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An analog integrator for thousand second long pulses in Tore Supra

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Abstract

In the year 2000, a new version of the analog integrator used in Tore Supra for magnetic measurements has been designed. Although based on the same principles, this new integrator was improved in order to satisfy the new long duration of pulses, up to 1000 s, expected in near future on Tore Supra. After recalling the basic principles of the analog integrators and recent improvements, this article explains the main characteristics of the new integrators, tests and obtained results. The conclusion underlines the most important results and, in particular, the capability of the new integrator to answer to the International thermonuclear experimental reactor (ITER) requirements.

Keywords: Tore Supra; Analog integrator; Magnetic measurements

1. Introduction

Magnetic measurements provide one of the most important diagnostics to control the plasma localization in tokamaks. The method generally used to perform these measurements in such an environment-high temperature, limited space, high-vacuum, radiation (n, γ)-is the association of a passive pick-up coil and an electronic integrator. For many years Tore Supra has acquired considerable experience in the development of analog integrators [1], and hence drift and saturation problems have now been minimized for several hundred seconds of pulse duration. In 2000, Tore Supra was stopped to allow the installation of the CIEL project components. We took advantage of this period to improve the performance of the existing integrator in order to satisfy conditions of 1000 s or more pulse duration, without modifying the basic principles, which confer reliability and low cost.

2. Requirements

In order to have good plasma position control in Tore Supra (<1 cm), measurement must have an accuracy better than 1%. Since coils are calibrated with an accuracy better than 1%, the relative

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accuracy of the integrator must always be lower than 1%. In absolute terms, the total integrator drift must remain less than ± 10 mV throughout the pulse.

3. Basic principles

3.1. Measurements of flux and induced field

The variation of flux through a loop can be expressed as a function of time from the induced voltage $e(t)$ as follows: $\varphi(t_1) - \varphi(t_0) = \int_{t_0}^{t_1} e(t)dt$. Considering the initial conditions as $\varphi(t_0) = 0$ at $t_0 = 0$, the output of an analog integrator will be: $u(t) = \frac{1}{\tau} \times \varphi(t)$ where τ is the time constant of the integrator. If the induction field can be considered as uniform through the coil sensor, the intensity of induced field $b_n(t)$ can be directly inferred from the relation: $u(t) = \frac{S}{\tau} b_n(t)$, where S is the equivalent surface (n turns x area).

3.2. Analog integrator

In Tore Supra, the magnetic measurement system is based on passive coils used in association with analog integrators. However, analog integrators are subject to intrinsic problems. The two most important are firstly the integrator drift, due to the offsets of the operational integrator [2] which introduces an absolute error that increases with integration time, and secondly the saturation of the integrator in the case of a high flux variation such as a disruption.

The analog integrators used on Tore Supra are based on a differential input structure principle with two frontal integration cells (Fig. 1). Each integration cell is based on an analog operational integrator with an offset correction implemented by a dynamic auto-compensation feedback (Fig. 2).

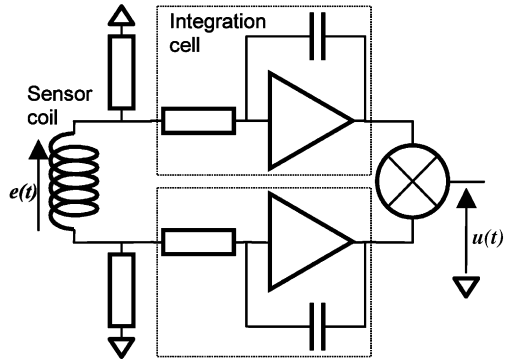

Fig. 1. Synoptic of differential structure.

