Wideband Beam DCCTs with Parallel Feedback Circuits

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Abstract

For the measurement of beam currents in the KEKB storage rings we have developed beam DCCTs based on parallel feedback loops, which are essentially free from parametric modulation ripple. This design overcomes the problems in the widely used DCCT circuits with series feedback loops related to the highly balanced magnetic core supply, and removes the necessity for a ripple suppression filter in the feedback circuit.

1 Introduction

Since the development of the first wideband parametric beam DCCT consisting of a parametric current transformer (CT) and an active feedback CT (L/R-integrator) by K.Unser in 1969, used to measure the ISR circulating beam current at CERN [1], the fundamental feedback circuit has not been changed. In this circuit the feedback winding of the DC current detection core L_3, the feedback winding of the AC current detection core L_2 and the current sense resistor R_f are connected in series, as shown in Fig. 1. Hereafter we call this configuration of the feedback circuit the series feedback. The flux modulation of the DC current detection cores induces modulation ripple current in the feedback coil due to the imbalance between the pair of DC current detection cores. The ripple current flows in the feedback circuit and causes residual modulation ripple in the output signal. Although a high open-loop gain in the L/R-integrator is required to suppress the residual ripple, the open-loop gain is usually limited by the closed-loop stability condition.

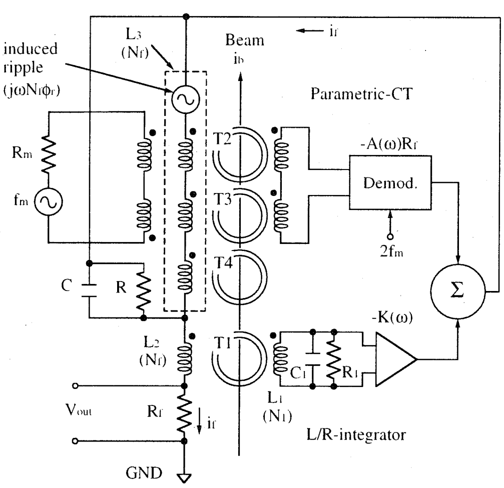

Fig. 1 Block diagram of the series feedback DCCT circuit.

One of the most efficient techniques to suppress the residual modulation ripple without degradation of the frequency response is to employ a highly balanced pair of magnetic cores for parametric modulation [2]. Another important technique for ripple suppression is the introduction of an additional inductance to the feedback coil L_3 of the parametric CT by inserting an additional core T_4 and a ripple current bypass capacitor C in parallel to L_3 [3]. Usually both of these techniques are required to suppress the residual modulation ripple to a sufficiently low level for beam current measurement without narrowing the signal frequency response. In designing the circuit, however, these techniques present some difficulties related to the balanced magnetic core supply and the somewhat empirical design of the ripple bypassing circuit. To overcome these difficulties, we developed new feedback circuits, called "parallel feedback circuits," which are essentially free from parametric modulation ripple.

2 Series-feedback DCCT

In a beam DCCT consisting of a parametric CT and an L/R-integrator, as shown in Fig. 1, the magnetic balance error of the flux-modulated cores of T_2 and T_3 induces a ripple voltage $j\omega N_f\phi_r$ in the feedback coil L_3, where ϕ_r is the difference of the modulation flux between these two cores. This ripple voltage generates ripple current in the feedback circuit, where the feedback coils of the parametric CT and L/R-integrator and the current sense resistor R_f are connected in series. Assuming that the open loop gain of the parametric CT is designed to be insensitive to the ripple in the ripple frequency region (see Eq. 11), circuit analysis of Fig. 1 gives the feedback current i_f, expressed by

$$N_f i_f = G(\omega)i_b + H(\omega)i_r, \tag{1}$$

where i_b is a beam current, i_r is the equivalent ripple current converted to the beam current,

$$i_r = \frac{N_f^2}{L_3}\phi_r, \tag{2}$$

and the output signal is given by

$$v_{out} = R_f i_f. \tag{3}$$

$G(\omega)$ is the signal response function called the closed-loop gain, $H(\omega)$ is the ripple response function, and N_f is the number of turns in the feedback coils L_2 and L_3, where we assume $N_2 = N_3 = N_f$.

