METHOD OF BROADBAND STABILIZATION OF THE VEPP-4 MAIN FIELD

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Abstract

The stability of the main field has great influence on precision experiments on particle physics which are performed on VEPP-4M facility currently. A method of broadband stabilization of the VEPP-4M main field allowing us to achieve field stability better than 0.5 ppm over DC - 50Hz frequency range is presented. The method combines NMR stabilization and feedback loop using induction signal.

INTRODUCTION

It is necessary to know the beam energy of cycling accelerators in the particle physics experiments. At VEPP-4M experiment of CPT-invariance test by comparison of spin precession frequencies of electron and positron simultaneously circulating in VEPP-4M storage ring with accuracy 10^{-8} is planned [1]. The error of this experiment directly depends on stability of guiding magnetic field therefore long-term stability and field ripples are of the great importance. Long-term (hours) stability 10^{-6} allow one to find optimal parameter for the measurements. High-frequency ripples (up to 5 Hz) results in broadening of resonance spin precession frequency. This effect increases statistical error of the experiment. The frequencies more 10 Hz result to side spin resonance harmonic and could be excluded by optimal experiment parameters choice. Furthermore field instability induces beam orbit pulsation which has negative influence on count rate of Touschek polarimeter and increases the systematic error of the experiment. So, detrimental influence of filed pulsation in a range from 0.01 to 10 Hz on statistic and systematic error in this experiment requires wide range stabilization system of guiding field of VEPP-4M storage ring.

THE VEPP-4M MAIN FIELD QUALITY

The VEPP-4M magnetic structure containing about 100 bending magnets are supplied by high current power supply IST. The main field varies in the range from 0.15 T at injection energy to approximately 0.55 T at maximum energy [2]. All magnets are connected in series, and current is changed from 2 kA to 5.5 kA. Long-term stability of supply current stays at 10^{-5} relative level. In series with the bending magnets, there is “out of ring” additional calibration magnet which is fully identical to bending magnets.

The precision NMR magnetometer [3] is used to measure absolute value of the VEPP-4M main field in the calibration magnet. Full measurement cycle consists a few elementary cycles. Each cycle includes only one excitation RF pulse and one NMR response signal. Typical NMR signal duration for the VEPP-4M dipole magnet in the field range 0.15-0.2 T is ~5 ms. Time interval between elementary cycles T_e is defined by NMR working substance relaxation time. For VEPP-4M NMR probe $T_e \approx 0.08$ s. So, during full busy time real measurement is performed only within short interval ~5 ms separated with 0.08 s, where no NMR signal presents. To improve measurement accuracy the accumulation of NMR response signals is used (usually 8 – 16 elementary cycles).

To increase stability of the VEPP-4M main field, the feedback loop was implemented into the power supply control using data given by NMR magnetometer. The difference between set point and measured field is converted to an additive to be added to value measured with DCCT. That “via-DCCT” way allows correcting the power supply current. The integral term of PID controller is used with integral gain approximately equals to 0.5. Higher gain value results in feedback loop instability. The correction rate is about 1 s, providing field correction in the band from 0 Hz up to 0.1 Hz. Fig. 1. presents the NMR magnetometer data with the feedback off and on.

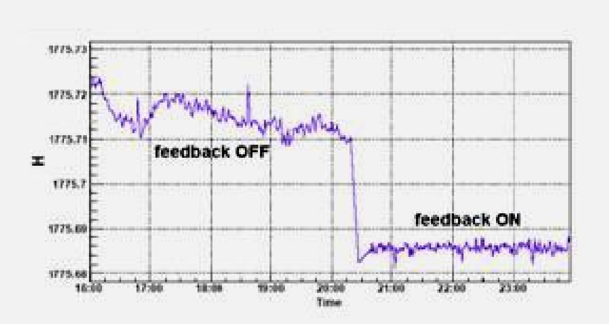

Figure 1: The NMR stabilization efficiency.

The long-term instability is about 1 ppm (RMS). However, NMR measurements don’t provide information about amplitude and frequency content of field instability for frequencies higher than 1 Hz. In order to measure high frequency ripples it was used the induction sensor placed into calibration magnet. The sensor is equipped with electrostatic shield which suppresses coupling with power supply rails. The sensor has magnetic area $wS = 7.7\ m^2$. Its output voltage is recorded by the multimode digital integrator VsDC3 [4] and these data are processed to get Fourier transform. The spectral components are divided by $2\pi F \cdot wS \cdot B$ factor giving magnetic field ripple amplitude relative to mean value B at frequency F. Fig. 2 (blue plot) presents the VEPP-4M field ripple spectrum.

