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MEASUREMENTS ON PROTOTYPE INDUCTIVE ADDERS WITH ULTRA-FLAT-TOP OUTPUT PULSES FOR CLIC DR KICKERS

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Abstract

The CLIC study is investigating the technical feasibility of an electron-positron collider with high luminosity and a nominal centre-of-mass energy of 3 TeV. The CLIC pre-damping rings and damping rings (DRs) will produce ultra-low emittance beam with high bunch charge. To avoid beam emittance increase, the DR kicker systems must provide extremely flat, high-voltage, pulses. The specifications for the DR extraction kickers call for a 160 ns duration flat-top pulses of ± 12.5 kV, 250 A, with a combined ripple and droop of not more than $\pm 0.02\%$ (± 2.5 V). An inductive adder is a very promising approach to meeting the specifications because this topology allows the use of both passive and analogue modulation methods to adjust the output waveform. Recently, two five-layer, 3.5 kV, prototype inductive adders have been built at CERN. The first of these has been used to test the passive and active analogue modulation methods to compensate voltage droop and ripple of the output pulses. Pulse waveforms have been recorded with $\pm 0.05\%$ relative (± 1.0 V) stability for 160 ns flat-top duration at 1.823 kV.

INTRODUCTION

The Compact Linear Collider (CLIC) would be a high-energy electron-positron collider [1]. It could provide very clean experimental environments and steady production of all particles within the accessible TeV energy range. To achieve high luminosity at the interaction point, it is essential that the beams have very low transverse emittance: the Pre-Damping Ring (PDR) and Damping Ring (DR) damp the beam emittance to extremely low values in all three planes.

Kickers are required to inject beam into and extract beam from the PDRs and DRs. Jitter in the magnitude of the kick waveform causes beam jitter at the interaction point [2]. Hence, in particular, the DR extraction kicker must have a very small magnitude of jitter: the 2 GHz specifications call for a pulse of 160 ns duration flat-top, 12.5 kV, 250 A, with a combined ripple and droop of not more than $\pm 0.02\%$ [1]. In addition, the kicker system must have low longitudinal and transverse beam coupling impedances [3].

THE INDUCTIVE ADDER

A review of literature of existing pulse generators has been carried out and an inductive adder (Fig. 1) has been selected as the most promising means of achieving the specifications for the PDR and DR kickers [4]. The inductive adder is a solid-state modulator, which can provide relatively short and precise pulses. With a careful

design of the adder, it may be possible to directly meet the ripple and droop requirements of the PDR kicker [5]. Simulation studies have shown that analogue modulation may provide a means to meet the demanding specifications for the DR kicker [5, 6]. Potentially, this method could also reduce the capacitance needed for the PDR kicker inductive adder [5, 6].

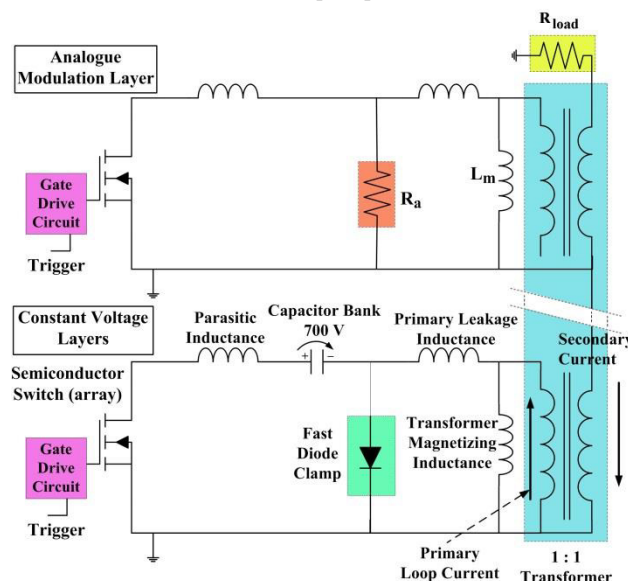


Figure 1: Schematic of an inductive adder with constant voltage layers and an analogue modulation layer.

