3 KA POWER SUPPLIES FOR THE DUKE OK-5 FEL WIGGLERS*

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Abstract

The next generation electromagnetic OK-5/Duke storage ring FEL wigglers [1], [2] require three 3kA/70V power supplies with current stability about 20 ppm and current ripples less than 20 ppm in their full operating range. Duke FEL Laboratory acquired three out-of-service SCR controlled power supplies (Trans-Rex, 5kA/100V), which were built almost 30 years ago. The existing archaic firing circuit, lack of any output voltage filtering and with an outdated DCCT, would not be able to meet the above requirements. To deliver the desirable high performance with very limited funds, all three Trans-Rex power supplies have been completely rebuilt in-house at DFELL. Modern high stability electronic components and a high precision Danfysik DCCT have been used. A new symmetrical firing circuit, efficient passive filter and reliable transformer-coupled active filter are used to reduce output current ripples to an appropriate level. At the present time, all three refurbished power supplies are in operation. One of these power supplies was used since August, 2004 to feed OK-4 wigglers with good overall performance. Others two have been tested and used as power supplies for magnetic measurements.

INTRODUCTION

The Trans-Rex power supply was originally designed to produce 500 kW and up to 5000 A DC at 100 V output. The configuration of the power supply is a 12 phase SCR controlled output, with the input AC fed through one Y-Y and one Δ-Y transformer, which provide a 30°-phase shift between the two halves of the power supply. The input transformer primaries are wired in parallel, and each secondary winding supplies one of the 12 SCR output switches, which are controlled by channels of the SCR firing modules (See Figure 1).

The old fashion firing circuit consisted of twelve identical analog-to-phase converters. Any disturbance of identity between channels increased ripples of the output DC voltage with a wide spectral band. Moreover, the original firing circuit was very bulky and took four NIM modules.

A DCCT based on a zero-flux comparator with 60 Hz excitation was not able to provide a high accuracy, low noise voltage for the current feedback. The Trans-Rex current regulator also needed to be rebuilt. It was designed 30 years ago when engineers put available operation amplifiers into an oven with a controlled temperature to obtain the required stability.

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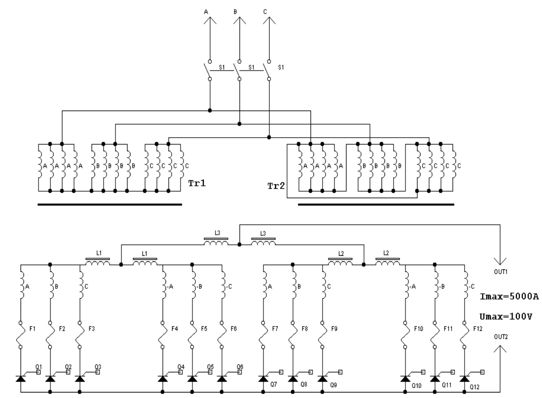

Figure 1: Original Trans-Rex power supply configuration.

Originally, the Trans-Rex power supply did not have any filter for output DC voltage and as a result, current and voltage feedback signals were contaminated by every possible harmonic of the 60 Hz line related noise.

NEW FIRING CIRCUIT

The SCR firing modules have been replaced with a circuit based on a design has been used at the Budker Institute of Nuclear Physics (Novosibirsk, Russia) for a number of years. The operation of this device is based on a single channel analog-to-frequency converter and further distribution of pulses between twelve thyristors. Such a configuration does not contribute internal sources of asymmetry in principle. The presence of a voltage feedback in this kind of a firing circuit enables the reduction of some components of noise in the output voltage. Fig.2 shows the difference in the spectrum of the ripples between the original and updated firing circuits. The magnitudes have been adjusted to the output of an ideal second order low-pass filter.

