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Long Pulse Analogue Integration

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1. Introduction

The most successful device for magnetic confinement of high temperature plasmas for thermonuclear fusion research is the tokamak. This uses a toroidal vacuum vessel, into which fusion gases (e.g. deuterium) are injected and heated. Part of the heating is by a large 'toroidal' electrical current (7MA in the Joint European Torus (JET) [1]) which is induced in the plasma and flows around the torus. The magnetic field from this current is referred to as the 'poloidal' field. In addition a toroidal magnetic field is applied by external electromagnets. The operation of the device is based on the reduced energy and particle transport properties of the resultant magnetoplasma.

Accurate knowledge of the position of the plasma boundary is essential in order to maintain a safe distance between the plasma and in-vessel components. This requires calculations of the magnetic topology inside the machine, and the inputs to these calculations are precise magnetic flux and poloidal field measurements around a poloidal cross-section of the device (see e.g. [2]).

These measurements are usually made by integration of signals from passive magnetic coils, which produce signals proportional to the rate of change of the required fluxes and fields (the use of Hall probes in high neutron fluxes is problematic). Over the years, pulse durations of tokamak plasmas have been increasing. In JET, ~1min. plasmas have been produced and in the International Thermonuclear Experimental Reactor (ITER), now being designed, initial pulse durations will be ~1 hour, extending later to a time-scale of days. The presence of temperature dependent drifts in analogue integrators meant that, after linear drift compensation in a controlled environment, integration at the required accuracies could not be sustained for longer than some minutes (see e.g. [3]) and even with ideal temperature control, the integration time was limited by the output voltage limits on the integrator. This posed a problem for magnetic measurements on long pulse machines.

In this paper an analogue integration scheme is proposed which addresses these issues through switching between two integrators and through digital compensation of the drift. This gives accurate results on time-scales relevant for long pulse fusion devices. Error estimates for ITER are given, based on initial tests of such a system.

The method makes it possible to obtain flux measurements from flux loops, which provide the dominant input to equilibrium calculations, and which clearly cannot be rotated or vibrated as proposed for poloidal field coils in ITER [3]. Additionally, these technically complex schemes would not be necessary using the proposed scheme.