The reasoning for choosing the main components of the inductive adder has been given in [6]. Recently, two 5-layer prototype inductive adders have been assembled at CERN. The design parameters and the initial results for these pulse modulators were presented in [7] and [8]. The first prototype inductive adder has been equipped with an analogue modulation layer, which can be used to compensate the droop and ripple of the output waveform. The operation of the passive droop compensation method has been verified with measurements and the initial results presented in [9]. More recently, the operation of the active droop and ripple compensation methods have also been verified with measurements. This paper presents the results of experimental verification of applying active analogue modulation for compensating both droop and ripple of the output waveform.

OPERATION PRINCIPLE OF THE ANALOGUE MODULATION LAYER

Passive Mode of Operation

The operation of the analogue modulation layer has been explained in detail in [4] and [5] and hence it is

described only briefly here. The schematic shown in Fig. 1 includes the analogue modulation layer of the inductive adder. This layer comprises a resistor R_a , in parallel with a power transistor, magnetizing inductance L_m and a 1:1 transformer. The power transistor of the analogue modulation layer is working in the saturation region, i.e. in the linear mode of operation. For passive modulation the power transistor is not operated.

In the passive mode of operation, during the output pulse, the resistor R_a is effectively in series with the load resistor R_{load} and the secondary winding of the adder stack [10]. At the beginning of the pulse flat-top, the full load current flows through R_a and the voltage across the analogue modulation layer is a maximum. The load voltage is the sum of the secondary voltages of the constant voltage layers of the inductive adder minus the voltage across the analogue modulation layer. During the pulse, a proportion of the load current transfers from resistor R_a to the magnetising inductance L_m . This causes a voltage decrease across R_a , which is effectively in series with the load, thus countering voltage droop for example of the capacitors of the constant voltage layers. By choosing the ratio of resistor R_a and magnetizing inductance L_m appropriately, the analogue modulation layer can be used to compensate the droop of the output pulse in a passive manner.

Active Mode of Operation

In the active mode the only difference, in comparison with operation in passive mode, is that the power transistor of the analogue modulation layer is conducting during the pulse. By controlling the impedance of the power transistor, the current sharing between resistor R_a and the power transistor can be changed: this causes the voltage over the analogue modulation layer to be modulated.

In principle, an active analogue modulation layer could work without the resistor R_a , thus comprising only a linear power transistor in parallel with magnetizing inductance L_m . However, the presence of the resistor R_a is advantageous because, when the value is properly chosen, during a typical operating condition of an active modulation layer, most of the current will flow through the resistor R_a , and only a few percent of the will flow through the power transistor [4, 5]. Therefore, the power dissipation in the power transistor is significantly less if the resistor R_a is included than without it. Also, if the resistor R_a is present, the passive analogue modulation can be used to compensate most of the droop and the active analogue modulation can be applied to compensate the remaining part of the droop and undesired ripple components of the output waveform.

THE FIRST PROTOTYPE INDUCTIVE ADDER

Figure 2 shows the first prototype inductive adder built at CERN. The nominal specifications for this 5-layer prototype adder are the following: 3.5 kV output voltage,

70 A output current into 50 Ω , 1 μ s pulse duration and up to 50 Hz repetition rate. The initial measurements on this prototype device, including the first high voltage tests and measurements when applying analogue modulation for passive droop compensation, have been reported in [8] and [9].

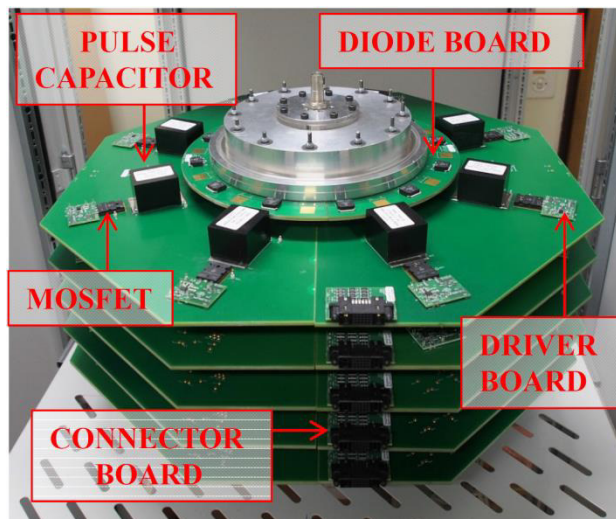


Figure 2: A five layer inductive adder at CERN.

