Design of DC Current Transformer Magnetic Sensor for Measurement of Beam Currents in Accelerators

[1]Suraj Nair
M. Tech. Student Electronics and Telecommunication
VJTI
Mumbai India

[2]Vikas Teotia
Scientific Officer Control Instrumentation Division
Bhabha Atomic Research Centre
Mumbai India

[3]Alice Cheeran
Associate Professor Department of Electrical Engineering
VJTI
Mumbai India

[4]Sanjay Malhotra
Scientific Officer Control Instrumentation Division
Bhabha Atomic Research Centre
Mumbai India

***Abstract*— The fluxgate magnetometer principle of second harmonic detection is applied for designing a DC Current Transformer (DCCT) based magnetic sensor for accurate measurement of beam currents in proton accelerators .This paper presents the most suitable magnetic material which can be used as the core. It also gives the geometrical model of the magnetic sensor with exact values for its height, outer radius, inner radius and the number of turns in the sensor winding. The magnitude of the AC excitation current along with its frequency is also mentioned. The sensor voltages and the second harmonic components obtained for different values of DC beam currents have been analyzed for a variety of magnetic core materials. A highly linear sensor characteristics with sensitivity in the order of 3V/A is obtained with the usage of Vitrovac 6025 Z as the core material for the modeled sensor.**

Keywords: Direct Current Current Transformer, Fluxgate, Accelerator, Magnetometer, Beam Current

I. INTRODUCTION

Bhabha Atomic Research Centre, Trombay is developing a Direct Current Current Transformer (DCCT) based magnetic sensor for accurately measuring the value of DC beam currents in proton Accelerators. A wide range of technologies are used for measuring the magnetic fields from particle currents[1].The DCCT technology[2] based magnetic sensors are highly accurate, compact and resistant to variations in temperature. Hence they are used extensively in accelerator applications. Proton beam accelerators in BARC are used for sterilization of medical products, improving properties of gems and stones, curing of adhesives, polymerization and for increased cross linking of materials. The beam currents passing through proton beam accelerators have a magnitude ranging from 0.1 mA to 30 mA with energy of 3 meV. The application of the accelerator changes with changing values of the beam current. The beam current needs to be adjusted precisely to a particular value depending upon the application. These beam currents cannot be measured by intrusive means such as ammeter. Hence the need arises to accurately measure the current value by non-intrusive means. In this paper we design a highly linear, sensitive and compact DCCT magnetic sensor for accurate measurements of the beam currents. In the following section the principle for measuring the beam current using DCCT is described. This is followed by a discussion on the selection of proper magnetic core material along with the simulation results and finally the conclusion.

II. MEASURING PRINCIPLE

The principle of Fluxgate Magnetometer [3, 4] for detecting the second harmonics has been incorporated for measuring the voltage generated in the sensor due to the beam currents. Fluxgate Magnetic sensors have a rectangular core [4]. The core of the DCCT magnetic sensor is in the shape of a toroid. Both the primary and secondary windings are placed on the same core such that they are 180 degrees out of phase with each other. AC current of a frequency 1000Hz is fed to the windings. The flux generated in the two windings will be equal and opposite to each other with perfect matching when there is no external magnetic field in the vicinity of the core. As a result the net flux generated in the core is zero as shown in green in Fig.1

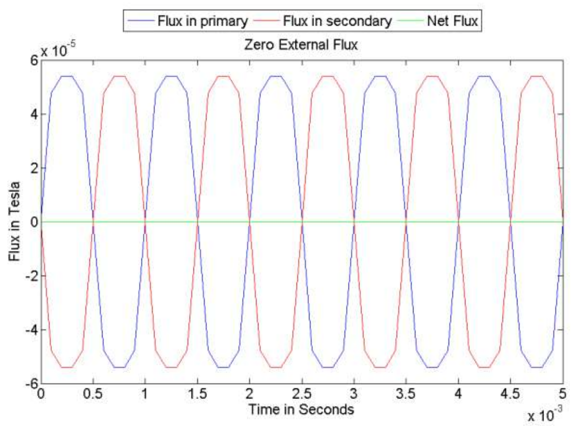

Fig. **1:** Net Flux in the absence of external field.