Before proceeding with the discussion, we will give a simple estimate of the equivalent ripple current. If we have a 1% imbalance of the magnetic flux in the pair of flux modulated cores, the maximum amplitude of the flux density difference ΔB between two cores will reach $\Delta B \sim 100Gauss$ because the flux in the cores is modulated beyond saturation. Therefore, supposing a core cross section of $S_c \sim 1cm^2$, an inductance of $L_3 \sim 20mH$ and $N_f \sim 30turns$, the induced equivalent ripple current is expected to be $i_r \sim 45mA$ at a modulation frequency of

$1kHz$. In order to suppress the equivalent residual ripple current to the order of μA, it is required to design the ripple response function $H(\omega)$ to be below $-90dB$ in the frequency range above the modulation frequency.

The signal response function $G(\omega)$ in Eq. 1 is given by the open-loop response function $G_0(\omega)$ called the open-loop gain:

$$G(\omega) = -\frac{G_0(\omega)}{1+G_0(\omega)}, \quad (4)$$

and the ripple response function $H(\omega)$ is given by

$$H(\omega) = -\frac{j(\omega L_3/N_f R_f)g(\omega)}{1+G_0(\omega)}, \quad (5)$$

where

$$G_0(\omega) = A_0(\omega)g(\omega) + K_0(\omega) + \frac{R_1 L_2}{R_f L_1} f(\omega) + j\frac{\omega L_3}{R_f} g(\omega), \quad (6)$$

$$A_0(\omega) = A(\omega)\{g'(2\omega_m + \omega) + g'(2\omega_m - \omega)\}N_f/2 \cong A(\omega)N_f g'(2\omega_m), \quad (7)$$

$$K_0(\omega) = \frac{N_f R_1}{N_1 R_f} f(\omega)K(\omega). \quad (8)$$

$A_0(\omega)$ and $K_0(\omega)$ are the open-loop gain functions of the parametric CT and of the L/R-integrator, respectively, and ω_m is the modulation frequency. $K(\omega)$ is the gain function of the L/R-integrator amplifier. The transimpedance of the demodulator of the beam current parametric modulation is defined by $A(\omega)R_f$, and

$$f(\omega) = \frac{j\omega L_1/R_1}{1 + j\omega L_1/R_1 - \omega^2 L_1 C_1}, \quad (9)$$

$$g(\omega) = \frac{1}{1 + j\omega L_3/R - \omega^2 L_3 C}. \quad (10)$$

$f(\omega)$ is the frequency response function of the signal detection coil L_1 of the L/R-integrator where R_1 is the load resistance of the signal pick-up coil L_1, and C_1 is dominated by the signal cable capacitance connecting L_1 to the amplifier. $g(\omega)$ is the response function determined by L_3, C and R in the feedback circuit for the ripple suppression based on Eq. 5. $g'(\omega)$ is given by Eq. 10, replacing R by $RR_f/(R+R_f)$. In the derivation of the above equations, we need the assumption that the ripple component in the parametric CT output is negligibly small, i.e., the ripple rejection LPF at the demodulator output stage is designed to satisfy the condition

$$|A_0(\omega)| << \omega L_3/R_f \quad (11)$$

in the ripple frequency region. To stabilize the closed-loop response, $K_0(\omega)$ must be designed so as to reduce to the level below $0dB$ at the higher cut-off frequency $\omega = 1/R_1C_1$ of $f(\omega)$.