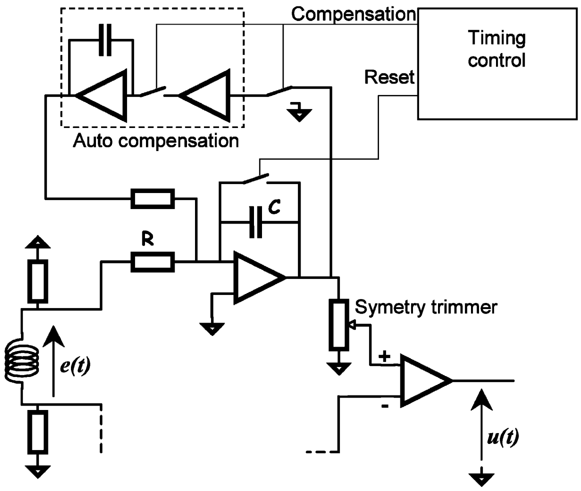

Fig. 2. Synoptic of one cell of integration.

4. Implementation, recent improvements

In order to minimize drifts, some high performance components are used over long times:

- The two integrator cells are realized with a dual “zero drift” operational amplifier, which has typically ± 0.05 μV input offset voltage, ± 10 pA input offset current and an average input offset drift of ± 0.01 μV/°C.
- the usage of polypropylene capacitors which have low leakage current.

Recently, some new improvements have been implemented:

– The auto-compensation system, typically a sample/hold amplifier (S/H), is also based on an integrator amplifier. Hence, the same care must be taken with its external capacitor.
– Corrections have been made to the thermal drift of the auto compensation system. In fact, when the S/H is in hold mode, there is no feedback on the input amplifier, so when differential input voltage increases, during the measurement phase, the amplifier saturates and temperature and the drift increases. Now a switch to ground the S/H input has been implemented and, as a result, the temperature of components has decreased.
– The drop of integration capacitors has been considerably reduced by the use of a relay with a certified open switch insulation of 10^{14} Ω (instead of usual 10^{12} Ω).
– During the design of the board, special care has been taken with the earth-screen layer design to reduce ground voltages. An integrator is easily implemented on a single 100 × 220 mm board, routed with two 70 μm copper layers.
– Finally, only one trim resistor is necessary to adjust the symmetry of gains between the two integration cells.

5. Laboratory results

Tests have been performed with the two first prototypes of the new version of integrator boards in comparison with the previous version. All the tested integrators have a time constant of 27 ms. The acquisition system used for this test has a resolution of 0.3 mV.

5.1. Drift measurements

The differential inputs of the integrators were short-circuited. After a 10 s long compensation phase, the integrators were switched into measurement mode for 1000 s. Two series of test were made, the first one at ambient temperature, without any special care, and the second at 40 °C (regulated temperature). The results are averages of two tests with 14 integrators and are summarized in Table 1. As we can see, the new integrators have a mean of the absolute values of drift voltage of 5 mV representing, when multiplied by the time constant (27 ms) an equivalent flux error of 0.135 mV s, instead of 18 mV (0.49 mV s) for old integrators. The performance of new integrators is about three times better and no significant differences were found between tests at ambient temperature—around 25°C and tests at 40 °C.

Table 1
Summary of drift measurements

Drift/1000 s	Min	Typ.	max	Unit
New integrators				
Average of absolute drift (6)	0.40	5.00	15.14	mV
Average drift (6)	0.011	0.135	0.405	mV s
Old integrators				
Average of absolute drift (6)	0.91	18.24	59.67	mV
Average drift (6)	0.25	0.49	1.56	mV s

5.2. Other measurements

– Measurement of drifts with high level outputs: after the reset of the integrator, a voltage was applied at the input during a sufficient time to obtain approximately and respectively, 2.5, 5, 7.5 and 10 V at the output, then the voltage source was disconnected and drifts measured during 400 s. The average drift on the new integrators is 4.77 mV (0.139 mV s) with a max value of 8.65 mV (0.233 mV s). Under the same conditions, the drift of old integrators increases with output level up to 1500 mV (40 mV s) for 10 V.
– The slew rate goes up to more than 10 V/50 μs (vs. 10 V/500 μs) without significant output distortion.
– The phase between the input and output remains in a range of [$\pi/2$ and $\pi/2+\varepsilon_\phi$], the phase error ε_ϕ being always lower than 3° (0.052 Rad).