2. System description

An illustration of the system is given below

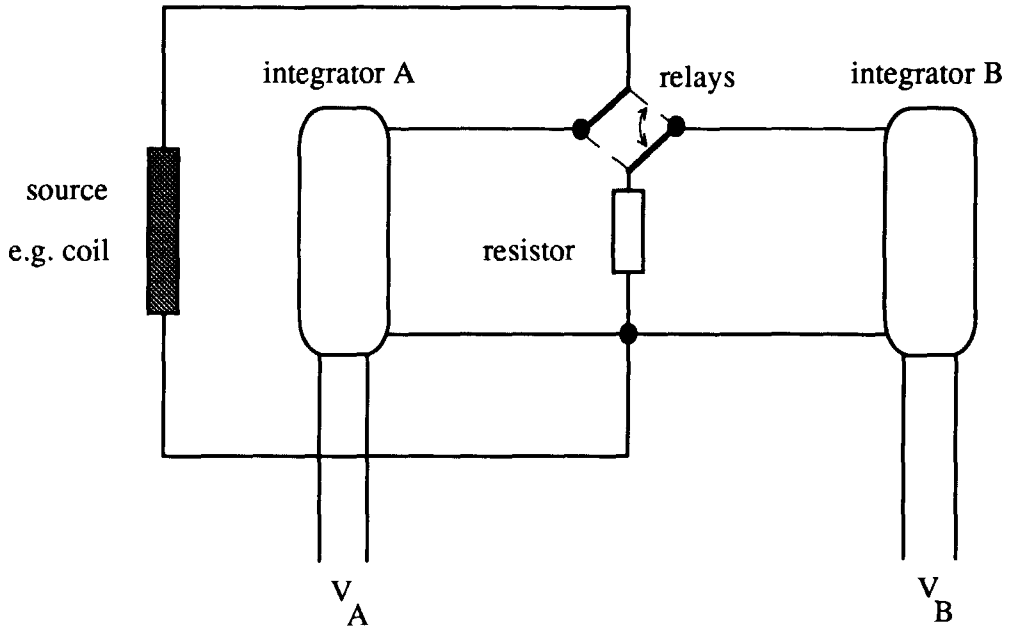

Fig. 1: Schematic of integrator

A pair of integrators is used, one, initially A, connected to the source (e.g. magnetic probe) and the other, initially B, to a resistor (matched to the dc resistance of the source and wires) via a set of switches. The system is run until the drift on integrator B becomes apparent. Integrator B is then reset and after resetting transients have settled, it is switched to the coil. Some data are acquired on both integrators subsequently before integrator A is switched to the resistor and reset. When the drift on integrator A becomes apparent the resetting and switching process is repeated.

The outputs of the two integrators can be combined to construct a continuous real-time integral of the source signal, with the contribution from each integrator corrected with the preceding drift measurement on that integrator. This can conveniently be done digitally. The rate of digitisation can be made fast enough to suit the requirements of real-time plasma position control, that is, it is limited only by the integrator frequency response and the minimal drift correction computation time, not by the switching / resetting operations.

A suitable timing sequence for the system is shown in fig. 2 below.

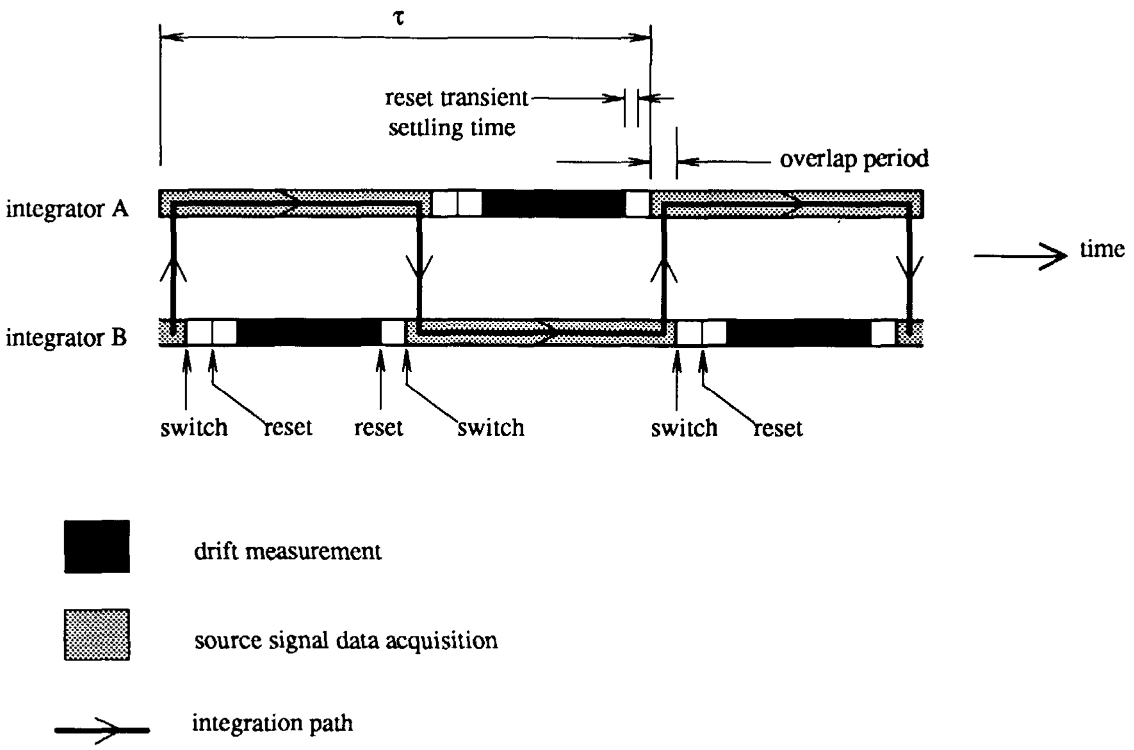

Fig. 2: Timing sequence

The integration path is along the solid line, excluding any contribution to the integration from the resetting transients, even if these exist at the input terminals. Note that there is no requirement that the two integrators should be accurately matched.