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The external magnetic flux due to the dc beam current will assist the flux in primary winding and oppose the flux in the secondary winding. Thus the time for which the magnetic flux remains in saturation increases in the positive half and decreases in the negative half cycle depending on the direction of beam current. This will generate a non-zero value of net flux in the core as shown in green in Fig. 2

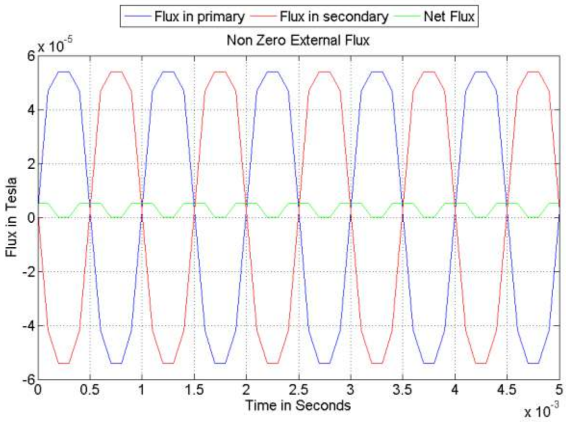

Fig.2**:** Net Flux in the presence of external field

The sensor coil wound around the core senses the voltage generated on account of the change of external flux. The second harmonic component of this generated voltage is proportional to the magnitude of the DC beam current which produced the net flux. The Fast Fourier Transform (FFT) of the voltage generated in the sensor gives the strength of the voltage harmonics and its frequency equals twice the frequency of the modulating current, thereby resulting in cancellation of the odd harmonics and retaining only the even harmonic components. The magnitude of the higher even harmonics is lesser than that of the first even harmonic. Thus the second harmonic component of the sensor voltage generated is the most significant component among all the harmonics and is used to detect the magnitude of the dc beam current.

III. SIMULATION RESULTS AND DISCUSSIONS

The B-H properties of various magnetic core materials have been considered for modeling the sensor. The frequency harmonics of the sensor voltages generated are observed in MATLAB for different values of DC Beam current starting from the value of 0.1 mA to 30 mA. Table 1 shows the core materials considered for modeling.

Table 1-Core Materials

Material Number	Material Name
M1	Electrical Steel NGO – Posco 35PN250
M2	Cobalt Steel- Hiperco 50
M3	Nickel Steel – Carpenter 49
M4	Stainless Steel- 416
M5	Low Carbon Steel – SAE1020
M6	Castings -Cast Iron
M7	Iron Powder Core: Micrometals
M8	Alloy Powder Core – Magnetics Koolmu 26
M9	Magnetics F Ferrite 100C
M10	Metglas type 2714AF(66%Co 15%Si 4%Fe)

Fig. 3(a) and Fig. 3(b) show the magnitude of voltage harmonics for DC Beam currents of 1 mA and 30 mA respectively for M10.

