INVESTIGATION AND DESIGN OF HIGH CURRENT SOURCES FOR *B-H* LOOP MEASUREMENTS

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Presented paper describes investigation and design approach for voltage controlled high current sources. The designed circuits are proposed for development of measurement system for B-H magnetic hysteresis analysis. Using the presented circuits and applying the concepts of virtual instrumentation, the laboratory experiments for investigation of ferrite torroids' parameters can be improved. In presented investigation two basic forms of voltage controlled current source using power operational amplifier are selected. The design process is accomplished using electronic design automation environments. Applying modern simulation technique, inductive load to test frequency transfer function is derived and presented graphically. Such design approach give opportunity to significantly simplify the design process, facilitate prototyping and reduce time-to-market in order to produce low-cost measurement systems or sensor platforms with fair metrological performances.

Keywords: *B-H* loop measurement, Ferrite toroidal cores, High current source, Inductive load, SPICE simulation.

1. INTRODUCTION

The magnetic induction, B, of a ferromagnetic material can be described as a function of the applied external magnetic field, H. As a result a *B-H* diagram or hysteresis loop is achieved. There are a number of parameters that can be determined from the *B-H* loop measurement [1, 2]. At the beginning, the magnetic induction starts from zero at zero magnetic field. When the external magnetic field reaches a maximum value, all the material forms a single domain having a net maximum magnetic induction value called the saturation magnetic induction, B_S. At zero magnetic field ($H = 0$), magnetic domains tend to reappear slowly, and there remains inside the material a residual magnetic induction, called remanence or remanent magnetic induction, B_R. The maximum residual magnetic induction when materials are fully magnetized is called the retentivity. This is the most recognized property of ferromagnets. In order to remove the retentivity of the materials completely, it is necessary to apply an opposite magnetic field called coercivity or coercitive force or coercitive magnetic field strength, H_C. Reversing the magnetic field leads to the completion of the *B-H* curve. The entire curve is called the hysteresis curve or loop. Therefore, magnetic properties of ferromagnetic materials are entirely described by the parameters B_S, B_R and H_C. To identify the hysteresis parameters, it is necessary to measure *B-H* characteristics as great accuracy as possible.

Many laboratories still use old swept sine measurement systems consisting of separate standalone hardware (sine generators, oscilloscopes, etc.) linked together by set of cables. In this traditional hardware-based test system, a sine generator performs a continuous sweep through the amplitude range of interest. The investigated ferromagnetic material usually has toroidal shape because toroids provide a convenient and very effective shape for many wide band, pulse and power transformers and inductors. The examined material contains two coils. The first coil is the excitation coil, which is controlled by the sine generator. The amplitude of excitation current in traditional systems is measured as a voltage of shunt resistor. The value of this resistor must be kept small in comparison with the inductive reactance of the wound sample. The second coil is used for measuring the induced voltage of coil. Flux density of the cores is determined by integrating the secondary voltage using the *RC* circuit. The excitation and induced voltages on the measuring coil usually are observed by two-channel oscilloscope. The curves depicted in oscilloscope's tube are converted in scale to *B*-*H* curve according appropriate equations [1, 5, 6].

Disadvantages of these traditional measurement systems are low resolution, impossibility to compare the loops of different materials in the same time, unattractive visualization, necessity of mathematical calculations, the equipment complexity etc.

