

Generating bipolar magnetic fields by using unipolar power sources

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A low cost current inversion system is presented as solution to achieve bipolar magnetic fields through a series array of analog programmable unipolar power sources. The system is based on a digital signal controller to provide an accurate zero-crossing detection of the voltage supplied to a commercial electromagnet, and a polarity inversion system composed of a set of switches in H-bridge configuration and optical isolators. Furthermore a stage of magnetic uncoupling is performed to generate a pair of independent signals to drive each power supply. In general the system have shown be able to generate fine and coarse magnetic field sweeps, which can be used to conduct studies of basic science or academic works in a physics laboratory, bypassing the absence of an expensive bipolar power source.

Keywords: Magnetic field; zero crossing; power inverter.

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1. Introduction

Between the large number of essential devices within a physics laboratory, a bipolar magnetic field generator is quite a versatile tool, it allows a wide variety of experiments such as magnetophoresis assays [1-3], vibrating sample magnetometer (VSM) [4-6] and ferromagnetic resonance (FMR) [7], among many others including all teaching applications [8-10]. Particularly the magnetophoresis and VSM techniques involve a coarse range of magnetic field application, in contrast with FMR which could to require finest sweeps of intensities. However, most of the commercially available devices for these applications require a bipolar power supply (BPS), capable of drive a high electric current into a configuration of Helmholtz coils with low impedance. This power supplies are at least difficult to acquire and they flaunt a high price, because they are specially designed for particular applications.

A sweep of magnetic field could be easily generated using a programmable unipolar power supply (UPS) by feeding an alternant triangular signal, with another analog power supply of low power, but the automatic inversion of its polarity is not a trivial fact. Nevertheless the BPSs do not meet any complication to invert it, because they work similarly to an audio amplifier [11]. For a best illustration of these statements the Fig. 1 illustrate the working of a programmable UPS and a BPS, both controlled with the same triangular alternant analog signal of very low power. In this figure the output signal (high power) of the UPS does not contains negative values, unlike the BPS which amplifies the control signal.

A voltage inverter (VI) connected to an UPS is an attractive choice to obtain electric currents in both senses (i.e. bipolar magnetic fields) and by attaching an automatic controller to detect the zero volts crossing on the load, it can works similarly to a BPS. Indeed, the VIs are very used to obtain AC through a DC power source since this circuits can be designed

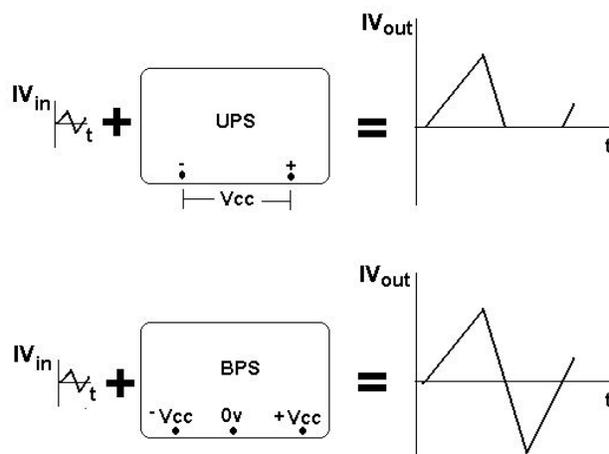


FIGURE 1. Illustration of the working of a programmable UPS and a BPS controlled with an input signal of low power (IV_{in}) and their output signal of high power (IV_{out}).

for several applications *e.g.*, motor driving, no-break systems, switching power supplies and induction heating devices [12-18].

