Control Loop for a Pulse Generator of a Fast Septum Magnet using DSP and Fuzzy Logic

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Abstract

A prototype of a fast pulsed eddy current septum magnet for one of the beam extraction's from the SPS towards LHC is under development. The precision of the magnetic field must be better than $\pm 1.0 \ 10^{-4}$ during a flat top of 30 µs. The current pulse is generated by discharging the capacitors of a LC circuit that resonates on the 1st and on the 3rd harmonic of a sine wave with a repetition rate of 15 s. The parameters of the circuit and the voltage on the capacitors must be carefully adjusted to meet the specifications. Drifts during operation must be corrected between two pulses by mechanically adjusting the inductance of the coil in the generator as well as the primary capacitor voltage.

This adjustment process is automated by acquiring the current pulse waveform with sufficient time and amplitude resolution, calculating the corrections needed and applying these corrections to the hardware for the next pulse. A very cost-effective and practical solution for this adjustment process is the integration of off-the-shelf commercially available boards into an active digital control loop. A 16-bit fixed point, 33 MIPS, DSP together with a 12-bit, 500 kSPS, ADC (total cost of under 250 $) has been used for this control process. The correction algorithm developed for the DSP uses Fuzzy Logic reasoning.

1   Electrical circuit of the pulse generator

The generator, providing a current pulse with a peak current of 15 kA ± 1.5 A during 30 µs, is composed of four main elements as shown in Figure 1: two capacitors, one variable inductance and a thyristor switch. The capacitors are pre-charged to about 3 kV and discharged into the magnet L_M.
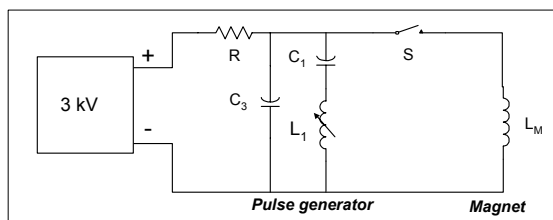

Figure 1: Electrical circuit

The single elements can be described as follows:

- Capacitor C_1 (310 µF) is connected in series with the high stability water cooled variable inductance L_1 (6.5 µH). This circuit branch is responsible for the 1st harmonic of the discharge current.

- Capacitor C_3 (188 µF) is connected in parallel with the above-mentioned branch and is responsible for the 3rd harmonic of the discharge current.
- A 4.5 kV semiconductor discharge switch S, transfers the energy from the two charged capacitors to the inductive load with a repetition rate of 15 s.

The choice of this basic circuit is determined by the pulse shape requirements. The capacitors C_1, C_3 and the inductance L_1 are dimensioned such that the total pulse length is minimised for the required 30 µs duration of the flat top. The optimisation of these elements reduce the generator volume and also the thermal and mechanical stresses. The pulse flatness is obtained by varying the inductance L_1, which is a solenoid wound coil, within a few nH. This adjustment is achieved by movable external disks, which influence the solenoid stray field.

2   Requirements

2.1   Precision

The typical magnet current pulse has a length of one cycle of the 1st harmonic sinewave, as shown in Figure 2. The addition of a 3rd harmonic component flattens the top of the first half cycle such that during 30 µs the absolute variation is less than 1.5 A or $1.0 \ 10^{-4}$. The two lobes are due to the optimisation of the flat top duration versus the total pulse duration.

Protons pass through the magnet only in this 30 µs interval. The magnet current must be, in addition to the flatness requirements, within a window of ± 1.5 A, or $\pm 1.0 \ 10^{-4}$.
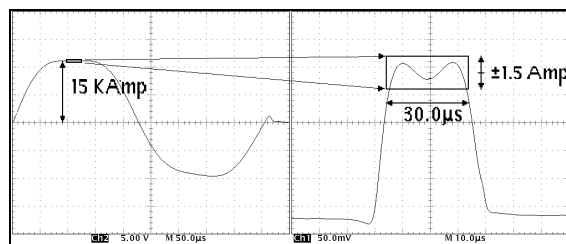

Figure 2: The magnet current waveform

2.2   Stability and reproducibility

The magnet current must be stable during operation. Amplitude instabilities, or jumps, outside the tolerance window are not allowed. However, different kinds of drift exist and must be cancelled.

