# A Highly Flexible Online Controllable FES-Pattern Generator for Basic Research

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## Introduction

Functional electrical stimulation (FES) is nowadays used in a wide range of applications, both for sport (e.g. muscle relaxation) and for medical use (e.g. iontophorese or to restore functional use of paralysed muscles). Various stimulator systems are commercially available for those applications where a fixed chronological course of the programmed stimulation pattern can be used, as for example the relaxation of muscles or iontophorese. These devices generate a stimulation pattern, which can be adjusted in amplitude, frequency, etc. using some buttons or menus or can be selected by a fixed program stored in a non-volatile RAM as well as a program, which can be downloaded from a PC.

However, this technology is not appropriate for applications where the stimulation pattern should be started, stopped or amplitude-modulated depending on time variant signals (obtained from a measurement or from a calculation by a program). Stimulation signal control tests were done with a stimulation system located in the upper price segment (used in a large rehabilitation centre). This offered an external trigger function, which enables the start and stop of a pre-programmed stimulation-pattern or stimulation sequence. Start and stop times result in a very large variance in the actual timing of the “controlled” pattern. With respect to the applied trigger signal a time delay variance between 20 ms to 160 ms was measured. This kind of variance is much too high given the required timing for control purposes or investigations of FES-forced actions. Therefore an online changeable stimulation system with precise timing, good reproducibility and high flexibility in modifying the stimulation pattern is needed for more specific investigations.

An interesting solution for an online changeable FES pattern generator has been introduced in [1] where the magnitude of the stimulation signal is controlled by a neuronal network via a so-called pattern generator/pattern shaper. This pattern generator produces a periodic signal with a predefined constant frequency and makes a cyclic movement possible.

An alternative concept is shown in [2]. A microprocessor-based eight channel distributed muscle stimulator is introduced in this paper. Based on the data from a tension transducer attached to the muscle, a computer calculates an “adjusted set of interpulse intervals”. The main goal using such a system is to produce smooth tetanic contractions both for fast and mixed muscles. There is no information in this paper about the resolution obtainable with respect to magnitude and time.

An interesting concept in [3] was already introduced in 1989, where stimulation patterns were generated from a PC card. The parameters for the pulse-shapes were directly sent to an interface board via the PC Bus. With the aid of such a specially developed PC-card, four biphasic signals can be generated and modulated in frequency and magnitude.

The goal of the study was to develop a compact and powerful stimulation pattern generator, which allows a user to realize quick and precise changes in the stimulation pattern directly by a PC-based program (steering or control with respect to external, time-variant signals). This device was developed as part of a research project where online optimisation of stimulation parameters for paraplegic cycling shall be realized. The target of the project shall be reached at the end of 2004.

Methods

In principle it is possible to generate stimulation signals directly on the PC using modern data acquisition cards and software. As described in [3] a version with multiple channels can also be realized. The advantage of such a solution is the quick realization. Basic knowledge of PC measurement technology and electronics is sufficient to generate a stimulation pattern. However, the disadvantage of generating the signal patterns with the computer is that a big fraction of the computer power is used due to the effect that optimisation- and other algorithms cannot be performed anymore.

The concept presented in this paper (Fig.1) was designed in such a way that only those parameters which are calculated by the control- or optimisation-algorithm on the PC have to be transferred via a standard interface, e.g. the serial interface. The specific transfer of the desired parameters for the biphasic signals (desired frequency, amplitudes, ramps, etc., see signal definition in Fig.2) is completely autonomous and based on a powerful and inexpensive **d**igital **s**ignal **p**rocessor (**DSP**, Texas Instruments, TMS320F2812). At a clock frequency of 150 MHz this processor needs only 6.67 ns for one instruction cycle.

By using the DSP integrated pulse width modulators (**PWM**) a 16-channel FES-generator can be realized with relatively few additional electronic devices. An FES-pattern generator with a higher number of channels can also be realized with this concept. One possibility is to generate additional stimulation signals by multiplexing the available PWM-channels in the intervals between the biphasic signals T3 – (T1+T2), which has not been realized yet. Because of the low cost for one DSP-system, a higher number of channels can be obtained alternatively by controlling several DSP-units from the PC via additional serial interfaces.

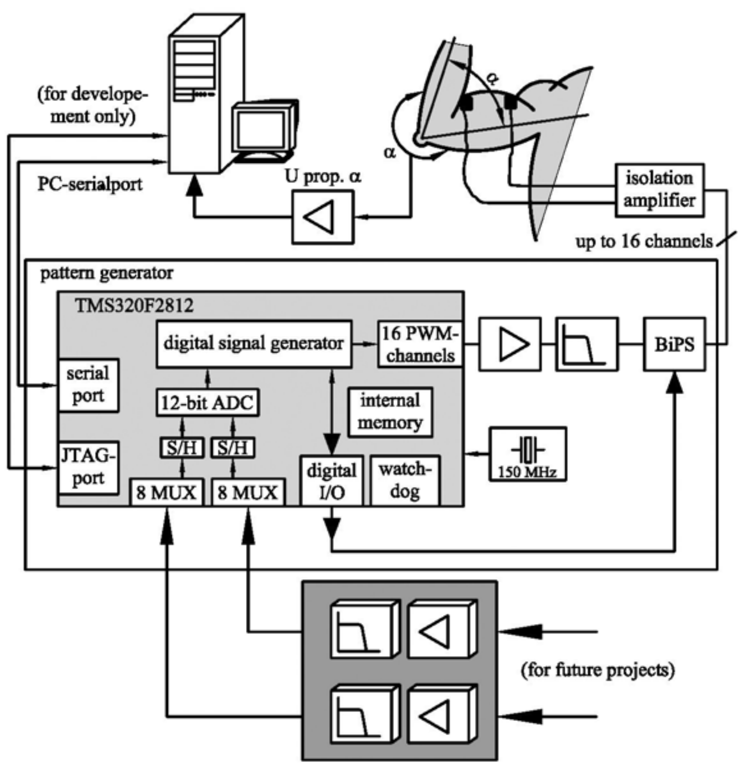


Figure 1. Block diagram of the PC-controlled pattern generator with high flexibility.