A standard VI is composed of a whole H-bridge configuration, whose basic architecture uses four power switches (either semiconductors or mechanic relays) as is described in the Figs. 2a), b) and c). These kinds of circuits are a common exercise in any instrumentation lab. The Fig. 2a) shows the basic operational states of a generic full H-bridge, first, at the *OFF-state* the four elements connected to the terminals of the load keeps any current flow blocked and therefore, no current flow is produced. When the H-bridge is commutated to the *Forward-state* Fig. 2b) the elements $S1$ & $S4$ goes to full conduction (saturation in the case of using semiconductors) and $S2$ & $S3$ are open, then a current flow through the load in one sense with a voltage polarity. The final configuration is called the *Reverse-state* Fig. 2c) with the elements $S1$ & $S4$

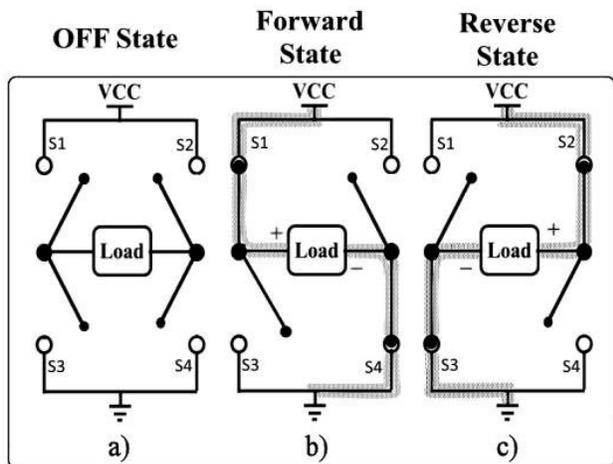


FIGURE 2. Schematic diagram of a full H-bridge in a) *OFF-state*, b) *Forward-state* and c) *Reverse-state*.

opened (cutoff) and the elements *S2* & *S3* get closed, then the current flows through the load in another sense with the voltage polarity inverted. It is of utmost importance to return to the *OFF-state* before a transition between *Forward* and *Reverse-states*, otherwise any conduction between the elements *S1* & *S3* and/or *S2* & *S4* represents a short circuit to the power supply. Furthermore, if the powered load for the VI of the Figs. 2a), b) and c) is a single coil or electromagnet, the sense of the dipolar magnetic field generated could be selected through the forward or reverse states of the VI. Indeed the quadrupolar magnetic field is a common alternative in physics labs to obtain regions of uniform magnetic fields.

The aim of this work is to present a simple alternative to obtain bipolar sweeps of magnetic field using UPSs by connecting a VI, which is controlled with a digital signal controller (DSC) and sensing the voltage of the coil. With this setup is possible to develop other experimental assemblies, for example VSM, FMR or other experiments avoiding the use of an expensive BPS.

2. Materials and methods

We have used two programmable UPSs in series configuration (of EMI company) TCR-20S30 and TCR-40S45, to increase the maximum voltage capability to 60 V with maximum current of 30 A. The main problem with this selection is the requirement of two identical control signals with independent floating ground to each UPS. In order to solve this fact, the control signal is duplicated by feeding a solenoid to generate a weak linear magnetic field, which is measured with a pair of Hall Effect sensors (HFS, as will be explained widely in the Sec. 2.2). Each signal of these sensors is amplified to sweep a ramp or triangular output voltage for both UPSs, to feed a VI connected to a Helmholtz electromagnet of Walker Scientific company, with 1.8 Ω of resistance, which is designed to drive up to 1.25 kW to obtain an uniform magnetic field of ± 1 T (10 kG). The control signal could be developed using a function generator or a regulable DC power

supply, in this work the triangular output of a VSM controller Lakeshore 7300 is used.