3. First test results

An integrator system as described above has been built and tested.

Two standard JET integrators were used. The circuit of these uses an operational amplifier with a series resistance $R=240k\Omega$, and a capacitor giving a time-constant of 27.5ms. The output stage contains an isolation amplifier with a gain of 2, and an electronically activated reset facility is available. A drift compensation system is also included, which is normally used in JET pulses. In these tests this system was not used.

The switching relay operation time was 1ms and the period τ was set to 27s. A sampling period of 1.5s was used with 8 drift data samples and 10 source signal samples, the first and last of which constituted the overlap data. As a signal source, a resistor of 150Ω was used, across which voltages could be applied with a cell, and a similar resistor was connected for the drift measurement. The ambient temperature was relatively uncontrolled, being that of an 'ordinary room'. A final linear correction of 5mVs per hour was applied (discussed in sec. 5).

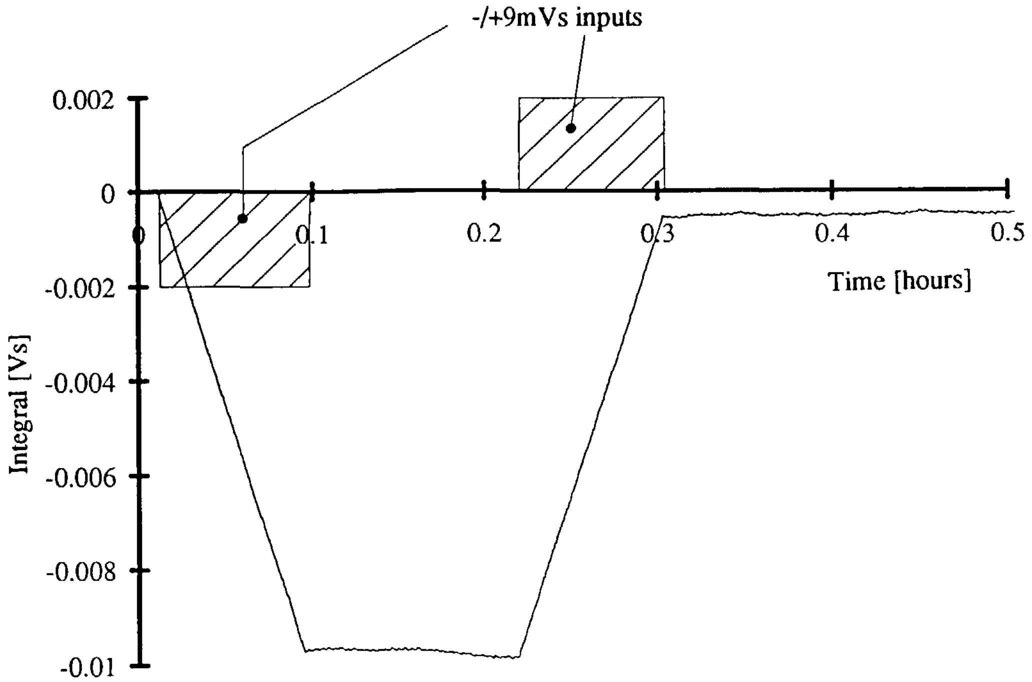

Fig. 3: Test of integrator with negative, then positive 9mVs inputs

Fig. 3 shows a test of the system to check it is operational. A 9V cell was used as a stable voltage source. With a potentiometer, the voltage was reduced to produce 30μV across the 150Ω resistance representing the signal source. A 300s pulse was applied with a timed relay, applying 9mVs to the integrator. The resulting linear ramp is seen in the figure. The cell terminals were then reversed when the relay switch was open and a similar pulse applied again, bringing the integral back near zero. Subsequently the system was run for about 6.5 hours (a data acquisition limit), before the same voltage sequence was applied to the integrator again. The result is shown in fig. 4, demonstrating integration accurate to within a few millivoltseconds throughout this period.