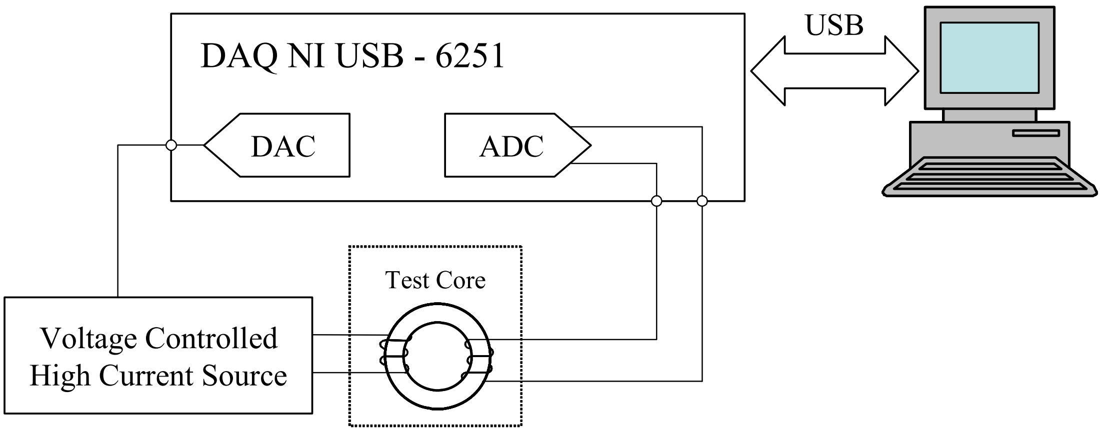

Fig. 1. The block diagram of *B*-*H* loop measuring system

The purpose of presented investigation is to design and develop a high current voltage controlled current source intended for *B*-*H* loop measuring system, based on virtual instrumentation. The block diagram of a proposed system is shown in fig. 1. The multifunctional data acquisition board is controlled by computer platform with appropriate device drivers and application development environment. This approach is used for programming the digital to analog converter (DAC) as waveform generator to produce the sinusoidal voltage signal with the frequency range from 1 Hz to 200 kHz. Then, it is converted to high current by the voltage-controlled-current-source (VCCS). In presented investigation power operational amplifier application circuits is selected to make the bridge between the low-voltage, low-current output from a DAC and the high current or high voltage required by the output devices. The analog to digital converter (ADC) is used for measuring the induced voltage of secondary coil. Flux density of the cores is determined by software integration of the secondary voltage. Such approach eliminates necessity of additional shunt resistor and *RC* circuit.

In the presented paper is considered the use of modern integrated power amplifiers [7] for driving the high current for inductive loads in order to achieve suitable and informative families of *B-H* loops.

2. VOLTAGE CONTROLLED CURRENT SOURCE WITH FLOATING LOADS

Voltage controlled current sources are useful for applications such as active loads for use in component testing or to drive excitation current in inductive loads. Achieving *B-H* loops by driving current in excitation coil of toroids is simplified since current is a direct function of magnetic field, *H*. There are two basic forms of VCCS's using power operational amplifiers, depending on whether or not the load needs to be grounded.

The basic circuit of an inverting VCCS for a floating load is shown in fig 2. The advantage of VCCS with floating load is absence of any common mode variation at the amplifier input, higher accuracy and lower distortion. The load is actually in the feedback path and a current sense resistor R_S develops a voltage proportional to load current. The input voltage results in an opposite polarity of current output according the equation [5]:

$$I_{out} = -\frac{V_{in}}{R_S}\frac{R_2}{R_1} \qquad (1)$$

for $R_S << R_1$ and R_2.

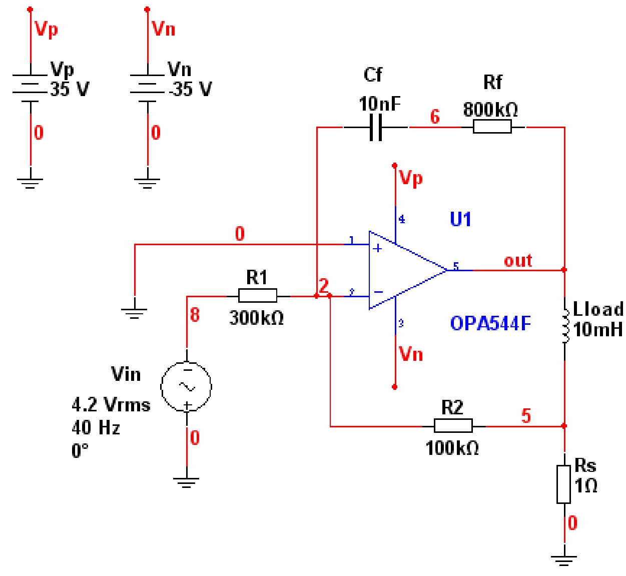

Fig. 2. Inverting VCCS with floating load

The output current of the designed circuit is changed from 0 A to 3.3 A, when the controlled voltage vary from 0 V to 10 V.