2.1. Voltage inverter and DSC

Regarding the resistance of the electromagnet, with a straightforward application of the Ohm’s law, the maximum ratings of current and voltage to be handled by the VI are given for the Eqs. (1) and (2).

$$I = \sqrt{\frac{P}{R}} \tag{1}$$

$$V = \frac{P}{I} \tag{2}$$

Based on these ratings and since we are particularly interested in experiments which involve very slow sweeps of magnetic fields or quasistatic fields, then the power commutation elements chosen for this application are four low cost electromechanical relays (EMR) HAT902ASDC24 (*S1*, *S2*, *S3* and *S4*) capable of handle up to 30A. The Fig. 3 shows the electronic schematic of the actual VI, where is also ob-

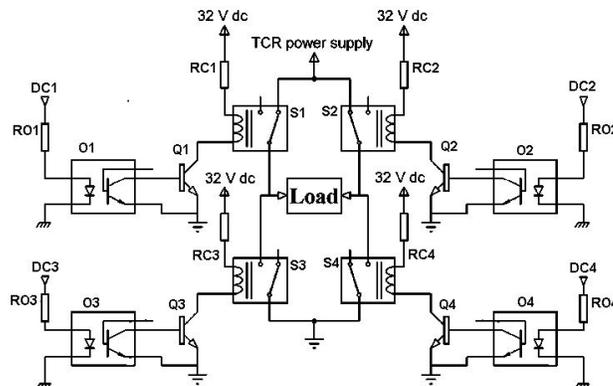


FIGURE 3. Power inverter schematic of the VI.

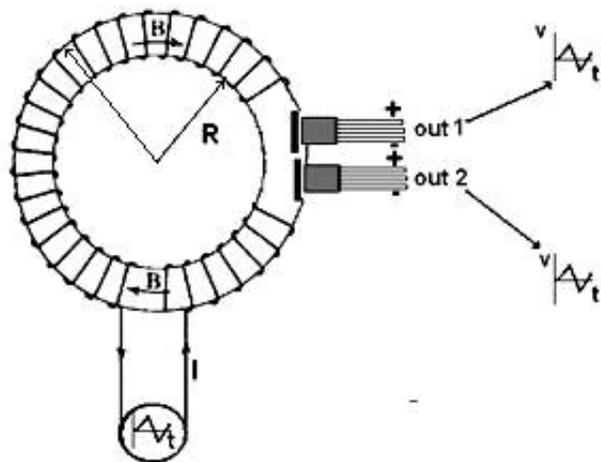


FIGURE 4. Scheme of the uncoupling procedure of the control signals to each UPS, a signal feed the coil and two signals with the HFS placed inside of its core.

served a set of four opto-transistors 4N25 (O1, O2, O3 and O4; one for each relay) to isolate the low power stage (digital control signal) of the one of high power. The VI is powered by the series array of UPSs and the activation of each opto-transistors is carried out using one digital output of a DSC (DC1, DC2, DC3 and DC4), with resistances $R01 = R02 = R03 = R04 = 330 \Omega$. Complemented with a current pre-amplification stage using Darlington NPN transistors TIP-120 (Q1, Q2, Q3 and Q4), powered with 32 V to ensure the fully activation of the EMR and including resistances in their collectors terminals $RC1 = RC2 = RC3 = RC4 = 1 \text{ k}\Omega$.

2.2. Analog control signals uncoupled

As was mentioned earlier, the analogical control signal of each UPS requires an independent floating ground reference, but we are using only a signal from the VSM controller. To solve this requirement, a magnetically decoupled interface is designed, which is composed of a small toroidal solenoid of 90 turns rolled on a nucleus of ferrite (recycled from a PC power supply), with inner diameter = 46 mm, external diameter = 89 mm, inductance = 6.75 mH and resistance = 1 k Ω . This coil is connected to the VSM controller to generate a weak linear magnetic field inside. The core has two small holes to place two HFS in order to detect the magnetic field; each sensor is powered with separated voltage sources of $V_{cc} = 8 \text{ V}$, as is shown in Fig. 4.