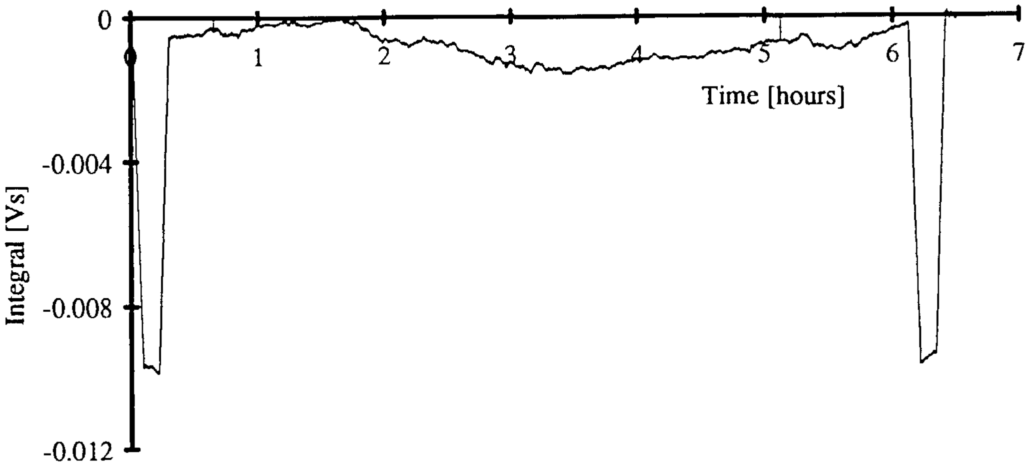

Fig. 4: Integration over several hours, accurate to within a few mVs. The pattern of the residual drift reflects the uncontrolled room temperature variations during the day

4. Estimates for ITER

With an integration drift error of E=5mVs, the error contribution to some measurements on ITER is estimated below. The ITER parameters used are:

$R_{\text{wall}} \sim 10\text{m}, I_p = 22\text{MA}, B_\theta \sim 1\text{T}$, probe $nA = 0.2\text{m}^2$, $m = 18$ probes, flux loop - to - plasma distance ~ 1m

1. Poloidal field

The voltage on the probe is

$$V = nA\frac{dB_\theta}{dt}.$$

The error in poloidal field measurement from an integration error E is

$$\frac{\delta B_\theta}{B_\theta} \sim \frac{E}{nAB_\theta} \sim 2.5\%.$$

With a ramp rate of 1MA/s, the voltage on an nA=0.2m^2 magnetic probe is ~9mV. Using a cell and potentiometer to produce 9mV and a relay to apply this voltage for 22.5s, the typical integrated signal from a magnetic probe on ITER can be simulated. This is shown in Fig. 5.

