DESIGN AND ANALYSIS OF SECOND HARMONIC MODULATOR FOR DC CURRENT TRANSFORMER

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Abstract

DC Current Transformers (DCCT) are widely used in particle accelerators. DCCT is a device which produces even harmonics, predominantly second harmonics corresponding to DC beam current flowing through two toroids. The second harmonics is detected by digital synchronous detector implemented in programmable logic. Current proportional to the detected second harmonic is passed through the toroids in a feedback loop such that the flux due to the DC beam current is cancelled by it. This feedback current is the measure of average beam current. The high permeability toroid's, excitation and output windings are collectively called magnetic modulator, which is a key component of DCCT. Design and analysis of a second-harmonic magnetic modulator used as a detector for DC Current transformer for high resolution current measurement is presented.

INTRODUCTION

Ion current in a particle accelerator is a key performance measurement parameter. Based on the requirement of a particular experiment various configurations of the particle beam are required, thus the characteristics of the beam are different for these configurations. In order to have a measure of performance the average beam current forms a useful parameter for measurement. DCCT is non-destructive current measuring instrument in particle accelerators which can be calibrated. We have been involved in a project of technology development for Accelerator Driver Subcritical Systems [1] and as a part of development of high resolution DCCT, a second harmonic magnetic modulator for DCCT was designed and implemented. The following sections describe principles of second harmonic magnetic modulator. Processing algorithm was implemented in programmable logic. Experimental results of the magnetic modulator in a feedback loop have also been presented.

SECOND HARMONIC MODULATOR

A second harmonic magnetic modulator in its simplest configuration consists of a single high permeability toroid core with excitation and output winding. The particle beam current through the core is considered as input signal. If the toroid is excited to saturation by an anti-symmetric waveform, the resulting magnetic flux and hence the signal induce in the output windings contains fundamental and odd harmonics of the excitation frequency. When a dc current is passed through the toroid, even harmonic contents also appear in the output. The main disadvantage of this configuration is the presence of large amount of odd-harmonics in the output. These odd-harmonics are comparatively much larger than the second harmonics and there is a probability of overloading the succeeding stages of electronics. So double core modulators are normally used for this applications as shown in Fig. 1. Two identical cores arranged in an opposition manner so that the odd harmonics would cancel each other. Ideally, output V_d will be zero if there is no input current, provided the cores are matched. In presence of input signal even harmonic components appear in the output and when the input signal changes sign V_d undergoes a phase reversal. But in practical conditions, imperfections in core matching and the presence of even harmonics in excitation signal causes zero error in all types of magnetic modulators. The earth's magnetic field and any other stray fileds, thermal e.m.f.s in circuit connections are the other causes of zero error and drift. The zero error caused by memory effects should be removed by proper demagnetization [2]. Either the peak value or second harmonic component of the output can be a measure of input signal. One of the advantages of second harmonic detection over the peak detection method is that, the succeeding amplifier gain can be more as the amplifiers are not loaded by other harmonic components [3]. Toroidal cores are the most critical components of the modulator. Magnetic properties of these cores are the main factors which determine the resolution and the zero stability of the instrument.

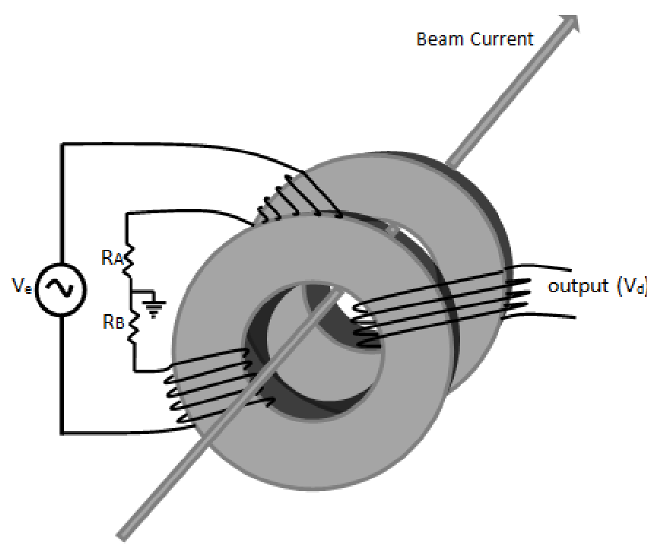

Figure 1: Schematic of second harmonic magnetic modulator.

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Core Selection and Characterization

The magnetic cores were selected based on criteria as discussed in paper by Unser [4]. Core dimensions were selected according to the beam pipe dimension.