The signal of each HFS model SS495 is amplified using four stages of amplification with low cost operational amplifiers TL071, as is displayed in the Fig. 5. The first one contains a buffer amplification or follower (upper dashed rectan-

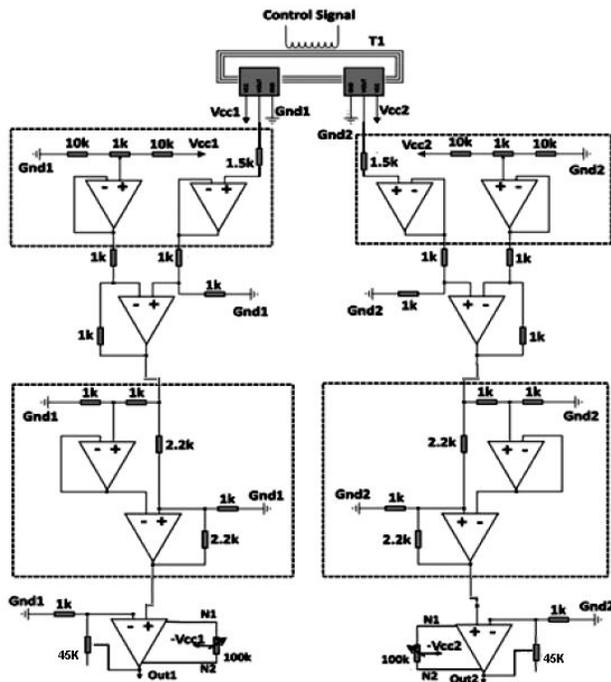


FIGURE 5. Schematic diagram of the decoupling interface for analog control of the power supplies series array.

gle) of the HFS outputs and a follower amplification of a DC constant signal using a resistances based voltage divider, to reach an output offset of $V_{cc}/2$ volts. These followers are connected to a differential amplification with unitary gain and its output feeds a full wave rectification circuit (lower dashed rectangle), composed of two operational amplifiers [19], since the UPSs admits a positive control signal only (see Fig. 1), this rectification is very important because this work is mainly based in the detection of the zero Volts on the load, to commute the polarity of the VI (see Fig. 3). The last stage is a non-inverting amplification with gain $G = 46.0$ given by Eq. (3), able to adjust its offset output remainder using a 100 k Ω potentiometer connected to its offset null terminals (N1 and N2).

$$G = \left(1 + \frac{R_g}{R}\right) = \left(1 + \frac{45 \text{ k}\Omega}{1 \text{ k}\Omega}\right) \quad (3)$$

Additionally the amplitude and period of the output signals can be fixed setting with the VSM controller, it drives a triangular signal with maximum output amplitude of 10 V and the final output of the decoupling interface do not reaches more than 5 V, this is the maximum value permitted for the UPS array to obtain a maximum value of 60 V on the electromagnet. The maximum noise level observed after the amplification is 20 mV of amplitude.

2.3. DSC driver

The DSC employed in this work is an integrated circuit *dsPic33FJ128MC802* of Microchip company and their algorithm embedded is summarized in the flow diagram of the of the Fig. 6, where the first action is to prevent any short circuit and current flow by commanding a commutation to

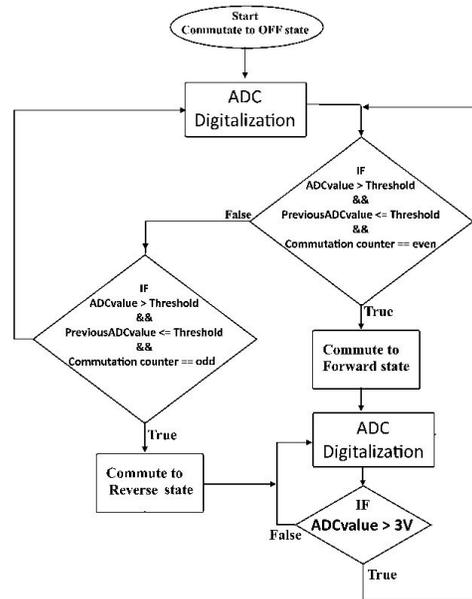


FIGURE 6. Flow diagram of the main program for the intelligent Zero Crossing detection and polarity inversion.