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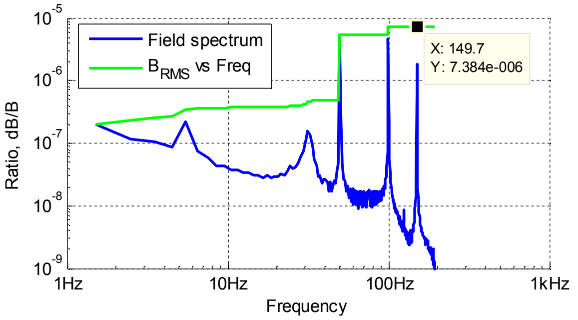

Figure 2: Ripple spectrum (blue) in terms dB/B and dB/B vs on band of observation (green).

There are spectrum peaks at 5 Hz and 30 Hz because of magnets mechanical vibration. Such system as vacuum, air-conditioning or cooling water pumps can provide it. Spectral components which are multiple of AC frequency (50 Hz, 100 Hz and so on) are influenced by IST power stage. Note that despite the fact that bending magnets have not laminated iron yoke the field spectrum contains significant components up to 150 Hz. Green plot in Fig. 2 represents dB/B rms depend on band of observation. One can see that dB/B rms level increases from $8{\cdot}10^{-7}$ at 5 Hz to $7{\cdot}10^{-6}$ at 150 Hz. This fact leads us to develop the stabilization system for frequencies higher than 1 Hz in addition to NMR stabilization.

THE BROADBAND STABILIZATION SYSTEM

To solve this task the following technique was proposed. By measuring instantaneous value of magnetic field variation with induction sensor, compensate it by adding directly into the magnetic structure a current of opposite polarity. The structure of the fast suppression system proposed is presented in the Fig. 3.

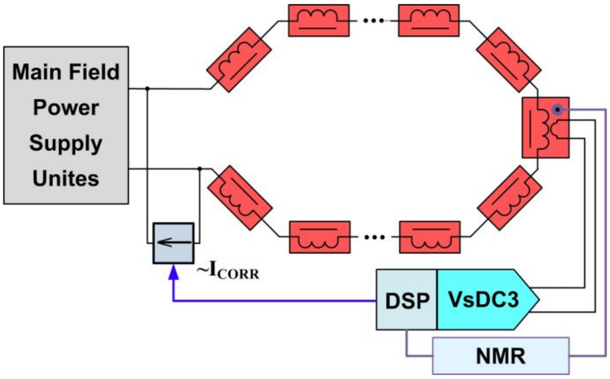

Figure3: The structure of the fast stabilization system.

The system consists of VsDC3 integrator and correction current generator, which is connected in parallel with IST. The distance between devices is about 200 m and they are connected via RS485 digital link. The achieved correction code computing rate equals to 2 kHz. The experimental results of fast suppression system testing are presented in Fig. 4.

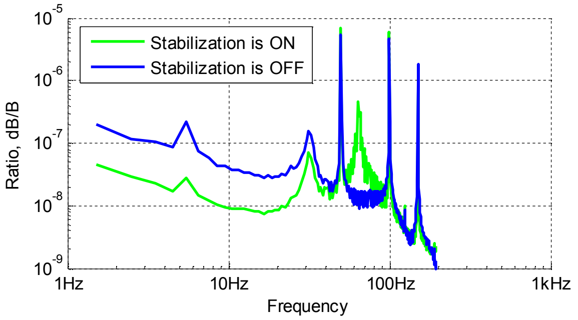

Figure 4: Ripple spectrum for stabilization is OFF (blue) and ON (green).

The blue plot represents typical magnetic field ripple spectrum with fast stabilization is off and green plot corresponds to on-state. The graph shows that at a frequency of 5 Hz suppression of ripples is about 10 times, at a frequency of 10 Hz - 3 times, at a frequency of 30 Hz - 2 times. However, the system demonstrates a lack of performance at 50 Hz and significant loop response rise at approximately 65 Hz. The reason for such system behavior is due to falling of IST output impedance and increasing of magnetic structure impedance with frequency. The measured ratio of magnetic structure current to correction current is presented in Fig. 5.

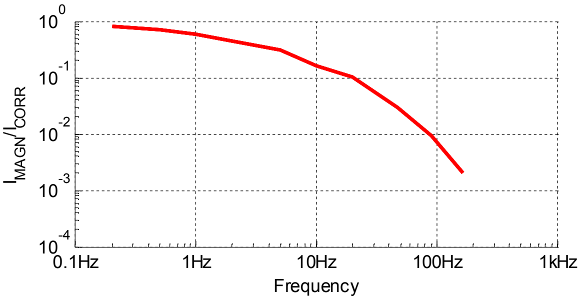

Figure 5: Ratio $I_{magnet}/I_{correction}$ vs frequence.

Less than tens part of correction current is flown into magnetic structure at 50 Hz. As a result the amplitude and phase response of correction current transfer function leads the system to fall in efficiency at frequencies higher than 50 Hz. At the same time attempts to obtain a higher suppression of field ripples in the band above 50 Hz results in unstable operation of the system.