For further identifying the matched pair from the set of toroids, B-H parameters were measured. Excited each cores up to saturation by sinusoidal signal and measured voltage across the resistor in series with primary winding (V_1), which is the measure of excitation current and voltage induced in the secondary terminal (V_2). From V_1 and V_2, magnetizing force (H) and magnetic flux density (B) were calculated as per the Equations (1) and (2) respectively.

$$H = \frac{NV_1}{R\,l} \tag{1}$$

$$B = \frac{V_2}{4.44 f N A_C} \tag{2}$$

where N is the no. of turns, *l* is the effective path length of the core and R is the series resistance, f is the frequency of the input sinusoidal signal and A_c is the cross sectional area of the core.

It is necessary to determine the permeability at different frequencies (as shown in Fig. 2). Inductance of the core was measured with LCR meter and permeability was calculated by using Equation (3).

$$L = N^2 \frac{\mu A_C}{l} \tag{3}$$

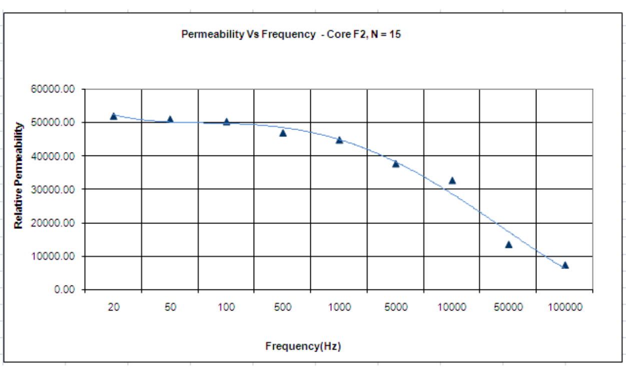

Figure 2: Permeability vs. frequency curve.

MODELING AND SIMULATION

In order to study the behaviour of second harmonic magnetic modulator, the selected toroidal cores were modelled in PSPICE based on Jiles-Atherton model of a ferromagnetic core [5]. Core models were made according to the core vendor data sheet as well as the experimental B-H curve data.

B-H curve in gauss vs. oersted was plotted by running the transient analysis on the test circuit. Jils-artherton parameters were extracted from the B-H loop and analysed the mismatches between cores. The magnetic modulator circuit was modelled (shown in Fig. 3) by using the two core models core1 and core2. L1 and L2 are the excitation windings of core1 and core2 respectively. L3 and L4 function as the output windings of core1 and core2 respectively. L5 and L6 are single turn signal windings on core1 and core2 respectively. Both the excitation windings are in parallel and there is a 1ohm resistor in each branch for limiting the current at the time of saturation. A sinusoidal voltage is used as excitation source.

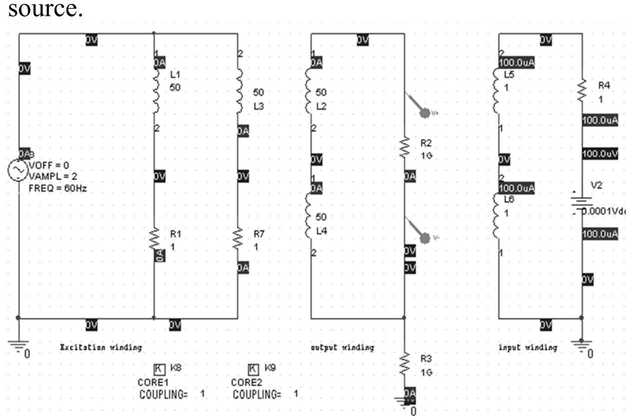

Figure 3: Magnetic modulator circuit.

The core1 and core2 (cores having mismatch) were replaced with ideal cores. If two cores are identical the combination doubles the even harmonic output components and reduces the odd harmonic output components to zero. If the cores are unbalanced there will be odd harmonics and hence a non-zero voltage in the modulator output even if it is operated with zero input signal. Figure 4 shows the magnetic modulator peak output for ideal and non- ideal core configurations. Here, it is seen that the unbalance in the cores causes noticeable zero error. But for the second harmonics zero error is comparatively small as shown in Fig. 5.

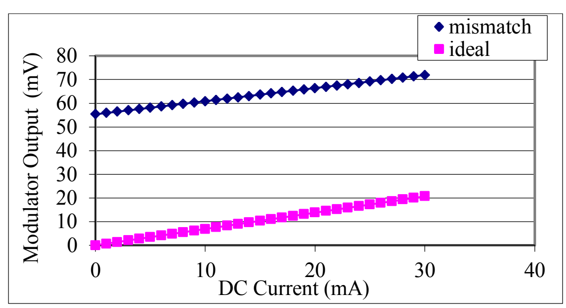

Figure 4: Peak modulator output vs. input signal.