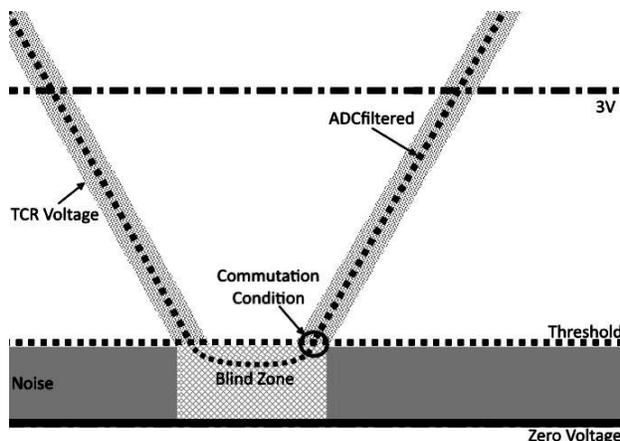


FIGURE 7. Zero Crossing diagram and commutation condition.

the *OFF-state*. Next an analog input of the DSC is used to digitize the voltage across the electromagnet coming from the UPSs. Assuming 50 V as the maximum voltage value to feed the electromagnet (see Eq. (2)), a voltage divider is used with a potentiometer to limit the analog input in the range of 0 to 3 V to be digitized with 12 bits of resolution through the DSC, which is powered with 3.3 V, then the minimum resolution of the measurement is of 0.8 mV.

The acquired values are sampled with a frequency of 300 S/s and stored in a linear array data, to obtain its mean value which is assigned to a variable called *ADCvalue*, this procedure works like a filter of the signals, later is compared with a constant *Threshold* value defined as the lower voltage amplitude that can be consider as signal, the noise level coming from the UPSs only allows 10 mV. However this *Threshold* value depends on the stability and filtering of the particular UPS.

As the DSC detects the zero crossing of the voltage sweep to select the polarity of the VI, this zero crossing condition is displayed in the Fig. 7, since a certain level of noise coming from the UPSs is always expected even when is commanded to zero voltage output, then a *Threshold* level is established over which it can be separated the signal from the noise. Once the *ADCvalue* overcomes the *Threshold* level and if the previous *ADCvalue* is below the *Threshold* (*Blind Zone*), a commutation to conduction is established, the resultant polarity depend on the even-odd state of a counter variable (*Forward* if the counter variable n is even, *Reverse* if n is odd). In order to ensure that the intrinsic noise of the UPS or inductive kicks coming from the load do not be mistaken as commutation orders, once the commutation is done, the DSC keeps tracking the *ADCvalue* value and do not allow a new commutation until the voltage has overcome a prefixed DC level, far enough from the *Threshold* level, close to 3 V (See Fig. 7).

3. Results and discussion

After the electronic work, the driver signals of each power supply are tested using the output of the VSM controller, pro-

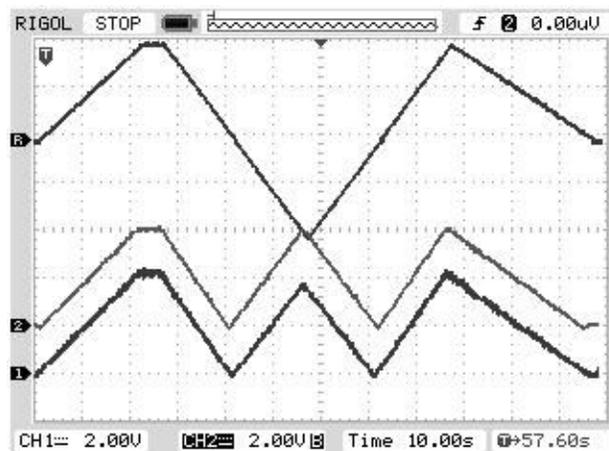


FIGURE 8. Control signal coming from the VSM Controller (upper reference 5V/Div) and the two rectified outputs of the decoupling interface with floating ground isolation (lowers 2V/Div).