Let us consider open loop response of the fast feedback system in order to demonstrate these statements. The simplified fast feedback loop signal chain is presented in Fig. 6. The digital integrator path gives magnetic flux increments $\Delta\Phi_n$ at 1/Ts sample rate. These $\Delta\Phi_n$ are accumulated in S(z) element giving instant magnetic field values Φ_n. The accumulator S(z) has relaxation time constant (1-δ) which determines low frequency level of the loop operation. Calculated field values are multiplied by gain constant G and pass through the optional five order loop filter H(z). Calculated values are transmitted to correction generator and converted into current using calibration constant α_C. All parameters such as relaxation

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constant δ, gain G or loop filter H(z) coefficients are remotely tunable.

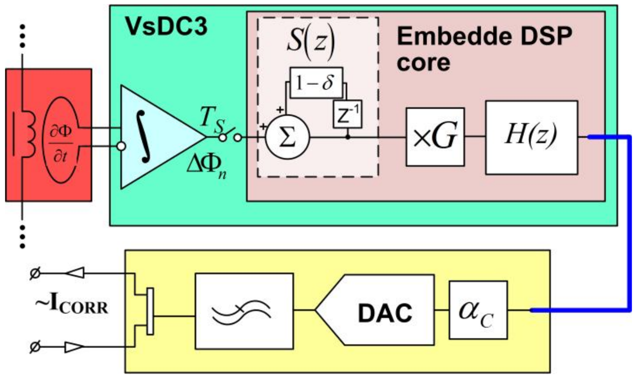

Figure 6: The simplified fast feedback signal chain.

Considering this the signal processing in feedback loop elements can be expressed a follows:

$$I_{CORR}(z)=\left\{\frac{1-z^{-1}}{1-(1-\delta)z^{-1}}\cdot G\cdot H(z)\right\}\cdot\alpha_C\cdot\Phi(z)$$

The numerator of the first term corresponds to z-transform of the sampled flux Φ(z) measurement process, denominator represents S(z) term. Magnetic flux value multiplied by calibration constant α_C approximates ripple current value so the term inside braces represents the gain of the feedback loop. This expression multiplied by measured ratio I_{magn}/I_{corr} (Fig. 5.) gives the model of the system behaviour which is presented in Fig. 7.

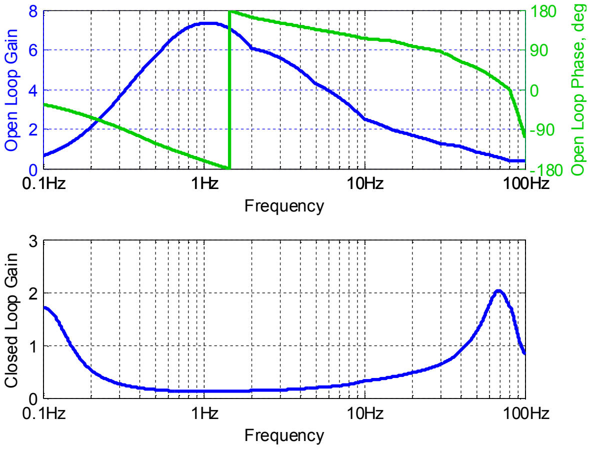

Figure 7: Amplitude and phase response for the case of closed and open-loop feedback.

The maximum stable loop gain G is chosen. The presented model demonstrates good agreement with experimental results: the suppression level and the high limit of working bandwidth match to Fig.4. The low level bandwidth limit is at approximately 0.1 Hz. This limit is determined by VsDC3 noise floor and is tunable via parameter δ.

The integration of broadband stabilization and NMR-stabilization is done by summing correction values from the NMR feedback and the fast feedback. An expected close loop gain is shown in Fig.8. Accordingly the way of slow stabilization "via DCCT" should be disabled.

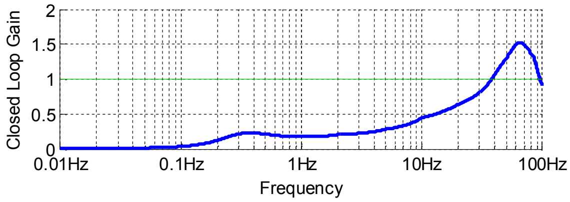

Figure 8: Typical induction signal of pulsed magnetic field and error source of "direct" digital integration technique.

The DSP block of the VsDC3 is able to receive and process NMR and broadband measurements. Up to now standalone operation of NMR stabilization via broadband system was implemented and tested while shared algorithm of stabilization is under development.

Main task in achieving this goal is to increase the NMR measurement rate by decreasing elementary cycle accumulation number. In addition, ways should be found to extend bandwidth of suppression system operation by finding optimal configuration of the loop filter.

SUMMARY

The method of reducing the magnetic field ripples in a band up to 50 Hz is described. In this band the proposed method improves the stability of the VEPP-4 main field in 3-5 times, reaching the level $3\text{-}5\cdot10^{-7}$. These new features should increase quality of future VEPP-4M CPT-invariance test experiments.

The nearest plans are to integrate the NMR and broadband stabilizations and try to increase the band of the ripple suppression using a faster feedback loop.

ACKNOWLEGMENT

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