EXPERIMENTAL RESULTS

The active analogue modulation method has recently been experimentally verified with the prototype inductive adder. Initially, the pulse capacitors of the four constant voltage layers were each charged to 553 V. The total capacitance per layer was 24 μ F and the load was a 50 Ω resistor. The fifth layer was an analogue modulation layer in which the resistor R_a was 7.96 Ω . The power transistor in this layer was type ARF463 from Microsemi [11]: it was chosen according to an evaluation study of suitable power transistors [12].

Without the active analogue modulation, the droop of a 160 ns flat-top duration, 1.8 kV pulse, was 24 V. The active analogue modulation was applied by feeding a control signal from a signal generator to the gate pin of the power transistor during the pulse. For compensating the droop, an experimentally defined piece-wise linear ramp function was created. This reduced the combined droop and ripple of a 1.825 kV pulse to $\pm 0.07\%$ (± 1.28 V) during the 160 ns flat-top.

To apply active ripple compensation, the ripple components of the output waveform were first computed using a fast Fourier transform. The most significant ripple component had a frequency of 3.9 MHz. A new control signal was generated, which consisted of the original piece-wise linear ramp and a 3.9 MHz sine wave with appropriate amplitude and phase. This resulted in a reduction of the combined droop and ripple to $\pm 0.05\%$ (± 0.96 V) for a 1.823 kV output pulse of 160 ns flat-top duration. The measured output waveform is shown in Fig. 3: the upper plot shows the output waveform and the lower plot shows a zoom of the pulse flat-top: the peak to

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peak ripple and droop of the pulse flat-top is ± 0.96 V. The curves shown in Fig. 3 are averages of 1000 measured pulses. The averaging reduces random noise and ripple of the measurements. The load current was measured using a Bergoz CT-E0.1-B current transformer [13] and a Tektronix DPO5034 oscilloscope [14]. The measured load current was converted to the load voltage by multiplying the current by 50Ω .

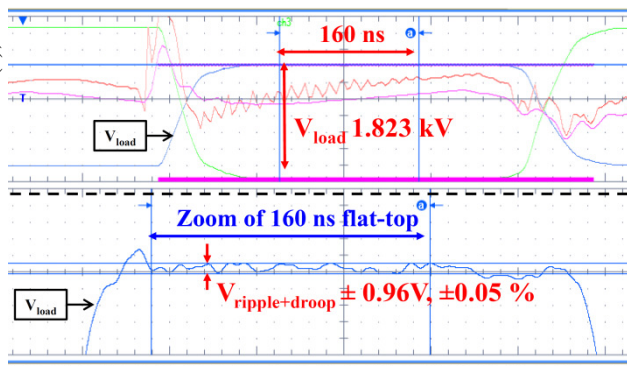


Figure 3: V_{load} (blue) of the first prototype inductive adder with four constant voltage layers, with initial voltage of 553 V across the pulse capacitors, and with an analogue modulation layer ($R_a = 7.96 \Omega$) operating in active mode. In upper plot, time scale for V_{load} is 100 ns/div and vertical scale 300 V/div, and in lower figure, time scale is 50 ns/div and vertical scale 3 V/div.

CONCLUSIONS

In this paper, the experimental verification of using active analogue modulation to compensate the ripple and droop of the output pulse has been presented. By applying active analogue modulation, a pulse flat-top stability of ± 0.96 V ($\pm 0.05\%$) was obtained for a 1.823 kV pulse for 160 ns flat-top duration. The ± 0.96 V is better than required for the CLIC DR kicker system (± 2.5 V), however the $\pm 0.05\%$ needs to be further reduced to below $\pm 0.02\%$. It has been shown that the active analogue method is effective at compensating both the ripple and droop of the output waveform of an inductive adder, allowing a very high precision to be achieved.

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