An application of resonant inverters for hysteresis-loop measurement

Kittipan Siangsanoh[*], Anawach Sangswang, Sumate Naetiladdanon, Chayant Koompai

Department of Electrical Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangkok, Thailand

Abstract:
This paper presents an application of a resonant inverter for hysteresis loop measurement of a ferrite core. The series resonant inverter is used as a replacement of the commonly used linear power amplifier where the bias current level is limited. The proposed system is design to measure a hysteresis loop of a ferromagnetic material at high frequency. The maximum flux density (B_m) and maximum magnetic field intensity (H_m) of a ferrite core is obtained through variation of the input voltage and frequency. A comparison of the experimental results and the specifications from the manufacturer is provided.

Keywords: *hysteresis loop; the resonant inverter; ferromagnetic materials*

*Corresponding author. Tel.:+66-85-485-1199
E-mail address: rerealiidad@hotmail.com

1. Introduction

Power electronic converters have played a key role in industry applications nowadays. The important advantages of the power electronic converters include efficient and reliable operation. The power density of the power electronic systems has continually been increased through operating frequency and the use of high performance ferromagnetic materials in high frequency transformers and inductors (Chudjuarjenn et al., 2010). Ferromagnetic materials are widely used as magnetic cores with the aim to concentrate on the strength and increase the effect of magnetic fields due to their high permeability. It is imperative for the circuit designers to be able to characterize the ferromagnetic materials of interest, especially the maximum flux density (B_m) and the maximum field intensity (H_m) which are frequency dependent. In order to meet the required operating condition, the suitable core must be selected. The use of low B_m materials may introduce the core saturation under specific operating condition while the use of high Bm materials are often discouraged due to its cost. In any case, the magnetic flux density must be less than the saturated magnetic flux density (B_{sat}). Operaing the magnetic core under the saturation region will cause damage in the component due to excessive current (Daut et al., 2013). Such parameters can be determined from the manufacturer's data. In many cases, the hysteresis loop provides additional information about the hysteresis loss related to the degree of saturation and operating frequency. In this paper, the measurement of hysteresis loop using the resonant inverter as a replacement of the costly power amplifier Daut et al. (2013) is proposed. The desired frequency and bias current can be controlled through the selection of resonant circuit parameters. In addition, the system implementation is easy and cost effective.

1.1 Conventional Measurement System.

The measurement system shown in Fig. 1(a) is composed of a controllable AC voltage source, a series resistor, a transformer with the test core, an R-C integrator and an oscilloscope (Chudjuarjenn et al., 2010; Daut et al., 2013). The magnetic quantities (H_m and B_m) can be determined through current and voltage measurements.

The magnetic circuit is excited by a frequency-variable voltage applied to the primary winding part of an RL circuit. The induced voltage is measured on the secondary winding through the RC integrating circuit, and the magnetic flux density can be determined. The waveform generator and a power amplifier are used as a controllable AC voltage source. Because the high-power linear

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19-21 November 2014, Bangkok, Thailand

amplifier is very costly, most designers tend to use the manufacturer's data.

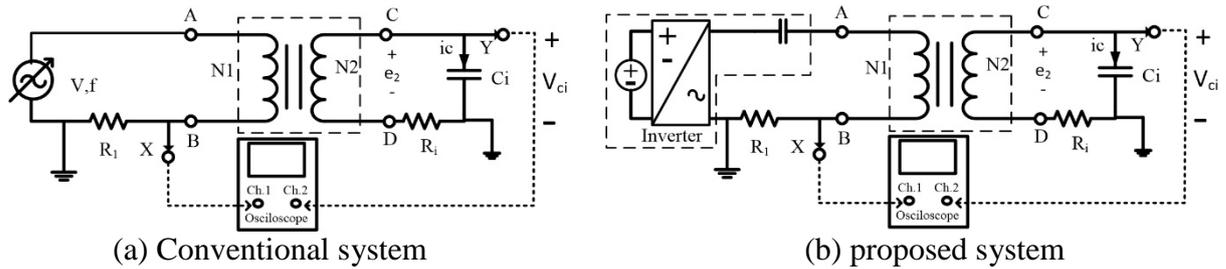

(a) Conventional system   (b) proposed system
Fig. 1 The hysteresis loop measurement system.

1.2 Proposed Measurement System.

The proposed measurement system shown in Fig.1-b), is composed of a DC voltage source, an inverter, a series capacitor, a series resistor, a transformer with the test core, an R-C integrator and an oscilloscope (Daut et al., 2013; Trans-Tech, 2007). The magnitude and frequency of the AC current for the hysteresis loop testing of the magnetic core can be controlled through the DC voltage source and the inverter, respectively. The magnetic quantities (H_m and B_m) can be determined through the current and voltage measurement. The current response of the square-wave input voltage source with the frequency approaching the resonant frequency of the RLC series circuit with high quality factor load is approximately sinusoid. This configuration allows an emulation of the targeted inductor's operating condition.

