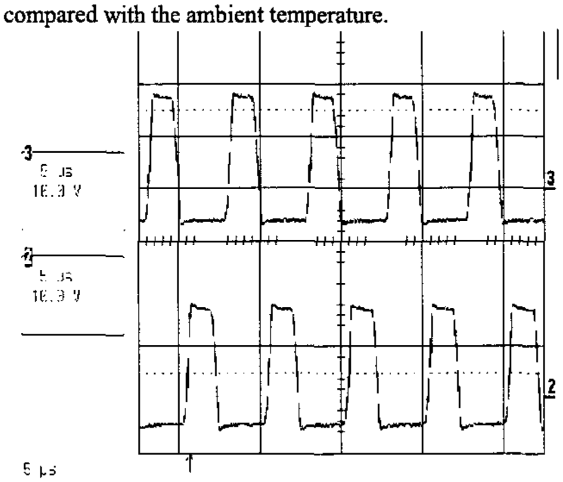


Fig 5 The phase-shift converter using the polymer bonded magnetic materials as a transformer

B. *The Experimental Results*

The converter under phase-shift of 180° is shown in Fig 6a-d. The condition of the converter when it is operated under Vo=44V and Po=17W. Fig 6a-d shows the measured waveforms of the circuit. Reasonable waveforms can be obtained for such as small size transformer. All the gate signals are switched at +14V for on-state and -6V for off-state to control the Mosfets (Fig 6a). The drain-source voltage as shown in Fig 6b has a DC level of 60V during the off-state. An ac parasitic resonance is also seen which due to the spray inductance in the PCB and the junction capacitance of the Mosfet. The secondary voltage of the transformer as shown in Fig 6c is a bipolar voltage energised by the inverter bridge and its current is therefore also a bipolar waveform with a slope which is modified by the filter inductance of the circuit. Fig 6d shows the transformer primary side voltage and current. It can be seen that the primary voltage is the same as the secondary voltage. Hence this confirms the operation of the transformer. However, the amplitude of the primary current is large because of the self-resonance effect. The self-resonant current is confined in the resonance loop formed by C_r and transformer primary winding. This is only a local loop and does not cause large loss if a proper design of the winding is used [2]. The converter has been tested from 0-60W and the power loss dissipated in the transformer is low. The maximum temperature rise measured on the transformer surface is 5°C compared with the ambient temperature.



(a) Gate-source signal of Q_1 (Ch3: 10V/div) and Q_4 (Ch2:10V/div)

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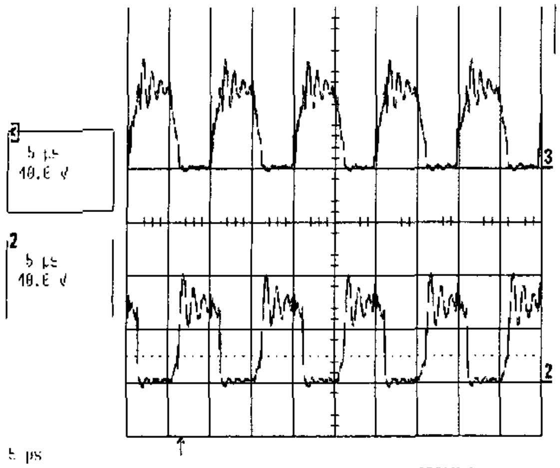
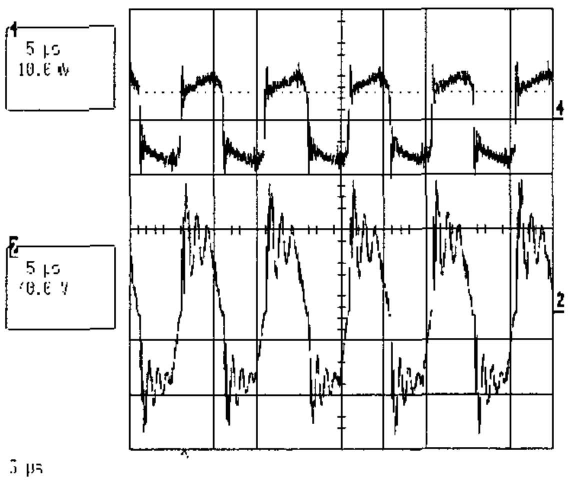
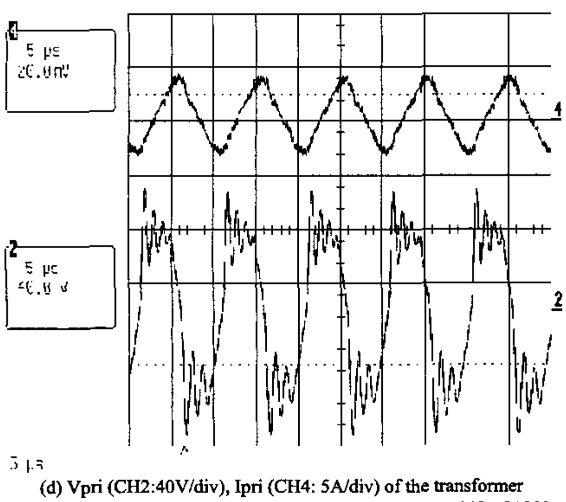