Firstly the drift during the periods after start-up, or temporary stop, when the components of the generator and the magnet coil must reach their stable operation temperature and that can last for about 1.5 hours. The magnet current pulse decreases than continuously as shown in Figure 3, where the black area represents the drift trajectory.

Next there are the thermal drifts, which are slow and small in amplitude, and are caused by fluctuations in the ambient temperature and the cooling system.

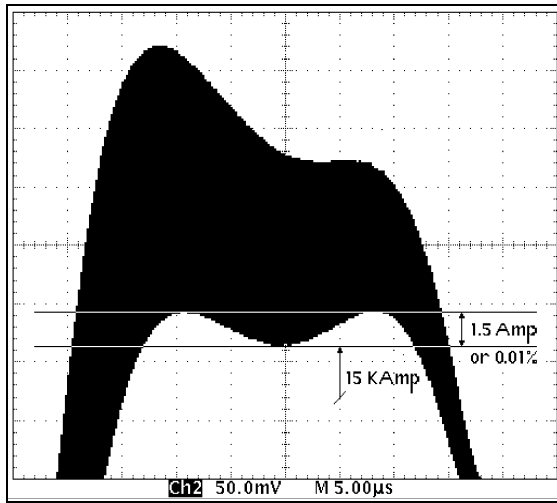Lastly, in the long term ageing drift effects can be expected.

Figure 3: Start-up drift

3 Control loop

3.1 General

To achieve the required stability and reproducibility, a digital control loop is used. This control loop, shown in Figure 4, measures from pulse to pulse the magnet current and makes the necessary adjustment so that it can be expected that the next pulse will satisfy the specifications.
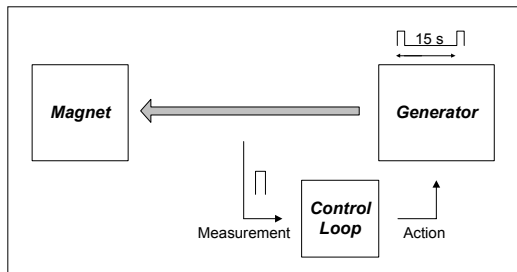

Figure 4: Control loop

3.2 Precision measurement of the waveform

The magnet current is measured with a high precision double shielded current transformer having a large bandwidth and a droop of 0.09 %/ms. The output source impedance is 1 Ohm giving a signal of 1 mV/Amp.

To measure the shape of the current waveform and the amplitude during the flat top with sufficient precision, several samples with a resolution at least a factor 10 times better than the required precision are needed, thus $\pm 1.0 \ 10^{-5}$. Taking into account that the preferable operation point of an ADC is well below the full scale, this would require a 17-bits ADC. About 10 samples along the flat top are sufficient for determining the shape, but this requires nevertheless a sampling rate above 300 kHz.

ADCs with these requirements are not (yet) available. Therefore the signal of the magnet current pick-up is first applied to a window amplifier with variable threshold. The amplifier has a gain of 100 and let thus pass 1 % of the full-scale signal. Figure 5 shows this principle. A careful selected threshold level has as result that the top of the magnet current pulse falls than inside the window. The gain of the amplifier improves the effective resolution of an ADC with a factor 100, or about 7 bits. In this way an 18 to 19 bits resolution can be obtained with a 12-bits ADC. The amplitude of the pulse is with this system the sum of the threshold voltage and the measured voltage by the ADC divided by 100, thus:

$$U_{Pulse} = U_{Threshold} + U_{ADC}/100$$

The waveforms of Figure 2 and Figure 3 have been measured with this window amplifier.
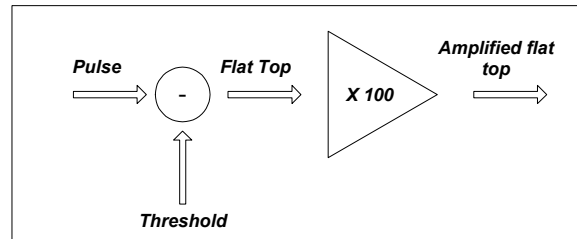

Figure 5: Precision window amplifier

3.3 Precision of the threshold and the reference setting

In order to be able to make adjustments of $\pm 1.0 \ 10^{-4}$ a better resolution for the settings of the threshold level of the window amplifier and pulse generator amplitude reference is needed. This can easily be obtained with 15-bit DACs that have a resolution of $3.0 \ 10^{-5}$, allowing about 6 distinct set points in the adjustment area.