As for ripple suppression, Eq. 5 requires a high open-loop gain of the L/R-integrator in the frequency region above the parametric modulation frequency to reduce the ripple noise induced in the feedback circuit by the modulation. For example, if C and R in parallel to L_3 are removed, we have $g(\omega) = 1$ and an extremely high open-loop gain of $|K_0(\omega)| > 50dB$ will be required in the ripple frequency region to reduce $H(\omega)$ to an order of $-90dB$. However, it is difficult to obtain such a high open-loop gain because of the decreasing response of $K_0(\omega)$ in the high frequency region and because of the many harmonics of the ripple. Therefore designing $g(\omega)$ to satisfy the condition

$$|g(\omega)| << 1 \quad (12)$$

is essential to reduce the ripple noise in series feedback DCCTs. Under the condition of Eq. 12 the design of the open-loop gain will be somewhat complicated because $g'(2\omega_m)$ decreases simultaneously with $g(\omega)$.

In a practical circuit design we need some know-how based on empirical determination of the circuit parameters of $g(\omega)$, because the cut-off frequency must be optimized to satisfy the closed-loop stability condition despite ambiguities in the effective inductance L_3, such as those due to the flux-modulated cores exceeding saturation and the effective resistance R being dominated by core loss. Indeed, we could not suppress the residual modulation ripple to a sufficient level for beam current measurement with non-selected magnetic core pairs by optimizing $g(\omega)$.

3 Parallel-feedback DCCT

To avoid complicated ripple-suppression problems, we will seek another feedback circuit. If the feedback circuit of the L/R-integrator can be separated from the feedback circuit of the parametric CT, we can make the L/R-integrator insensitive to ripple noise. To separate the feedback circuits, we consider the "parallel feedback circuit" as shown in Fig. 2, where the feedback coils L_3 and L_2 of the parametric CT and of the L/R-integrator, respectively, are driven in parallel and the output signal is taken from the current sense resistor connected in series to L_2. The signal response function of Fig. 2 is the same as that of Fig. 1, but we obtain a different ripple response function which is free from ripple noise if the parametric CT is designed to satisfy the condition of Eq. 11, since the neither transformer of the L/R-integrator nor the current sense resistor pick up the induced ripple current in L_3.

The open-loop gain is given by

$$G_0(\omega) = A_0(\omega) + K_0(\omega) + \frac{L_2 R_1}{L_1 R_f} f(\omega), \quad (13)$$

and the magnitude of the ripple response function is on the order of $H(\omega) \sim O\{A_0/(1+G_0)\}$, so that $H(\omega)$ can be ignored in the ripple frequency region:

$$H(\omega) = 0, \quad (14)$$

in the limit of Eq. 11, where

$$A_0(\omega) = A(\omega)N_f \frac{1 + (L_2R_1/L_1R_f)f(\omega)}{1 + j\omega L_3/R_f} \cong A(\omega)N_f, \quad (15)$$

$$K_0(\omega) = \frac{N_f R_1}{N_1 R_f} f(\omega)K(\omega). \quad (16)$$

Therefore a ripple-free response function is expected in the parallel feedback circuit without a special filter like $g(\omega)$.

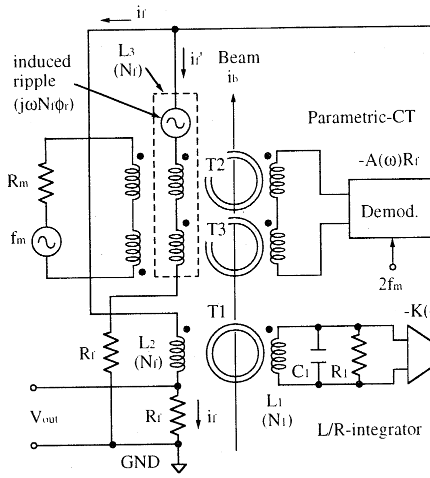

Fig. 2 Block diagram of the parallel feedback DCCT circuit.