(b) Vds of Q_1 (Ch2: 40V/div) and Q_4 (Ch3:40V/div)



(c) Secondary voltage (Ch 2: 40V/div) current (Ch4: 0.5A/div)



(d) Vpri (CH2:40V/div), Ipri (CH4: 5A/div) of the transformer

Fig 6 Experimental waveforms of the converter at phase-shift of 180°

V. Application to a Phase-shift DC/DC Converter

A. Description of the Flyback converter

The polymer-bonded magnetic core is then used to construct a coupled inductor which has a primary inductance of 17.2μH with 1:1 turns ratio for the use in a flyback converter [9]. Again, stranded wire is used for the windings. Fig 7 shows the circuit used in the test. Table IV shows the parameters used in the circuit. Table V shows the Electrical Specification of the circuit.

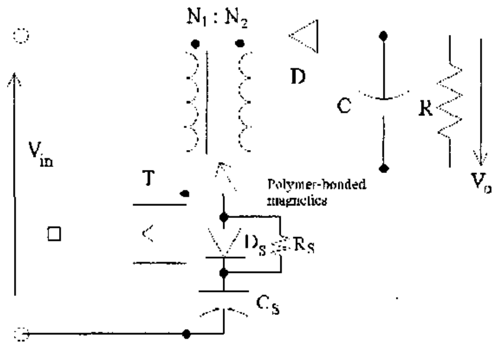


Fig 7 The flyback converter with a polymer-bonded magnetic coupled inductor

TABLE IV
List of Components of the Flyback Converter with the Polymer-bonded Transformer

Components	Parameters	Remark
N_1	50	Primary turns
T	IRF540	Switching
D	MUR820	Rectifier
C	33μF	Smoothing
R_s	1kΩ	Snubber
C_s	0.03μF	Snubber
D_s	MUR820	Snubber

TABLE V
Electrical Specification of the Converter

Operation	Specification
Input voltage V_{in}	25-30V
Output voltage V_o	15-20V
Output power P_o	0-30W
Switching frequency f_s	100kHz

B. Experimental results

The experimental waveforms with duty ratio of 0.2 and 0.3 and input voltage of 30V and 25V is shown in Fig 7a and 7b respectively. It can be seen that the flyback converter is operated under discontinuous inductor conduction mode. The efficiency of the converter is around 68-80% when the output power varies between 5W-30W. It can also be seen that the inductor current is very linear because the inductor does not saturate at all. An RCD snubber is added to the switching devices T because of the switching noise generated by the switching which is especially serious because the converter is under discontinuous mode. On the whole, the operation of the converter is normal and it confirms that the polymer-bonded material is suitable for a coupled inductor used in a switched-mode flyback converter.