2. Magnetic Quantitative Calculation

The primary winding in Fig. 1 has N_1 turns. The magnetic field intensity is found as Trans-Tech (2007),

$$H(t) = \frac{N_1 i_{1(t)}}{l_a} \tag{1}$$

where l_a and $i_1(t)$ are the magnetic circuit mean length and exciting current, respectively. The current $i_1(t)$ can be measured of through the voltage across the sensed resistor (R_1). The maximum magnetic field intensity H_m is given as,

$$H_m = \frac{N_1 v_{R1,m}}{R_1 l_a} \tag{2}$$

where $v_{R1,m}$ is the peak value of the sensed voltage. The magnetic flux density (B) is found as,

$$B(t) = \frac{1}{AN_2} \int e_2(t)\, d\tau \tag{3}$$

where A is the cross sectional area of the core and e_2 is the secondary voltage. With a simple RC integrator circuit, the relationship between the capacitor voltage v_c and the secondary voltage e_2 are given as,
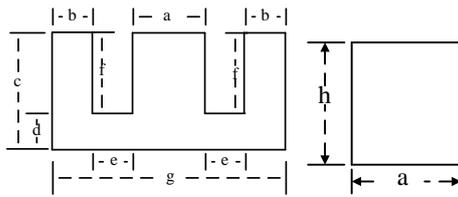
$$v_c = \frac{1}{C} \int_0^t \frac{e_2}{R}(\tau) d\tau \tag{4}$$

From (4) and (5), the maximum magnetic flux density (B_m)

$$B_m = \frac{RCV_{c,m}}{N_2 A} \tag{5}$$

Therefore, the B_m value can be quantitatively determined from the above relationships.

3. Experimental Setup and Result

To demonstrate the proposed method, an E-type ferrite core, shown in Fig. 2, is used as the test core with the following physical dimension. The averaged length of equivalent magnetic path (l_m) is 43.5 mm. and the average crosssectional area (A) is 475 mm^2. The inductor under test consists of 2 windings with 20 turns of 40*No.32 SWG litz wire and 15 turns of No.32 SWG wire. The latter winding of 15 turns serves as the secondary winding for induced voltage sensing. The parameter of the proposed mesurement system is shown in Table.1 where the resonant frequency is set at 1.08 kHz.

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Diamention	a	b	c	d	e	f	g	h
mm.	17	8.5	28	9	11	19	55	25

Fig. 2 Physical dimension for the core under test

Table 1 Measurement systems parameters

Equivalent inductance (L_{eq})	2.90mH	Equivalent resistance(R_{eq})	1.08Ω
Resonant capacitor (C_r)	7.5µF	Load quality factor (Q_L)	30.57

The inverter input voltage and the operating frequency are set to 7 V and 1.60 kHz, respectively. This is to avoid the hard switching operation. The hyteresis loop is measured through the waveforms of V_{ci} and V_{R1} as shown in Fig. 3. The calculated maximum magnetic flux density (B_m) is at 0.406 Tesla and the maximum magnetic field intensity (H_m) is 587.1 A/m from the peak values of V_{ci} and V_{R1}. (The Y-axis scale is 0.133Tesla/Division and the X-axis scale is 150.54 A/m/Division.) Next, the switching frequency is adjusted to 1.06 kHz while the inverter's input voltage is maintained at 7 V. As shown in Fig. 4, the maximum magnetic flux density (B_m) is 0.406 Tesla and the maximum magnetic field intensity (H_m) is 587.10 A/m. Evidently, the test frequency has an effect on the B_m and H_m values
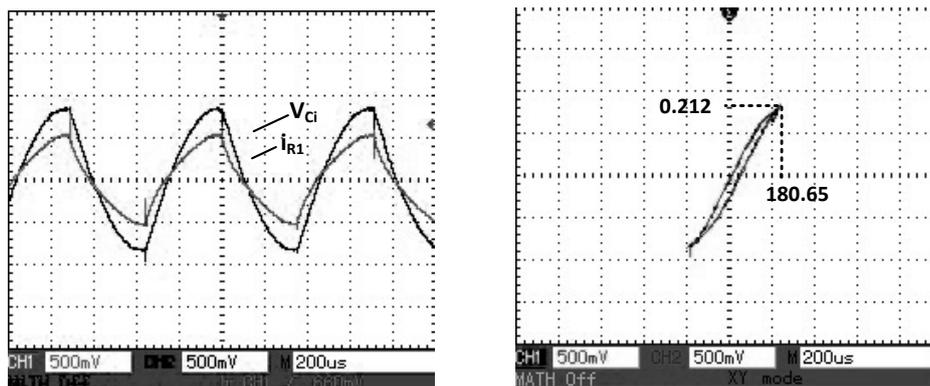