viding 10 V of amplitude to the solenoid of Fig. 4. In the Fig. 8 are displayed in the lower part two identical triangular-like signals along 2 min, with 2 Volts of amplitude and offset values (amplitude = 4 Volts in total), *i.e.* the negative values are shifted up due to the full wave rectifier stage. However the output of each power supply is proportional to their driver signal, but regarding the series array of EMI sources feeding the VI, which is controlled by the DSC, an alternant triangular signal with 8 V of peak to peak amplitude is obtained as output, indeed the signals do not have the first peak, being a spurious mistake of the VSM controller. In this experiment is used a resistance of 1 Ω designed to support up to 1 kW and the signals are acquired using an oscilloscope Rigol mod. DS1102E, through a flash memory via USB. Clearly the DSC have commuted the polarity of the voltage and are not observed spurious or artifacts in the curve, additionally is very important to observe a non-magnetic saturation of the core, to maintain the triangular shape of the signals, but if this fact is present could be easily solved connecting a resistance in serie with the turns of the toroid to limit the current and their magnetization.

Once the control signals are properly matched to the power supplies and the power inverter can drive power to the load with both polarities, the resistance is replaced for the Walker Scientific electromagnet, to perform fine sweeps of magnetic field. Furthermore, the Fig. 9a) shows the output voltage half-wave rectified of the EMI sources array, sensed at the input of the power inverted along of 6 min (upper triangular signal). In this case the maximum amplitude obtained from the amplifier is 0.16 V and again a triangular alternant output signal of the current is observed crossing the electromagnet, with a maximum power consumption of 2 W, due to a maximum current of 1.1 A (lower triangular signal). The current is sensed using a Hall current probe Tektronix A6303 connected to the oscilloscope. The distortion due to the blind-zone inherent to the noise of the power supply is about almost negligible even at this fine sweep. In this experiment the maximum range of magnetic field B , measured using the trans-

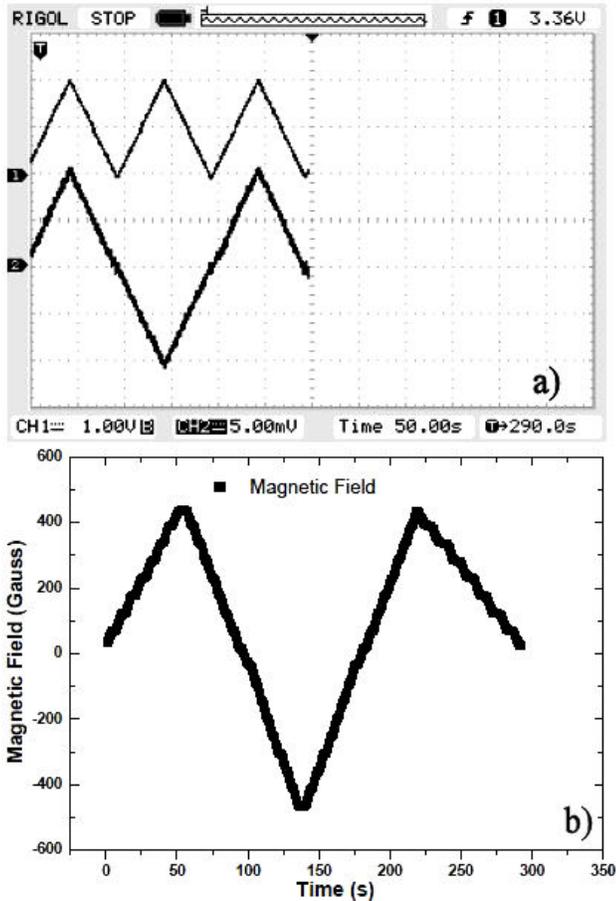


FIGURE 9. a) Output Voltage of the TCR series array (upper 1 V/Div) and the corresponding current signal at the terminals of the electromagnet (lower 5 mV/Div = 0.5 A/Div) for a fine sweep and b) its corresponding magnetic field curve.

versal probe of the Gaussmeter Bell 5180 placed on its homogeneous region, is approximately ± 430 G as is displayed in Fig. 9b), where is observed a little of distortion due to the signal to noise ratio of the uncoupled signals. This amplitude is a typical sweep range of magnetic field used in FMR or EPR studies, in order to diminish magnetic remanence in the materials, or well to discover their gyromagnetic factors in a segment of the spectrum.