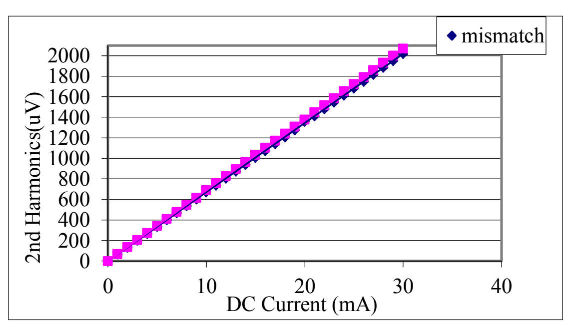

Figure 5: Second harmonics output vs. input signal.

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DESIGN AND DEVELOPMENT

The toroid cores used for magnetic modulator are made up of amorphous magnetic alloy tapes. Core dimensions were decided according to the beam pipe diameter. By analysing the BH curve and permeability variations with respect to frequency, we selected the operating frequency and number of turns for excitation coil winding. The mismatch in excitation windings were adjusted by adjusting the number of turns. The magnetic modulator in a closed loop is shown in Fig. 6.

The major criterion of designing excitation generator is its capability to provide sufficient mmf to saturate the core. A sinusoidal excitation signal of 10 kHz frequency with the help of programmable logic and 16 bit DAC module was generated. DAC output was filtered and amplified with power amplifier.

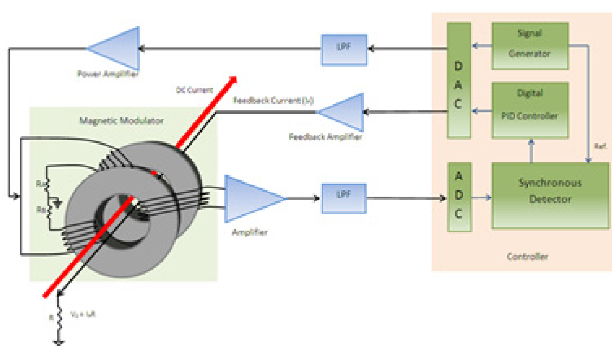

Figure 6: Magnetic modulator in a closed loop – low frequency channel of DCCT.

The second harmonics of the modulator output was extracted by a digital Lock-in Amplifier implemented in programmable logic. Hardware also detects the phase of second harmonics and it was adequate for the control action and feedback loop implementation

A digital PID controller was implemented using programmable logic. Final PID output was fed to the amplifier which provides a current in order to nullify the effect of beam current.

RESULTS AND CONCLUSIONS

The magnetic modulator was tested with both primary and secondary side pick-ups. Primary side output was taken across the series resistors R_A and R_B as shown in Fig. 1 and summed up by an instrumentation amplifier. In secondary side pick-up, the output was directly taken from the output winding. The modulator having secondary side pickup showed better common mode rejection and fundamental harmonic suppression than that of primary side. The memory effect observed in the transfer curve was reduced by proper adjustment of excitation voltage. The output of PID controller is shown in Fig. 7. There is noise below 30 µA is visible. DCCT implemented with the second harmonic modulator was tested in laboratory with the help of a calibrator kit which is capable of supplying DC current with a resolution of 1 µA. We achieved a 30 µA resolution of measurement in the range of ±30 mA. Bandwidth of the measurement was DC to 0.1Hz. Figure8 shows the final output of DCCT vs. the input DC current.

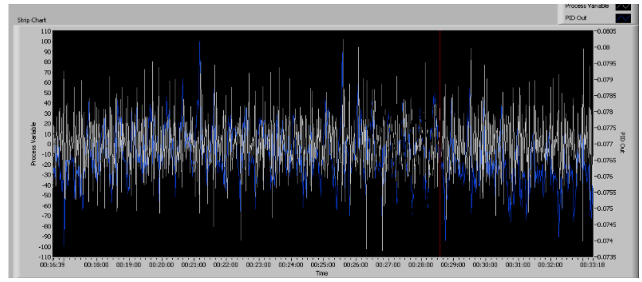

Figure 7: PID output for zero input signal.

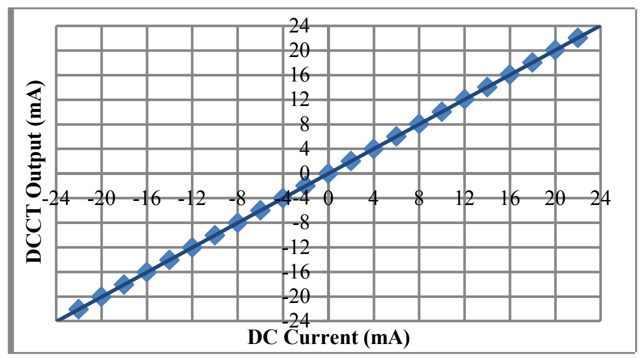

Figure 8: DCCT output vs. input DC Current.

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