3.4 Adjustment of the shape and the amplitude

The generator has two elements that allow adjustment of the waveform, a variable inductance and the voltage to which the capacitors are charged. As can be seen in Figure 6, a variation in the value of the inductance changes the slope between the two peaks of the lobes and the amplitude of the pulse. On the contrary, a variation in the capacitor voltage changes only the amplitude of the waveform.

It is thus possible, by varying the inductance and the capacitor charging voltage simultaneously, to modify and adjust the current pulse waveform. The correction factors to be used initially can be derived from Figure 6. A fully adjusted generator delivers a pulse with the correct amplitude and which has two lobes of equal amplitude (slope zero).

The inductance is changed by moving one of the external disks of inductor L_1 with a DC motor; whilst the capacitor voltage is simply changed by modifying the reference of the high voltage power supply.
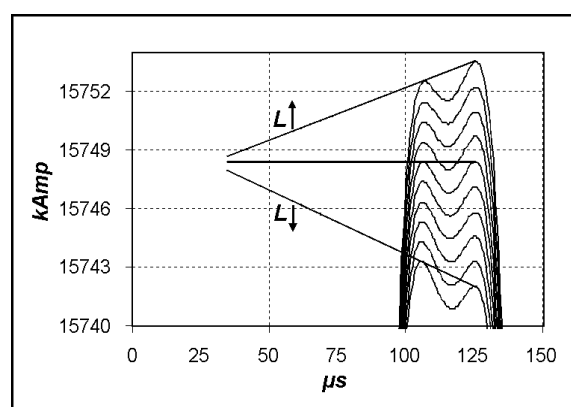

Figure 6: Variation of the inductance L_1

3.5 Implementation

Figure 7 shows the block diagram of the pulse generator and magnet system together with the implementation of its control loop.
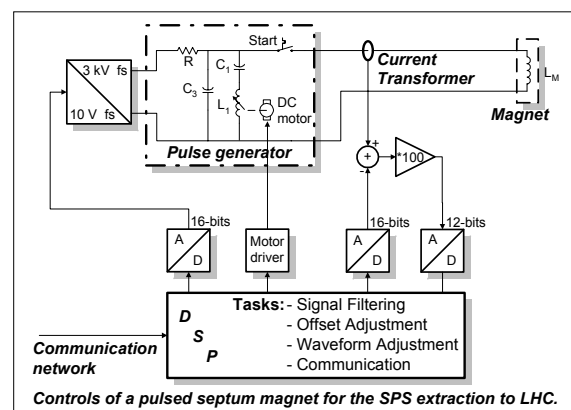

Figure 7: Block diagram

The control loop is build around a Digital Signal Processor (DSP) that executes the algorithms that acquire the data of the measured waveform, condition and filter this data, and finally calculate the corrections to be applied for tuning to the generator.

ADC, DACs and motor driver for the inductance variation are directly controlled by the DSP. Via a communications port remote control can be done.

The hardware used consist of:

- The EZ KIT LITE evaluation kit, that provides access to the on board DSP via a serial port. The on-board DSP is the ADSP2181; a 16-bit fixed point processor having 33 MIPS. On-chip have been integrated 80K bytes RAM and a separate I/O memory space that permits glueless system design.
- Another evaluation board, the EVAL-AD7891-2CB takes care of the data acquisition. The on-board ADC is the AD7891-2, which is an eight-channel multiplexed, sample, and hold buffered, 12-bit data acquisition system. The sample rate is maximum 500 kSPS and the input range is +5 V. The analogue inputs are buffered with OP467 high-speed op-amps. An AD780 ultra high precision bandgap reference is used for the ADC.
- A G-64 bus standard dual 16-bit DAC module is used for the generation of the threshold and reference settings. Both DAC's are completely opto-isolated from the bus. The output voltage range is from -10 V to +10 V with 16-bit resolution.
- The precision threshold amplifier is a newly designed module built in CERN. Very low noise precision operational amplifiers, such as the OP27, and high stability resistors are used.
- The motor driver interface is also developed in CERN and consists of an I/O port of the DSP, which is buffered with some transistors and relays.
- All the above mentioned components have been lodged in a 3U high 19" crate together with the necessary low voltage power supplies.