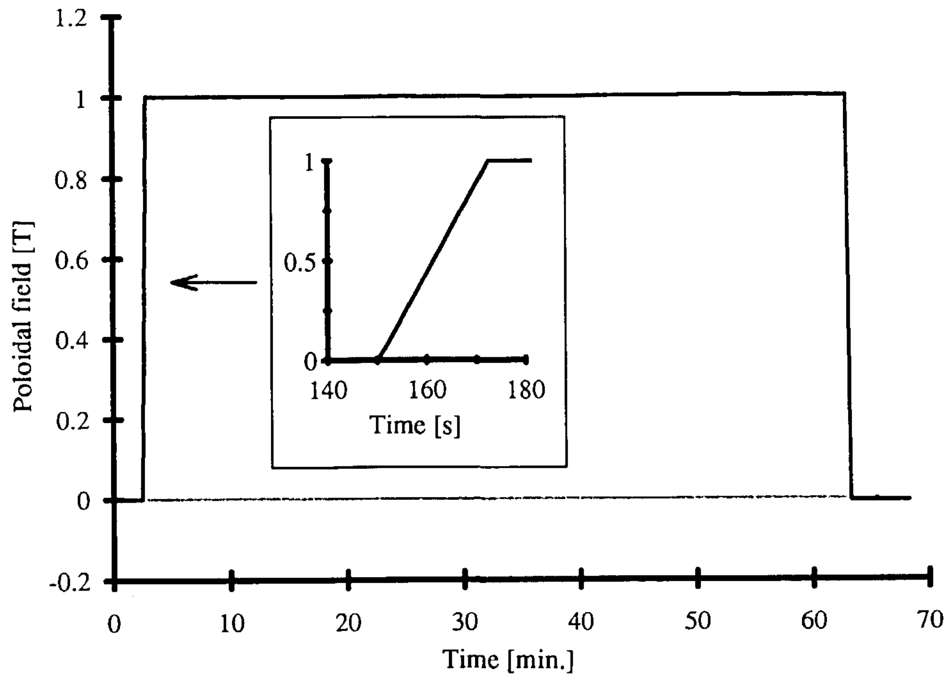

Fig. 5: Simulation of ITER poloidal field including integration error, with a 1MA/s current rise / decay giving ±9mV into the integrator

2. Plasma current

The plasma current is calculated with a summing integrator

$$\mu_0 I_p = \frac{1}{nA}\int_0^t \sum_i V_i l_i dt,$$

so that with a plasma circumference of l

$$\frac{\delta I_p}{I_p} \sim \frac{El}{m\mu_0 I_p nA} \sim 0.1\%.$$

3. Flux

$$V = \frac{1}{8}\frac{d\phi}{dt}, \text{ (single turn, one octant)}$$

$$\delta\phi \sim 8E.$$

The point with measured flux is within a distance δR of the flux loop coordinates where

$$\delta R = \frac{8E}{2\pi R B_\theta} \sim 0.6\text{mm}.$$

4. Boundary position

For the simple arrangement of fig. 6, the error in boundary identification is estimated below

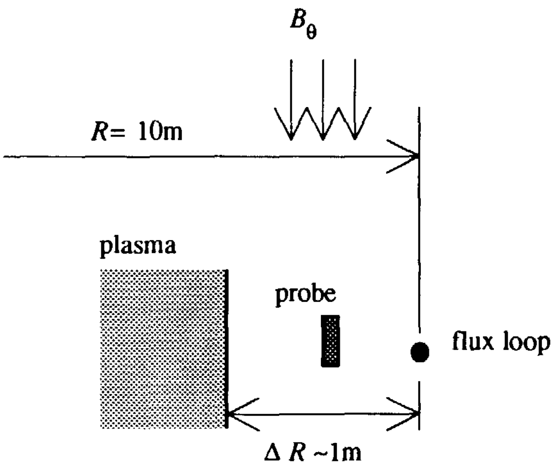

Fig. 6: Geometry for boundary position error estimate

The flux at the plasma boundary is calculated by extrapolating the flux loop measurement with the probe giving a flux error

$$\delta\phi_{\text{total}} = E\left(8+\frac{2\pi R\Delta R}{nA}\right) \sim 1.6\text{Wb},$$

corresponding to a boundary identification error of

$$\delta R \sim \frac{\delta\phi_{\text{total}}}{2\pi R B_\theta} \sim 2.5\text{cm}.$$

The dominant contribution to this error is from the large extrapolation distance. With flux loops close to the plasma, the integration error contribution to boundary identification is not larger than a few millimetres (see 3 above).

5. Sources of error

Various mechanisms which are potential sources of error in the described integration system are discussed below.