Based on the above arguments we developed new DCCTs for the KEKB electron and positron storage rings. To overcome core selection problems, we designed parallel feedback DCCTs so as to make possible the use of non-selected magnetic cores. For DC current detection by parametric modulation, a pair of magnetic cores of strip-wound toroids ($25\mu m$ thick tape of Ni-Fe-Mo alloy, TMC-V/TOKIN) are employed without pairing. The CT head is assembled inside a magnetically shielded case and installed in the core housing mounted on the accelerator. A ceramic break in the beam pipe inside the core housing is straddled by a cylindrical capacitor ($\approx 100pF$) made from double layers of thin Cu plates insulated with Capton film, in order to bypass the high frequency components of the beam induced current on the beam pipe. In order to avoid radiation damage from the strong beam current of the KEKB ring, the electronics of the DCCTs are installed in a local control building and the CT head is connected to the circuit with 100 meter-long cables, though the response bandwidth is limited by the cable capacitance. The parametric modulation frequency is designed to be $1kHz$ and the demodulation frequency is $2kHz$. The LPF of the demodulator is carefully designed to satisfy the condition of Eq. 11.

The performance of the newly-developed DCCT with the parallel feedback circuit is summarized as follows, where the output is converted to the equivalent beam current.

Frequency response	$DC - 22kHz$
Residual modulation ripple	$\sim 40\mu A(p-p)$
Temperature dependence of offset	$\sim 4\mu A/°C$
Long term offset drift	$< 10\mu A$

Figure 3 shows the frequency response, where the cut-off frequency of $22kHz$ is limited by the signal cable capacitance of $C_1 \cong 18nF$ and the input impedance of the L/R-integrator amplifier of $R_1 = 220\Omega$. In spite of the wideband response, we succeeded in suppressing the residual ripple noise to a sufficiently low level for beam current measurement, as shown in Fig. 4, without selected pairing of the magnetic cores. The 3rd harmonic of the modulation appears to be the main ripple component.

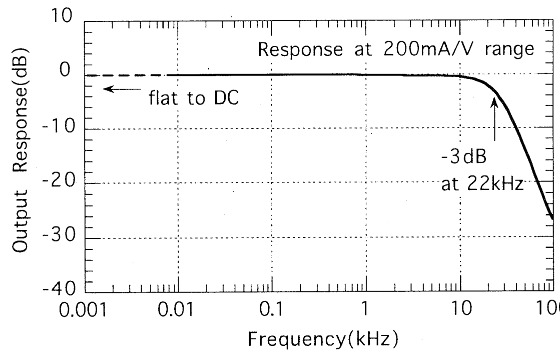

Fig. 3 Frequency response of the parallel feedback DCCT.

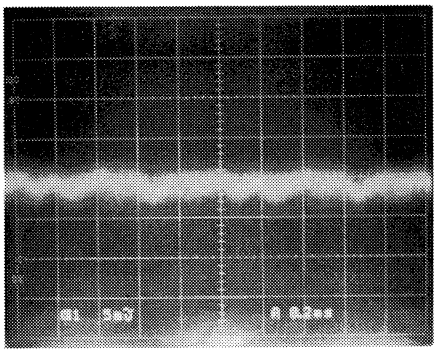

Fig. 4 Residual ripple in the output of the parallel feedback DCCT at 20mA/V range.

4 Summary

Based on a detailed analysis of the ripple response function, we successfully developed wideband parametric DCCTs with new feedback circuits, "parallel feedback circuits", to suppress the residual ripple caused by parametric flux modulation without selective pairing of the magnetic cores. For approximately half a year of operation of the KEKB rings, the parallel feedback DCCT has shown good performance during accelerator operation and has no heating problem from the beam.

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References

[1] K.B. Unser, IEEE Trans. Nucl. Sci., NS-16, 1969, pp.934-938.
[2] K.B. Unser, Proc. 1991 Accelerator Instrumentation Workshop, CEBAF, 1991; AIP Conf. Proc. No.252, 1992, pp.226-275. (CERN SL/91-42 (BI), 1991).
[3] K.B. Unser, IEEE Trans. Nucl. Sci., NS-28, No.3, 1981, pp.2344-2346.