4 The software in the DSP

The software created has mostly been made in C and then cross-compiled to the DSP assembly code.

4.1 Data acquisition

The sampling of the magnet current waveform starts on the reception of a external timing signal. 18-19 samples are then taken with a sampling rate of 2 µs and stored in memory for further use.

4.2 Filtering

The 2µs sampling rate allows just 15-16 samples of the flat top. To calculate the amplitude and slope with more precision more samples are needed. With digital signal processing [1] this can artificially be obtained by insertion of "zero" samples in between the original samples and than filtering all samples with a low pass FIR filter.

4.3 The threshold adjustment

The window amplifier circuit requires a threshold value. An algorithm to calculate the correct value of the threshold has been implemented with Fuzzy Logic [2] and works as follows:

The amplification of the precision threshold amplifier is 100 so after subtraction of the threshold voltage (see

Figure 8), any rest voltage greater than 50 mV will be converted by the ADC to 5 V, a "*five*", and any sample under the threshold to 0V, a "*zero*". The Fuzzy Logic algorithm adjusts the threshold voltage so that no "*fives*" are present and a minimum number of "*zeros*" is obtained.
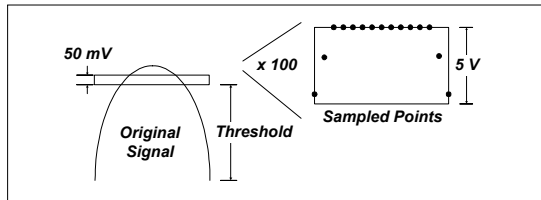

Figure 8: Threshold adjustment algorithm

4.4 The generator adjustment

After calculation of the slope and the mean amplitude it must be decided exactly how the inductance and the reference voltage should be modified in order to obtain the desired pulse shape. The implementation of this algorithm in Fuzzy Logic is underway.

5 Software Development and Supervision

The DSP controller crate has been connected via its RS232 port to the accelerator controls network. This means that the equipment can remotely be accessed and monitored.

5.1 Remote access

The following application programs have been created:
- A process supervisor surveys the control process, checks the adjustments made by the control process and displays the results of them. The communication with the controller crate is made with standard CERN SL-Equip calls. From this application the parameters like the reference value for the magnet current, sampling rate, delay, number of samples, etc, can be sent to the DSP.
- A program to download the executable file into the DSP from any PC or workstation on the network.

The following tools have been used:
- A special LabVIEW® http server that captures the window of the process supervisor and makes it accessible through the Web by any Browser. It allows multiple user access to the process information.
- On-line debugger. The software tool *fuzzy*TECH® [3], running under MS-Windows, is used to develop and to debug the Fuzzy Logic algorithms that controls the generator.
  *fuzzy*TECH® can communicate continuously with another program running in the same PC using DDE (Dynamic Data Exchange). An established communication allows interactive debugging because the parameters of the algorithm, and even the algorithm itself can be changed while the whole control process is

working. This eases the tuning of the algorithm. Once it performs to satisfaction *fuzzy*TECH® creates an ANSI-C version of it, that is then compiled and can be integrated with the software running locally on the DSP. This has already been done with the threshold adjustment algorithm.

5.2 Local access

All the features available with remote access are also available for a direct access between a serial port of a PC and the DSP.

6 Conclusion

The feasibility of a pulse to pulse precision adjustment of a magnet current pulse generator by using a DSP for data acquisition and control has been successfully demonstrated.

The use of a digital control loop is simple compared to an active analogue loop and certainly much more economic.

Fuzzy Logic tools ease the development of the control algorithm and improve flexibility and insight in the process.

The use of off-the-shelf boards accelerates the development phase and is an additional cost reduction factor.

7 Acknowledgements

8 References

[1] Discrete-Time Signal Processing, Alan V. Oppenheim, Ronald W. Schafer, Prentice Hall, Englewood Cliffs, New Jersey 07632.

[2] Fuzzy Logic and NeuroFuzzy, Applications Explained, Constantin von Altrock, Prentice Hall PTR, Upper Saddle River, New Jersey 07458.

[3] *fuzzy*TECH® User's Manual. INFORM Software Corportation. INFORM GmbH. Pascalstrasse 23, D-52076 Aachen, http://www.fuzzytech.com/.