AUTOMATIC RESONANT EXCITATION BASED SYSTEM FOR LORENTZ FORCE COMPENSATION FOR FLASH*

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Abstract

The cavity is the key element of each linear accelerator used for high-energy physics purpose. The resonant frequency of cavities depends on its shape. Due to the pulse operation they are deformed by dynamic Lorentz force (LF) caused by accelerating electromechanical field. As a consequence, the cavities are not working on resonance but they are detuned from master oscillator frequency by few hundreds of Hertz depending on accelerating field gradient. The paper presents an automatic control system for LF compensation applied to fast tuning mechanism CTS. The active element is multilayer low-voltage piezoelectric stack (EPCOS). The resonant excitation with adaptive feed forward algorithm is used to drive actuator. Test performed at FLASH on cav5/ACC1 showed that detuning during flat-top period (800 μs) might remain below 10 Hz for accelerating field gradient of 20 MV/m.

INTRODUCTION

A Fast Active Cold Tuning System (FACTS) is mandatory for pulsed-mode operation of superconducting cavities at high field. Research on such a system is performed at DESY. The main function of FACTS is to counteract the Lorentz force (LF) and microphonics. Thus the system must quickly react during the RF pulse. To perform fast action at the 2 K the piezoelectric or magnetostrictive elements are used as actuators. Usage of the piezoelements was firstly demonstrated by M. Liepe in horizontal stand test called CHECHIA [1].

During the initial test the EPCOS element has been operated. It is a low voltage (up to 160V), multilayer stack initially developed for injection system for automotive engines. The cross-section of this element is only 7x7 mm^2 and the total length is 30 mm. The blocking force of the actuator is 3.2 kN and the total stroke at room temperature is around 40 μm. However, the stroke is reduced by 85 % at the desired operation temperature of 2 K [2].

The special fixture was developed to integrate the FACTS with existing slow tuner used for pre-tuning purpose. The single piezostack with holder was placed instead of one of the anchor of Cold Tuning System (CTS) developed for TESLA type cavities. The system is used in FLASH accelerator (former name VUV-FEL) [1].

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Hitherto, the Lorentz force was compensated using the manually signal settings. However, there was a need to develop the algorithm which could automatically adjust signal applied to piezoelement. It is especially important when the FACTS will be applied to more than one cavity. In case of the X-Ray Free Electron Laser there will be around 2000 systems, while in case of the International Linear Collider even 20 times more is expected.

The paper presents the current status of research on the automatic, resonant excitation based system for Lorentz force compensation.

DETUNING MEASUREMENT

One of the key elements of the proposed system is a detuning measurement algorithm. In the contrary to the previous solution, there is no longer need to shorten the RF pulse to monitor the phase decay for given time. The new developed algorithm base on the electromechanical model of the cavity. The detuning might be calculated for each pulse, without changing the pulse settings, especially its length. Moreover it is a fully passive measurements and as a results does not disturb the end users experiments.

The detuning is calculated using the formula:

$$\Delta\omega = -\frac{1}{2\pi}\left(\frac{d\phi_{probe}}{dt} - 2\omega_{1/2}\frac{\left|U_{for}\right|}{\left|U_{probe}\right|}\sin\left(\phi_{for} - \phi_{probe}\right)\right) \quad (1)$$

where:

U_{for} is a magnitude of forward power,

ϕ_{for} is a phase of forward power,

U_{probe} is a magnitude of probe signal,

ϕ_{probe} is a phase of probe signal,

The forward and probe signal are taken from ADC converters each single microsecond. Both signals are initially filtered to minimize the noise, which strongly influences the first order derivative. The algorithm have been implemented in MATLAB and was successfully tested and verified with the previously used solution. However, the calculation takes few milliseconds and the results cannot be used in the same pulse. Nevertheless, the LF is repetitive and the calculation outcome might be used in the next pulses.

Recently, there was an preliminary attempt to implement the algorithm in the FPGA based system. As a result, the information about the detuning is available on-line due to the hardware-supported calculation.

PIEZO CONTROL PANEL

The main tool, which was used for algorithm improvement and later for piezostack control is a selfdeveloped Piezo Control Panel (PCP). It is a GUI based script written in MATLAB, which communicates with the hardware part of the control system using the DOOCS servers.

The PCP has five main functions. First of all, it illustrates the forward and reflected power as well as probe signal for given cavity. Using these parameters the detuning in single pulse is calculated using the previously described algorithm. Then, the detuning during the RF pulse flat-top is linearly approximated. Additionally, to investigate the estimation error a standard deviation between the measurement and linear approximation is calculated. As a result for each RF pulse three parameters are registered – decay of the detuning during the flat-top, the offset of the detuning in the middle of the RF flat-top and the average error due to the approximation.