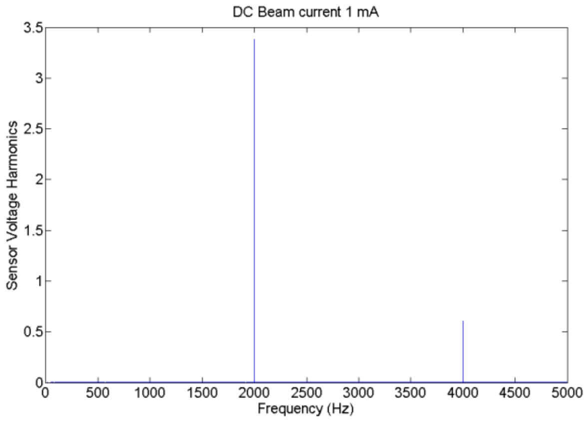

Fig.3 (a): Sensor Voltage harmonics for Metglass when beam current is 1mA

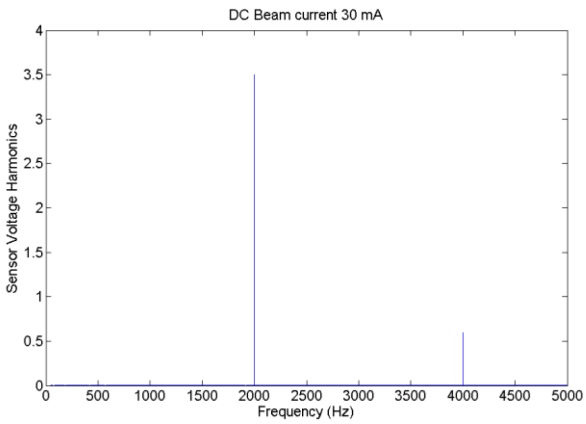

Fig.3 (b): Sensor Voltage harmonics for Metglass when beam current is 30mA

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The second harmonic component remains fairly constant at 3.5 even after increasing the value of dc beam current by 30 times. Table 2(a) and Table 2(b) gives the comparison of the sensor voltage values and the corresponding second harmonic components for all materials considered.

Table 2(a)-Sensor Voltages and Harmonics when beam current is 1mA

Core Material	Sensor Voltage(Volts)	FFT Harmonic(Volts)
M1	8.1419e-4	16
M2	1.2591 e-4	2.5
M3	0.2028	3750
M4	6.4925 e-7	0.013
M5	4.4942 e-6	0.09
M6	5.1657 e-5	1
M7	8.6396 e-7	0.017
M8	6.0217 e-8	0.0012
M9	0.0024	47.5
M10	7.1369 e-4	3.4

Table 2(b)-Sensor Voltages and Harmonics when beam current is 30mA

Core Material	Sensor Voltage(Volts)	FFT Harmonic(Volts)
M1	8.1381 e-4	16
M2	1.2583 e-4	2.5
M3	0.1996	3750
M4	6.4932 e-7	0.013
M5	4.4927 e-6	0.09
M6	5.1554 e-5	1
M7	8.6387 e-7	0.017
M8	6.0216 e-8	0.0012
M9	0.0024	47.5
M10	7.3603 e-4	3.5

It was observed that the variation in sensor output voltages with DC Beam current was negligible; as a result, the second harmonic component remained constant even when the DC beam current was changed. Thus it was concluded that such normal magnetic core materials does not respond to small current variations of the order of milliamperes and hence are not suitable for the development of magnetic sensors which requires a high degree of sensitivity and linearity. Hence we considered another material named Vitrovac 6025 Z. The B-H property of this material was such that magnetic flux density B reaches a saturation of 0.54 Wb/m^2 at a magnetic field intensity H of 10 A/m and increases steadily with a slope of 2.16e-3. Fig. 4(a) and Fig. 4(b) shows the magnitude of voltage harmonics for DC Beam currents of 1 mA and 30 mA respectively for Vitrovac 6025 Z.

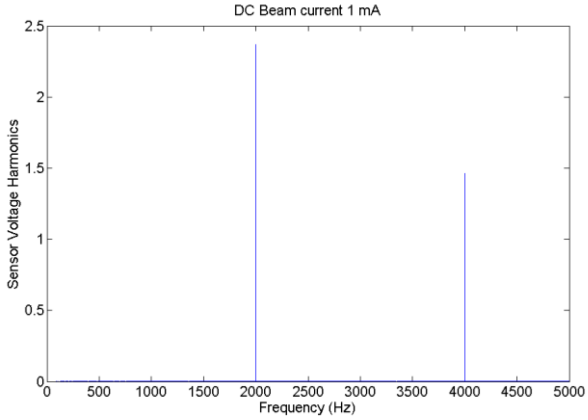

Fig. 4(a): Sensor Voltage harmonics for Vitrovac with H_{sat}=10A/m when beam current is 1mA