Following with the characterization of the system, the Fig. 10a) shows a coarse sweep with a maximum power consumption of 1.1 kW due to a maximum current of 22 A (lower triangular signal) provided to the electromagnet and sweeping a maximum voltage of 48.5 V (upper triangular signal), while the maximum amplitude obtained from the amplifier is 4.0 V, so the corresponding maximum range of magnetic field **B** measured is approximately ± 9.2 kG. Indeed the Fig. 10b) display the curve of magnetic field obtained from the PC using the Gaussmeter and a small artifact is observed around of $B = 0$, due to the blind zone and the delay to satisfy the commutation condition (see Fig. 7), nevertheless there is not distortion in the curve in contrast with the one of the Fig. 9b). This sweep range of magnetic field could be useful for ex-

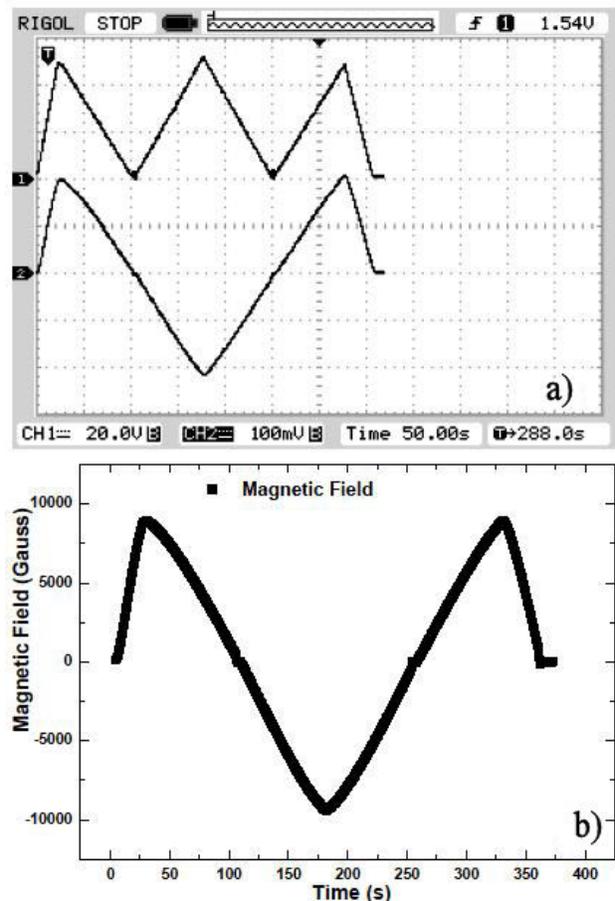


FIGURE 10. a) Output voltage of the TCR series array (upper 20V/Div) and the corresponding current signal at the terminals of the electromagnet (lower 10A/Div) for a coarse sweep and b) its corresponding magnetic field curve.

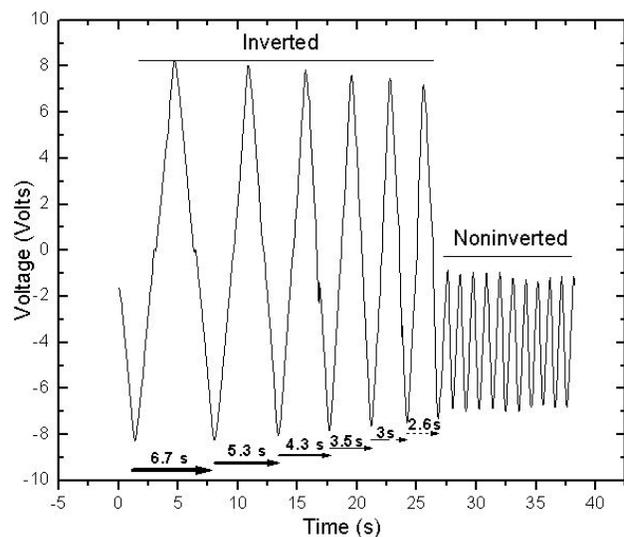


FIGURE 11. Output voltage inverted in a several range of sweeping times.