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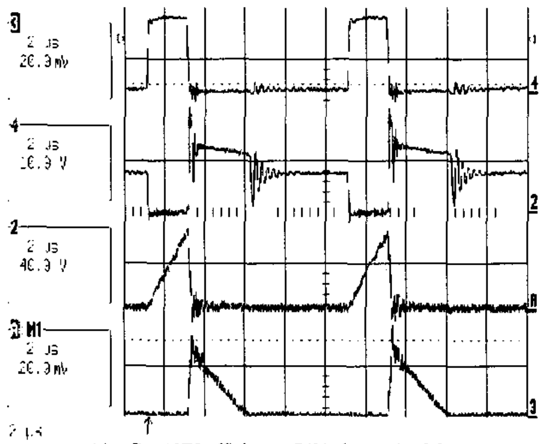
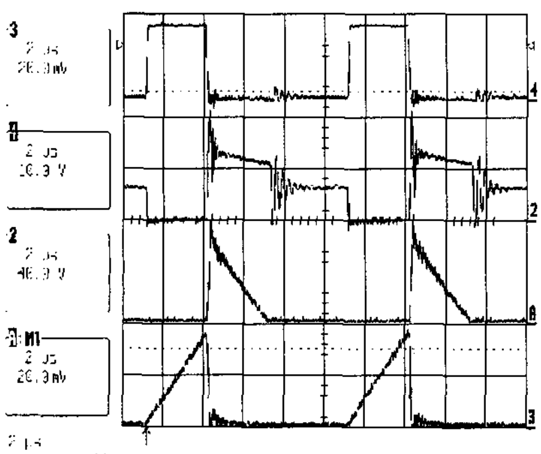
VI. Discussion of the Materials and the Applications

From the above tests, it can be confirmed that the polymer-bonded magnetic device can be operated as a normal magnetic material. It is very similar to the powder iron. Because it also very a very good distributed air-gap due to its composition, the material is suitable for high frequency application. The material also has a very high saturation field. Although for the present test, we can only test up to 0.25T, no trace of start of saturation can be seen. Therefore it is believed that the material has a saturation filed of higher than ferrites, and probably similar or higher than the MPP. The measured hysteresis loss is also small as compared to many MPP materials.

The application to two popular DC/DC converters has also been conducted. For both applications, the function of the inductor/transformer built by the materials works satisfactory. Reasonable effect can be obtained.



(a) Po=13W, efficiency=74%, duty ratio=0.2
(Ch3: Secondary current: 2A/div; ChA: Primary current 2A/div, Ch2: V_{DS}:10V/div; Ch4: V_{GS} 10V/div)



(b) Po=20W, efficiency=70%, duty ratio=0.3
(Ch3: Primary current: 2A/div; ChA: Secondary current 2A/div, Ch2: V_{DS}:10V/div; Ch4: V_{GS} 10V/div)

VII. Conclusion

A polymer bonded magnetic core was developed. The base material was prepared by an epoxy resin and two monomers. The filler of the composite materials was micro cobalt particles and micro nickel particles. The materials were then examined with its electrical characteristics. The composition of the magnetic core is up to 32 grams of cobalt micro-powder and 10 grams of nickel micro-powder. Different compositions have been used to construct a core. It has been found that very low permeability has been achieved. The loss of the core is also small that was confirmed from the measurement of the B-H loop. A phase-shifted power converter and a flyback converter respectively using a transformer and coupled inductor based on the materials had been prototyped. The experimental results show that the material is suitable for making the power transformer and inductor. However, because of the low permeability of the materials, if for medium to high frequency operation, the transformer is required a self-resonant techniques. For the use as the coupled inductor, because of the low permeability of the core, usually only discontinuous inductor conduction mode is used for this frequency of operation.

Acknowledgement

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