Secondly, the PCP is able to form several types of pulses which is later transferred into the electrical signal by the function generator. The signal after amplification is applied to the piezostack actuator. The scheme of the control system is presented in figure 1.

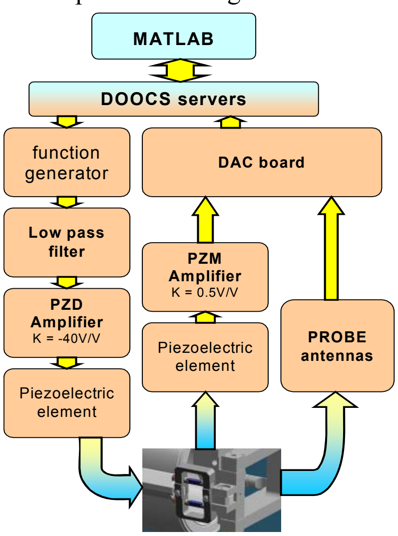

Figure 1: Overview of control system for FACTS.

The next function which is contained in the PCP is the ability to store and recall the settings from the hard drive. Additionally, the PCP presents the current status of the system and shows the current amplitude and phase of the RF field. At last but not least, it allows to apply the automatic, resonance based algorithm for Lorentz force compensation.

SYSTEM INVESTIGATION

During the research several test connected to FACTS performance, which is assembled in FLASH accelerator ACC1 cavity 5, were performed. Different shapes of the pulse applied to the EPCOS piezoelement were investigated. According to the performed test there were no possibility to compensate the detuning caused by field gradient of 18 MV/m in single pulse. It is due to different initial pre-stress applied to the actuator than it was earlier done in CHECHIA test stand. It is impossible to exchange the actuator and the pre-stress adjustment. As a consequence, there was a need to develop other method to compensate the Lorentz force effect.

The authors propose to use a multi-periods sin-wave-like signal. The overview of used pulse with marked parameters is illustrated in figure 2. There are five variables which defines this pulse shape - the frequency *f*, amplitude *A* and offset of the sine wave, the number of periods and the delay time in respect to the RF pulse begin (*t_delay*).

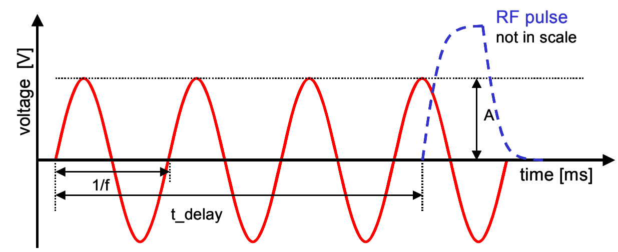

Figure 2: Shape of the pulse applied to piezoelement. Parameters which can be set in the system are marked

The optimum value of each of the above mentioned parameters where found in the experiments. The value of given variable was changed step by step and the parameters of the linear approximation of the detuning measurement were registered. At the end of these time consuming experiments, the quasi optimal parameters has been found.

The frequency of the signal should be either around 284 Hz or 430 Hz to cause the highest compensation. The length of the pulse were set to four periods. Then, the delay between the beginnings of RF pulse and the one applied to the piezoelement is optimal if equal to -11.84 ms. The offset should be zero.

According to the performed test, all above parameters are optimal and constant for different gradients from 8 to 18 MV/m. The only parameter, which need to be changed in respect to the RF field gradient is the amplitude of the signal applied to the piezoelement. These values are presented in the figure 3. The red curve is a quadratic approximation of measured values.

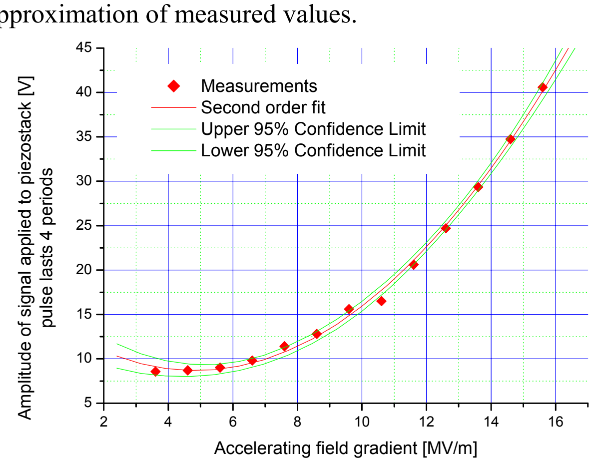

Figure 3: Measured amplitude of signal applied to piezostack needed for optimal compensation of Lorentz force in function of accelerating field gradient.