Fig. 3 experimental results of the below-saturation case with constant input voltage.
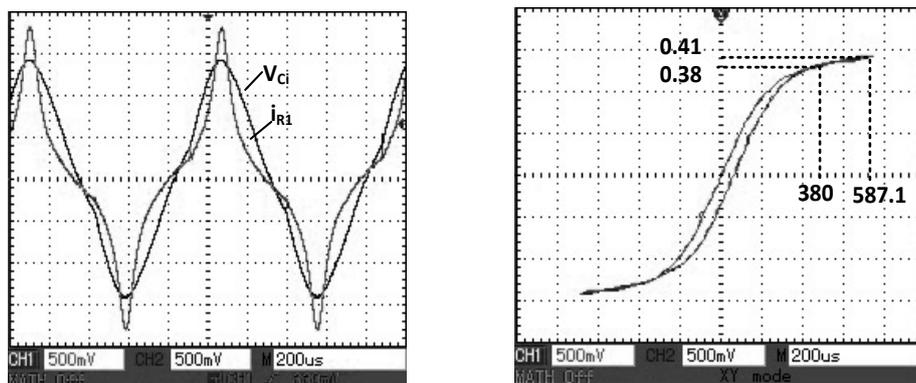

Fig. 4 experimental results of the over-saturation case with constant input voltage.

To illustrate the effect of the test current, the input voltage is varied while fixing the test frequency. With the input voltage set at 4.3 V, the test results are shown in Fig. 5. The B_m is at 0.266 Tesla and Hm is 193.55 A/m. By increasing the DC voltage to 6.3V. The scales on the Y and X axes remain the same. Note that the latter condition yields the saturated magnetic flux density. This again

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demonstrates the effect of the test current level on the ferromagnetic core. A comparison of measured values and the manufacturer's specifications are provided in Table 2. Where the results are close to the manufacturer data.
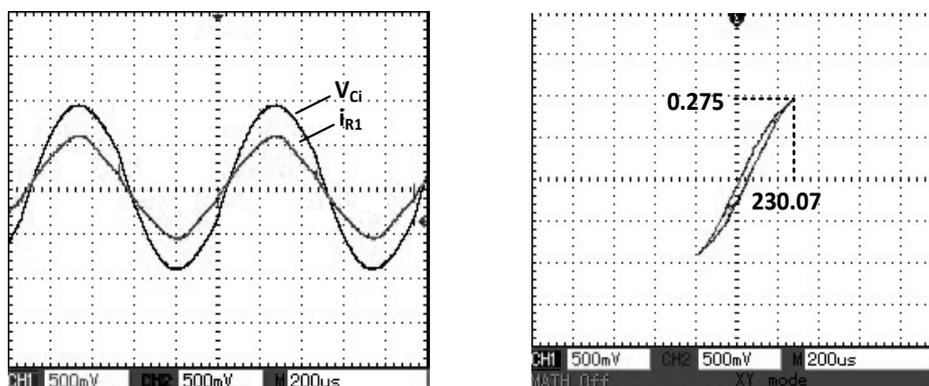

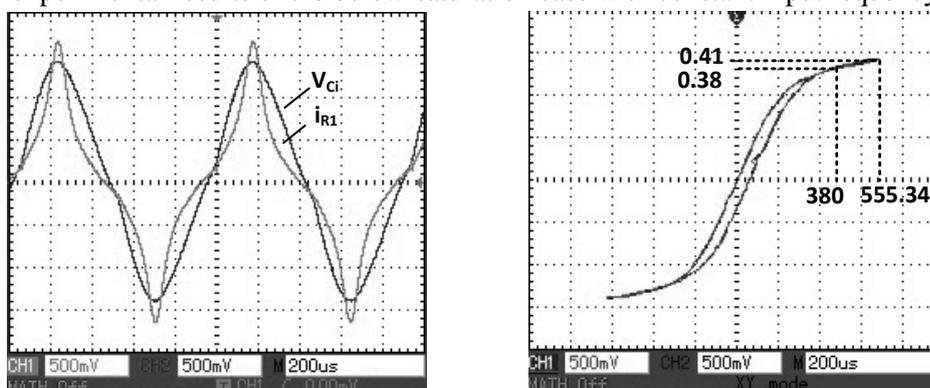**Fig. 5** experimental results of the below-saturation case with constant input fequency.

Fig. 6 experimental results of the over-saturation case with constant input fequency.

Table.2 Compare between measurements and manufacture data

Parameter	Average measurement result	Manufacture data
B_m (Tesla)	0.35	0.31
H_m (A/m)	490.5	496

4. Conclusion

An application of the cost effective series resonant inverter for hysteresis loop measurement of a ferrite core is present in the paper. The maximum flux density and maximum magnetic field intensity of the ferrite core can be obtained through variation of the bias current and frequency. The experimentally measured values has shown an agreement with the specifications from the manufacturer

5. References

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