ample to magnetize diamagnetic, paramagnetic or ferromagnetic samples in order to determine their magnetization curve or well their magnetic susceptibilities.

Furthermore, a set of sweeping times with fixed amplitude are programmed to the device with the aim of analyse the minimum sweep time, or well, the minimum response time of the complete system. This is very important because it is restricted due to the sampling frequency of the DSC driver, also the high capacitance of the power supply and principally the slow time of operating/release of the mechanical relays of the VI. In the Fig. 11 are displayed the waveforms and is observed a correct performing in the commutation of the voltage when is sweeping along of 6.7, 5.3, 4.3, 3.5, 3 and up to 2.6 s, nevertheless the system does not invert the voltage when is programmed time intervals smaller than 2.6 s. In contrast, the system is not restricted to work in ranges of sweeping times higher than this value. Another effect observed in the Fig. 11 is the diminishing of the amplitude when the sweeping time decreases below 6.7 s, this is due to the charging time of the capacitors of the UPS, but it can be easily compensated by increasing the input signal to the driver of Fig. 5. In largest sweep times as the used in the Fig. 9b) and Fig. 10b), this behaviour is never observed and clearly it depends of the kind of UPS employed.

Summarizing the results, the system have shown be able to generate fine and coarse intensities of magnetic fields sweeps, which make it possible to conduct studies of magnetic properties of materials, in several scales of magnetic field intensities. More tests were realized in minor intensity ranges but the distortion of the curves is increased. In fact, the sweeps could be finest by diminishing the noise of the driver signals, for example including several analog or digital filters in the amplifier circuits of the Fig. 5. Moreover, according the Fig. 11, the minimum time of sweep the magnetic field of the complete system is up to 2.6 s.

4. Conclusions

In this work was introduced a versatile and low cost device which can be adapted to any UPS, in order to replace the use

of an expensive BPS. Indeed the device was performed to be used with a programmable UPS but is not restricted to be adapted to others in any presentation, such as: manual, adjustable, fixed, commuted, etc [20]. Moreover with a suitable control signal the system allows continue using it of unipolar manner. The device has been tested using a commercial electromagnet to generate magnetic field sweeps in fine and coarse ranges (± 0.43 kG and ± 9.2 kG respectively), thus these features indicate the possibility of be used to conduct studies of basic research or academic purposes in a laboratory of physics. Additionally, is studied the minimum sweeping time of magnetic fields of the complete system, due to the slow response time of some components, principally the relays of the VI and the charging time of the capacitors of the UPS. The observations realized indicate that the minimum sweep time of the device is 2.6 s and this is not restricted to sweep magnetic fields in time intervals higher than this value. This fact is a disadvantage intrinsic to the system which is not expected be observed in a BPS.

On the other hand, the system was realized using a programmable digital signal controller with a special embedded algorithm, but this component could be easily replaced for a commercial card with digital and analogical inputs and outputs from a PC, for example: the DAQ cards of National Instruments and Labview. This inverting system and controller could be reproduced with a cost of 80 US\$ approximately, but this value depends of the kind and capability of the switch of the VI. Indeed, the array of UPSs and its controller can be increased easily to fit with the needs of the user. Currently is used in our biophysics laboratory to conducts studies of characterization of magnetic properties of solid and liquid materials [21] by VSM. Moreover also can be used in industrial applications: for example to drive motors or fluids in both senses.

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