COMPENSATION ALGORITHM

The developed method base on the adaptive feed forward algorithm. As it was shown previously it is possible to predict a distortion of the cavity because Lorentz force depends on the accelerating field gradients and the properties of the system. Since the structure is stable, it is possible to develop algorithm, which will rely only on the measurement of the field gradient. Moreover, the previously presented data indicates that multi-pulse compensation might be used and there is need to control only the amplitude of the signal.

In presented solution the initial setting for amplitude of the sine signal is taken from the preset table depending on the accelerating gradient. The other parameters are constant and equal to the previously presented ones.

The signal is applied to piezostack and the measurement of detuning in next pulse is done. Usually, due to the imperfections of the system, the detuning curve is not really horizontal during the RF flat-top (what corresponds to the positive or negative detuning). As a consequence, a fine-tuning is needed, which could cancel these small errors. If the slope of the linearized detuning $\Delta\omega/\Delta t$ is different from zero, then an amplitude correction is calculated. The value of the adjustment ΔA is given by the formula:

$$\Delta A = \Delta\omega/\Delta t * b \qquad (2)$$

where b is found in the experiment and equal to 0.005

Then, in next iteration a new signal is applied and new detuning is measured during RF pulse. If the error is smaller than previous one, the new settings are stored in the preset table. If the error is different than zero then a further correction is calculated and signal is properly modified. After that the last step is iterated.

The presented algorithm was tested with success in ACC1 cavity 5. The detuning for accelerating field gradient above 15MV/m, which if uncompensated is around 180Hz, was usually reduced to below 10 Hz in only 2-3 iterations. The results are shown in figure 4.

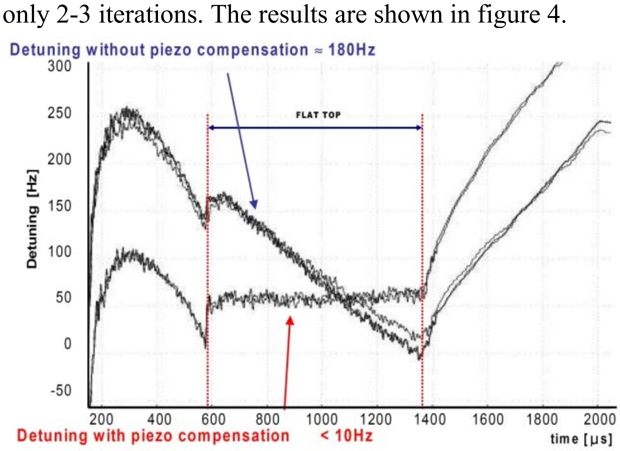

Figure 4: Cavity detuning with and without piezostack-based system measured in cavity 5, ACC1, FLASH accelerator. The accelerating field gradient is 20 MV/m.

Another benefit of proposed algorithm is an ability to track the changes of accelerating field gradient. Moreover, it also follows the system parameter change i.e. beam current or stepper motor position. It also quickly adapts to the new systems parameters, therefore it can be used when the FACTS will be assembled to many cavities even if there will be different mechanical constraints.

Nevertheless, the main advantage of presented algorithm, beside of the fact that it suppress the Lorentz force effect, is its simplicity. As a consequence, it would be easy to implement the presented algorithm in the low-level radio frequency control (LLRF) system realized either in DSP or FPGA. Moreover, the implemented online detuning measurement allows to develop new methods to compensate not only the Lorentz force but also the microphonics.

CONCLUSION

The piezoelectric based FACTS is successfully applied to compensate the Lorentz force detuning in superconducting radiofrequency cavities used as accelerating structures in FLASH. It allows tuning the cavity by 200 Hz with reasonably low voltage applied to the actuator (up to 50 V). The multi-pulse, automatic algorithm is used which was successfully tested in real system (ACC1/cav5). Additionally, the low voltage, which is needed for compensation allows to improve the lifetime of the actuator [4] or permits to use the weak EPCOS piezostacks also for higher RF field gradients.

Further development of control are foreseen. Especially, the presented methods will be implemented in FPGA based system. Moreover, it is foreseen to use a single board to control several piezodrivers. The proper experiments will be done as soon as the next module for FLASH will be available. Then, each cavity will be equipped with FACTS.

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