6. In situ results

The first in situ measurements of drifts was made with the integrator boards fully installed in their crates (two crates of 17 integrators), the coil sensors connected, in operational conditions (noise, temperature) but without toroïdal or poloïdal fields. These measurements were performed with the standard data acquisition system, which has a resolution of 4.88 mV/bit (±10 Vencoded with 12 bits). These tests confirmed that drifts remain lower to ±10 mV after 1000 s. In order to increase the low accuracy, we averaged the measurements over 100 consecutive points. As shown in Fig. 3, only two integrators exceed the range of ±10 mV after 1000 s. The mean value of drift voltage at the output after 2000 s is ±11 mV which represent an average equivalent flux error of ±0.3 mV s.

The second in situ measurements were carried out with toroïdal and poloïdal fields, with 100 integrators. To achieve such a test in operational conditions during a long integration time, we had to modify the timing control to remove the reset and auto-compensation phases during several consecutive pulses. The tests were performed during a period of poloïdal field tests. In order to have a sufficient resolution with such low drifts, we had to run the test over about 7000 s. The main result, illustrated on Fig. 4, is the average value of the equivalent flux error: ±1.3 mV s after 7000 s.

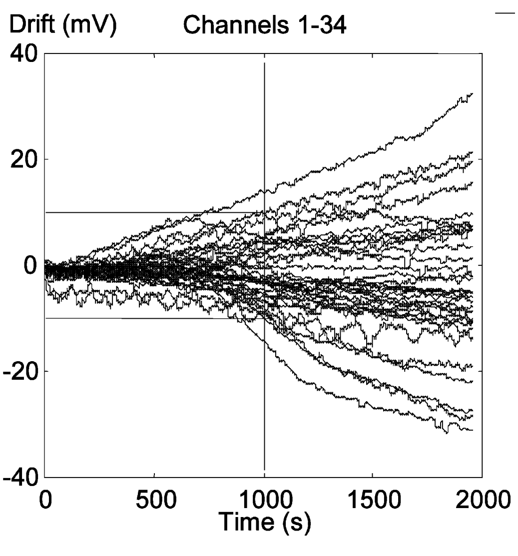

Fig. 3. 2000 s in situ drift measurements.

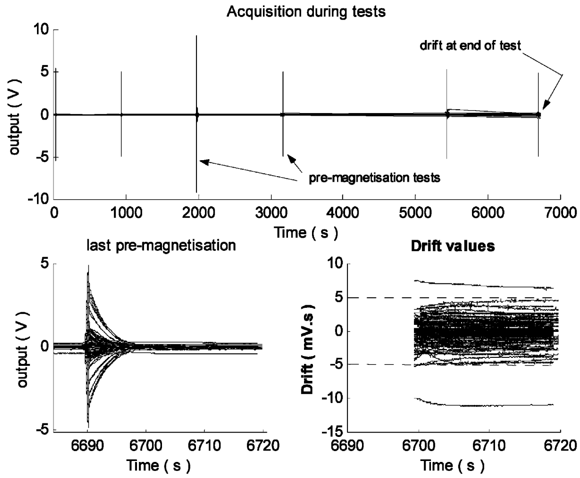

Fig. 4. Measurements of drifts during tests.

We also note that only two integrators exceeded the range of ±5 mV s, and six integrators measure 0 mV s, implying that they remain lower than 0.1318 mV s, which is the minimum resolution (e.g. 4.88 mV).

7. Conclusion

During the 2001 campaign about 150 new integrators have successfully operated for several months, providing high quality magnetic measurements. The main objective of the new integrators was to improve the precision and reliability of the magnetic field measurements for long time pulses of up to 1000 s. This objective has now been surpassed.

For International thermonuclear experimental reactor (ITER) magnetic measurements, the lowest maximum values allowed for flux error are 1.6, 1.9 and ~2 mV s for normal, tangential and diamagnetic loop compensation in-vessel coils [3,4], the others being greater than 5.8 mV s. Integrator drifts will be an important part of this permissible flux error and have to be as low as possible. Based on results presented in this report, we can reasonably hope to reach soon the ITER objectives for several thousand seconds.

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