For high current and high voltage applications safe operating area (SOA) of the amplifier must be take into account. The SOA from amplifier's datasheet [7] shows the permissible range of voltage and current. If voltage and current exceeds the SOA limits for OPA544 it will activate the thermal shutdown circuit. Therefore in this case is necessary to do heatsink calculations and to use good mounting practices [5].

In this circuit the inductive load is in the feedback loop, and it will have a significant effect on stability. Because current lags voltage in an inductor, current feedback is delayed and thus decreases the phase margin of the current amplifier. Consequently, ringing or oscillation occurs.

In presented study stability analysis is accomplished using "Rate of Closure" techniques where the response of the feedback is plotted against the amplifier open loop gain [5]. This technique uses information easily obtained on any amplifier data sheet. In the circuit from fig. 2 to provide compensation feedback, additional components $R_f = 800\ \text{k}\Omega$ and $C_f = 10\ \text{nF}$ have been selected following the consideration and recommendations from reference [5].

To calculate the maximum value of the inductive load the following relationships are used:

$$Z_{L\max} = \frac{V_{out\ \max}}{I_{out}} - R_S \text{ and } Z_{L\max} = 2\pi f L_{load}\ , \qquad (2)$$

where f is the frequency of the output current I_{out}, $V_{out\ \max}$ is the maximum output voltage of the power amplifier (for OPA544 $V_{out\ \max} = \pm 30$ V at $V_S = \pm 35$ V) and L_{load} is the inductance of the load (investigated ferrite material).

In order to choose the appropriate range for investigated load inductance it is suitable to use the data, from catalogues of the modern manufacturers of high quality magnetic materials and components [3, 4]. In these catalogues more manufacturers used the parameter inductance factor (A_L) or a constant for a given geometrical shape that when multiplied by the square of the number of turns, gives the inductance in nH. Initial permeability of the ferrite core is assumed in the inductance factor.