For each channel the desired amplitude of a biphasic signal train is defined by the dedicated PWM signals. If necessary it can be generated independently or synchronously. The PWM signal is 1st order low pass filtered and is sent into the **Bip**hase **S**haper, **BiPS.** It consists of one operational amplifier, which inverts the signal and two DSP controlled analogue switches. The output signal is directly used for the control of the isolation amplifier. The pulse duration of this biphasic signal (T1 and T2) can be controlled for any value greater than 1 µs.

The DSP additionally offers 2 x 8 analog Input-channels with 12 bit resolution. They can be used e.g. to turn off the stimulation automatically and can be decoupled from the PC for a very fast respond with high reliability. This can be relevant in case of spasms or danger of overextension of joints during practical tests on human volunteers.

## Results

Fig. 2 shows some examples for test results with the new stimulation device. The time delays are shown with respect to the start of the data transfer, which was measured directly at the serial port (signal on top, channel 1). Channel 2 shows the needed time to change the duration of the positive phase (T1). In channel 3 the duration of the negative phase (T2) is set to a very short value (about 20 µs). These are just arbitrary examples, which are supposed to illustrate flexibility, precision and time delays, available in this concept. The time period T3 was chosen to be shorter than in common stimulation application to allow high resolution measurements of changes over time.

Channel 4 shows an amplitude-modulation of the biphasic signals. Currently the DSP program is designed so that it generates the same amplitude for the positive and negative phases of the biphasic signal. Generally the amplitudes can be varied by modifying the pulse width modulation during the time intervals T1 and T2. Finally, an example for changing the time period is shown in channel 5.

With a signal parameter definition as outlined in Fig.2, all details of the signal can be defined by 10 parameter values per channel and modified again in the next parameter transfer. Changes by the pulse width control are immediately effective after the end of the current PWM periode (< 20 µs). The digital I/Os of the DSP, used to control T1, T2, and T3 of the biphasic signals are changed within the time of only a few instruction cycles (<< 1 µs).

By using the serial port-routine in LabView (Version 6.1) from National Instruments, and a baud rate of 115 200 bit/sec a parameter transfer takes 0.944 ms per channel. The 10 signal parameters and the channel-ID are transferred for each channel. The time delay caused by the parameter transfer to the serial port in the program depends on the available computer power.

Basically the transfer speed of the serial port combined with the number of channels defines the actual attainable velocity for changes of the FES signals. Applying the described detailed transfer protocol all parameters of the 16 channels can be adjusted in less than 20 ms.

## Discussion

Important advantages of the described concept for an FES pattern generator in comparison to the systems that have been described in the literature so far are the high flexibility and precision in the definition of the stimulation signal. All combined within the need for only a few additional components. This is possible by using a very powerful DSP, which has integrated all essential components for the FES-pattern generation (serial port, 16 channel PWM, 2*8-channel A/D-converters, digital I/O-ports and a powerful interrupt structure). All tasks concerning the generation of the stimulation signal can be done by this processor within an instruction cycle time lower than 10 ns. Consequently, all of the PC’s computing power is available for application specific tasks like control or optimisation.

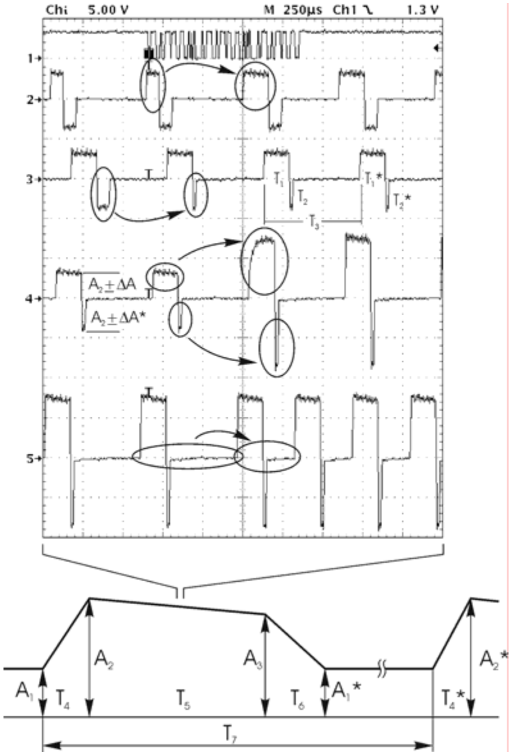


Figure 2. Parameter definitions and examples of generated stimulation patterns.

The transfer rate is dictated by the serial port. If required, the transfer time (maximum 0.944 ms per channel at 115200 bit/s, 10 parameters) can be decreased by adaptation of the transfer protocol to the specific application. For instance parameters which do not have to be changed during the test series can be transferred at the beginning and fixed afterwards.

Alternatively, if an even faster actualisation is necessary, a synchronous serial port can be used instead of the simple standard asynchronous serial port (increase factor 8). As a disadvantage, the length of the connecting wire is limited to less than 0.5 m. By using the PC's parallel port the transfer speed can be increased by the factor 10. In this case the wire length is not strictly limited, but a special hardware and protocol has to be developed for this DSP.

References

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