1. Temperature variation and noise

The effect of varying temperature is to introduce a time dependence in the drift rates of the two integrators. The error contribution from this effect depends on the degree of temperature variation, and on the time-scale of variation compared with τ, being smaller when the ratio is large.

A lower limit on τ will be imposed by noise levels (from the integrator outputs and bit noise) and possibly transient settling times of the integrators. The noise must be small compared with the drift at the end of the drift data acquisition sequence, for accurate calculation of the drift per sample. The effect of integrator noise can be reduced by low-pass filtering the integrator outputs. If the drift correction is then applied to the integrator outputs *before* the filtering, the frequency response of the integral is unaffected. The effect of residual noise is to introduce a random error in the drift per sample calculation, so that the integral drifts linearly for a period $\sim\tau/2$, changing slope randomly after this time. The result is a fluctuation in the integral (i.e. there is no net contribution to the integral from this effect after a period many times $\tau/2$). The effect of filtering the drift data is to reduce the amplitude of these fluctuations.

2. Overlap drift

During the overlap period shown in fig. 2, both integrators drive currents through the signal source, so that the drift rate on both is modified. A short overlap period reduces this, but the period is limited by relay operation times. To first order this effect will produce a linear drift in the integral, with fixed slope for given overlap. Changes in relay bounce characteristics with age could put some variation in this, so that relay characteristics need careful consideration.

3. Resistance mismatch

The signal source and resistor should have closely matched dc resistances, otherwise a linear drift will result. This error can be reduced by making the resistance inside the integrators dominant.

4. Non-linear drift evolution

Under fixed temperature conditions, after resetting, the drift on an integrator may be some *reproducible* curve in general, close to a straight line. With the timing sequence of fig. 2, the drift data acquisition period is shorter than the signal acquisition period, due to the overlap period and reset transient settling times, and this difference, together with a reproducible curvature of the drift evolution after resetting, means that the average drift rate during the drift data acquisition period is slightly different from that in the signal acquisition period. The consequence is a fixed linear drift of the integral over many periods τ.

Under variable temperature conditions, if the curvature of the drift after resetting varies, then in addition to the linear drift, temperature dependent fluctuations are introduced in the integral through this effect.

Thus various mechanisms can be identified whose primary effect is to produce a linear drift in the integral. With a carefully designed system such drifts should be much smaller than the drift on an individual integrator, and they should be much more reproducible, so that a final correction for net drift can be effective. As mentioned earlier a linear correction of 5mVs per hour was applied in the tests shown above. Over several weeks this slope varied between 5 and 10mVs per hour, in the 'ordinary room' environment.

Higher accuracy is expected with modern hardware (the JET integrators are not optimum for this application) and with controlled operation temperature.

6. Alternative integrators

Other possible integration schemes for high accuracy long pulse applications might include purely digital integration, or integration by voltage-to-frequency conversion.

In the former case the stringent requirements are put on the bit resolution and sampling frequency. Such a scheme might incorporate low-pass passive filtering at the input stage for treatment of fast variations.

In voltage-to-frequency conversion the integral is proportional to the count of output cycles. Such a system would require high conversion linearity. To treat the zero-voltage case a bias voltage might be applied, and this will require high stability.

7. Summary

An integrator system is demonstrated, accurate to within a few millivoltseconds, with no special temperature control of the environment. Integration at this accuracy is shown for over 6 hours, limited by data acquisition. Estimates show that this could meet the requirements of long pulse fusion devices.

The first results suggest that with some improvements, such as the use of optimised integrators and operation at controlled temperature, the system could be applicable on time-scales much longer than hours, and with higher accuracy.

The complete circuit of this system could be conveniently put on a small board.

References

[1] Fusion Technology, Vol. 11, No. 1 (1987).

[2] D. P. O'Brien *et al.*, Nuclear Fusion, Vol. 32, No. 8, p1351 (1992).

[3] ITER diagnostics, ITER documentation series No. 33, p35, IAEA, Vienna (1991).