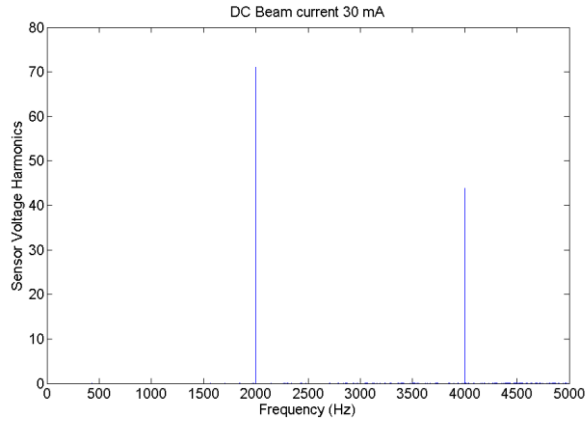

Fig. 4(b): Sensor Voltage harmonics for Vitrovac with H_{sat}=10A/m when beam current is 30mA

The second harmonic of the sensor voltage is seen to be varying linearly with variation in DC beam current with a sensitivity of the order 0.62208 V/A. In addition to the above core material, two variants of the same material were also considered, wherein the material reaches saturation at lower values of magnetic field intensity at 5 A/m and 2 A/m. The Sensor Voltage harmonics for different values of dc beam current when $H_{sat=}$ 5 A/m are shown in Fig. 5(a) and Fig. 5(b)

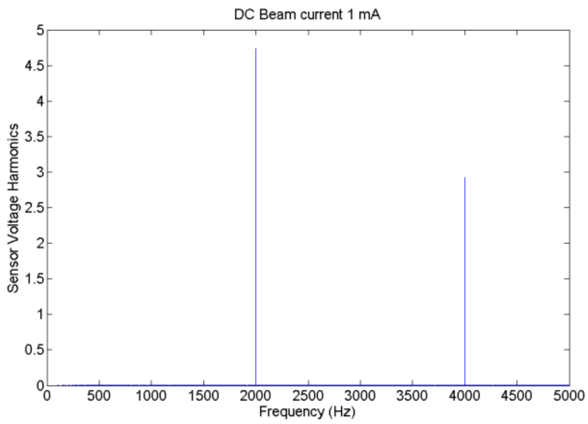

Fig. 5(a): Sensor Voltage harmonics for Vitrovac with H_{sat}=5A/m when beam current is 1mA

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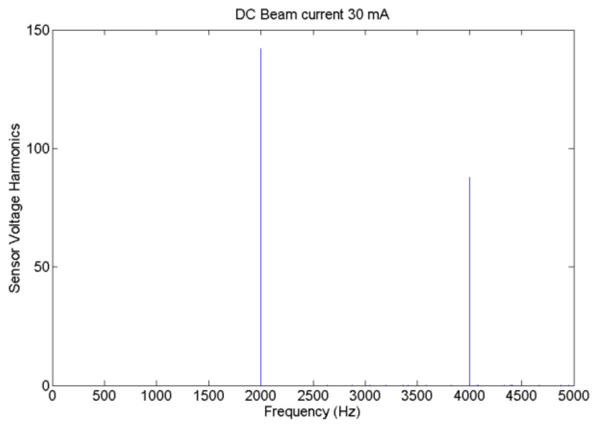

Fig. 5(b): Sensor Voltage harmonics for Vitrovac with H_{sat}=5A/m when beam current is 30mA

Fig. 6(a) and Fig. 6(b) shows the sensor voltage harmonics of the material when $H_{sat=}$ 2A/m.