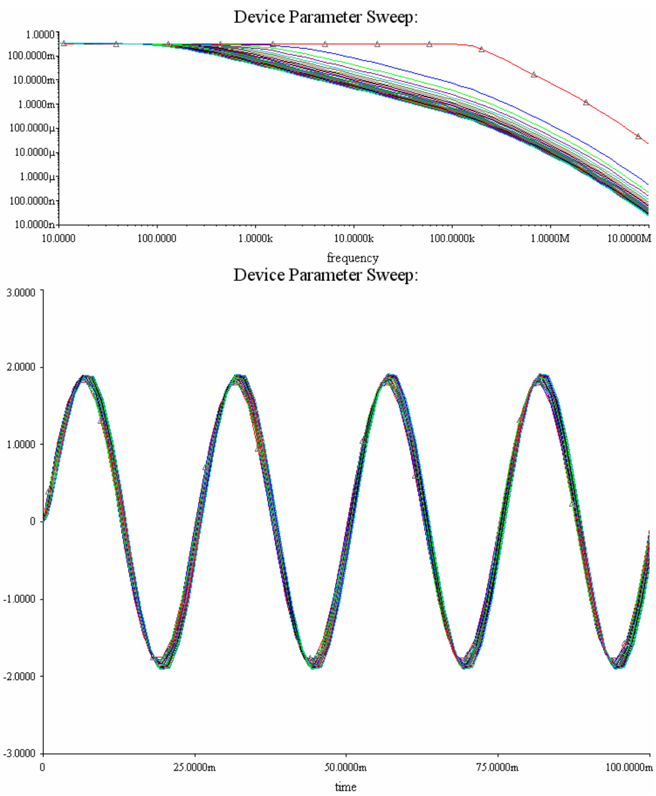

Fig. 3. Simulation results for VCCS with floating load

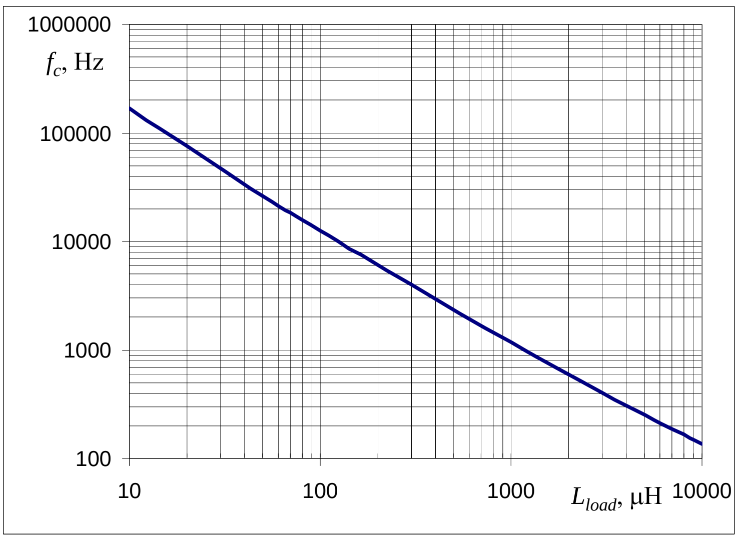

Fig. 4. Simulated L_{load} to cut-off frequency f_c function for inverting VCCS with floating load

The maximal inductance factor given in catalogues is $A_L \approx 20000$nH/turn. This mean that if the turns of the excitation coil are 10 (this is standard value for *B-H* loops investigation), then the maximum $L_{load} \approx 2$ mH.

The results of the frequency and time domain simulation of the circuit are shown in fig. 3. These graphics are obtained for the inductive loads from 10 μH to 10 mH. As can be seen the current source is stabile and the output current is not depending of the load.

In the fig. 4 is shown function of simulated L_{load} versus cut-off frequency f_c. This curve and equation (2) are suitable for determining appropriate test frequency for the different inductive loads and ferrite cores.

3. IMPROVED HOWLAND CURRENT PUMP

The VCCS for a grounded load often is referred to as the "Improved Howland Current Pump". It is actually a differential amplifier which senses both input signal and feedback differentially. The improved Howland current pump uses the differential capabilities of the operational amplifiers to detect the voltage across the sense resistor R_S, and use that to control the current flow through the load.

The schematic diagram of improved Howland circuit is shown in fig. 5. The necessary relationship between the values of the resistors is [8]:

$$R_3.R_4 = R_1.(R_2 + R_S) \text{ or} \qquad (3)$$

if $R_S << R_2$ then $R_1 = R_3$ and $R_2 = R_4$.

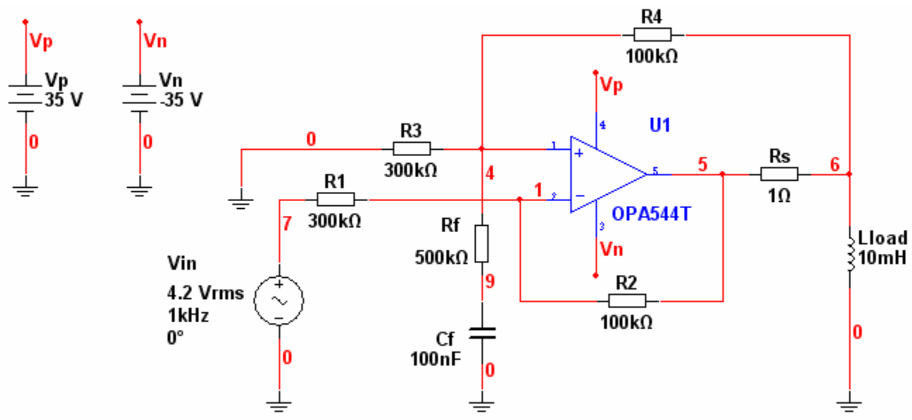

Fig. 5. Improved Howland current pump

The special considerations for this circuit are that the two input resistors (R_1 and R_3), and the two feedback resistors (R_2 and R_4), must be closely matched. Even slight mismatching will cause large errors in the transfer function and degrade the output resistance causing the circuit to become less of a true current source.

The output resistance is obtained from equation [8]:

$$R_{out} = \frac{R_1 R_S (R_1 + R_4)}{R_1 R_2 - R_1 (R_2 + R_S)}. \qquad (4)$$

The ideal output resistance will approach to infinite. That is to say, the performance of current source may be very good for measurement applications.

Any stability problems that do arise are likely to be a result of the output impedance of the circuit appearing capacitive. This capacitance can resonate with inductive loads, resulting most often in ringing problems with rapid transitions. The only effective compensation is a simple "Q-snubber" technique [5, 8] that determines the resonant frequency of the inductive load and output capacitance of the circuit.

An infrequent second cause of instability in this circuit is due to negative resistance in the output impedance characteristic of the circuit. This problem can be solved by trimming the feedback resistors to improve matching [5, 8].

It can be seen that if the ratio (3) is carry out, the equations for the transfer function and the maximum inductive load of the VCCS with grounded loads are identical with these of the VCCS with floating loads and are given by (1) and (2). The circuit simulations, give identical results also (fig.3 and fig.4).

4. VOLTAGE CONTROLLED VOLTAGE SOURCE

For completeness of presented investigation should be noted that good results for *B-H* loops measurements can be achieved with voltage controlled voltage source - fig. 6. This circuit is more stable for wide frequency range than VCCS's. The main disadvantage of voltage source is the necessity of measuring the excitation current with appropriate shunt resistor R_{SH}.

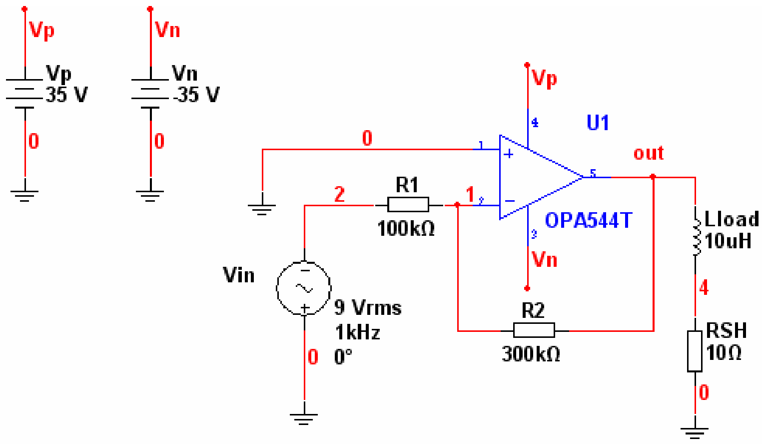

Fig. 6. Voltage controlled voltage source

5. CONCLUSION

The presented design of two voltage controlled current sources for *B-H* loops measurement based on power operational amplifier, offers single amplifier circuits for cost-sensitive applications. Presented design approach and considerations can significantly simplify the design process and facilitate prototyping of high current sources. Implementation of the presented circuits and application of the concepts of virtual instrumentation give opportunity for engineers and scientifics to build flexible and accurate measurement systems for various laboratory experiments. Designed circuits can be used for different applications concerning investigation of ferrite materials, or physical phenomena observing by magnetic and inductive sensors.

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