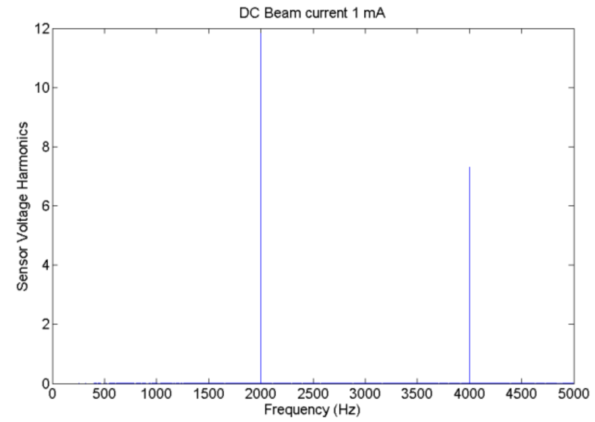

Fig. 6(a) - Sensor Voltage harmonics for Vitrovac with H_{sat}=2A/m when beam current is 1mA

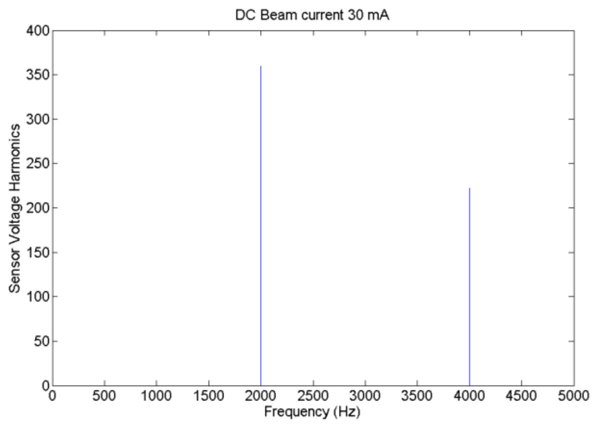

Fig. 6(b) - Sensor Voltage harmonics for Vitrovac with H_{sat}=2A/m when beam current is 30mA

Table 3(a),Table 3(b) and Table 3(c) shows the sensor voltages and their corresponding harmonics for the three varieties of the material used.

Table 3(a)-Sensor Voltages and Second Harmonics when H_{sat} is 10

DC Beam Current (mA)	Sensor Voltage(V)	FFT Harmonic(Volts)
0.1	6.2208e-05	0.23
0.5	3.1104e-04	1.15
1	6.2208e-04	2.3
5	0.0031	11.5
10	0.0062	23
15	0.0093	35
30	0.0187	70

Table 3(b)-Sensor Voltages and Second Harmonics when H_{sat} is 5

DC Beam Current (mA)	Sensor Voltage(V)	FFT Harmonic(Volts)
0.1	1.2442e-04	0.48
0.5	6.2208e-04	2.4
1	0.0012	4.8
5	0.0062	24
10	0.0124	48
15	0.0187	72.5
30	0.0373	145

Table 3(c)-Sensor Voltages and Second Harmonics when H_{sat} is 2

DC Beam Current (mA)	Sensor Voltage(V)	FFT Harmonic(Volts)
0.1	3.1104e-04	1.2
0.5	0.0016	6
1	0.0031	12
5	0.0156	60
10	0.0311	120
15	0.0467	180
30	0.0933	360

Sensitivity of the material with H_{sat}=5A/m is found to be 1.2442V/A. It is seen that the sensitivity becomes more in the core material which saturates at a lesser value of magnetic field intensity (H). Vitrovac6025 which saturates at 2A/m is chosen as the core material for the sensor as it has the maximum sensitivity of 3.1104V/A among the other two variants. Table 4 gives the modeled geometry of the DCCT Magnetic sensor.

Table 4- Geometrical values of DCCT Sensor

Parameters	Value
Core Material	Vitrovac 6025 Z
Number of turns in winding	50
Height of Core	10mm
AC Current in winding	10mA
AC Current frequency	1000Hz
Outer Radius	31mm
Inner Radius	21mm

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IV. CONCLUSION

In this work a mathematical model of a linear, highly sensitive and compact DC Current Transformer (DCCT) based magnetic sensor is proposed for the proton accelerators at Control and Instrumentation Division, BARC. Experiments show that the sensor exhibits excellent linearity for the entire range of DC beam currents from 0.1mA to 30mA with a high sensitivity of 3.1104 V/A.

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