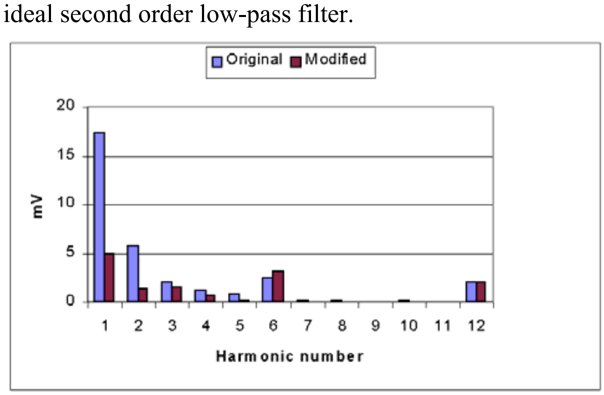

Figure 2: Rectifier ripples spectrum.

PASSIVE FILTER

A traditional LC filter with a resonant frequency of about 16 Hz (L=200 μH, C=0.5 F) has been employed to reduce ripples of the thyristor rectifier to ~200 mV peak-to-peak level. Adjustable AC voltage feedback enables the suppression of the resonant peak of the frequency response of the filter. Attempts at further reduction of the ripples by installing a lower frequency filter significantly deteriorate dynamic behavior of the power supply. Fig. 3 shows the filters layout and feedbacks configuration.

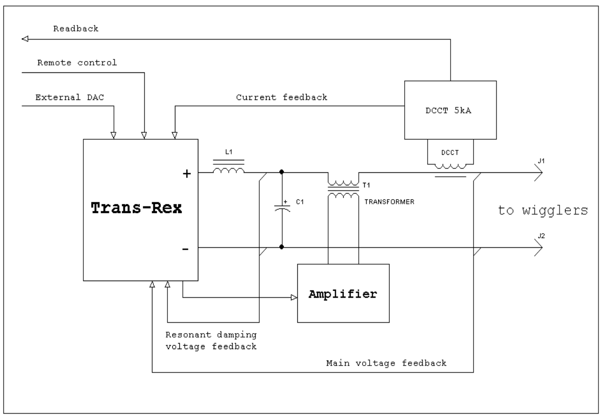

Figure 3: Feedback block diagram.

ACTIVE FILTER

To achieve the required level of ripples in the output current of less than 60 mA peak-to-peak over the frequency range 1 Hz – 1 kHz, an additional fast voltage regulator is necessary. A wideband transistor amplifier in series with the thyristor converter would be the best solution. A linear transistor regulator for full current (3000 A) is possible but is not ease to accomplish. For this reason a transformer-coupled configuration for the amplifier has been chosen. The required peak power of the linear amplifier depends on the inductance of the transformer primary coil and can be derived from expression [3]:

$$S_W \cdot S_Y \cdot Q_{AP}=(5\cdot(I_0)^2\cdot 10^{-7}/B_0)\cdot \Sigma U_j \cdot \Sigma(U_i/\omega_i) \quad (1)$$

Where: I_0 – DC current of the secondary coil;
B_0 – DC component of the magnetic induction inside the gap (≅0,8 T);
S_W – window area of transformer;
S_Y – yoke area of transformer;
Q_{AP} – peak power of amplifier;
U_i – magnitude of the ripple with frequency ω_i in the output voltage of transformer.

The design of the transformer for the active filter is the same as a choke for the passive LC filter. These devices have been manufactured by Polyphase Instrument Company, USA. The peak power calculated from (1) in our case does not exceed 20 W. The functioning of the linear amplifier loaded with high inductance and very low resistance is an essential feature of our chosen configuration. Reliable operation of the amplifier demands effective over-voltage and over-current protection. The output current has been limited to a level of less than 1 A. A combination of clamping diodes and a shorting solid-state relay has been employed and has demonstrated reliable protection against induced voltage surge.

CURRENT AND VOLTAGE REGULATORS

Another issue associated with the transformer-coupled active filter is the matching of the DC converter's and AC amplifier's frequency responses over the frequency range 1 Hz – 5 Hz. Fig.4 presents the open loop frequency responses with two different values of DC gains. The controlled thyristor rectifier has sufficiently nonlinear transient characteristics especially close to zero output voltage. This makes it impossible to have good performance of the active filter for small current. Fortunately, the wiggler's operation does not require high quality current below 100 A. The voltage regulator holds the AC feedback disconnected until output current reaches the threshold. Nonlinear frequency compensation inside the AC feedback loop matches frequency responses in wide range of the output current as well.

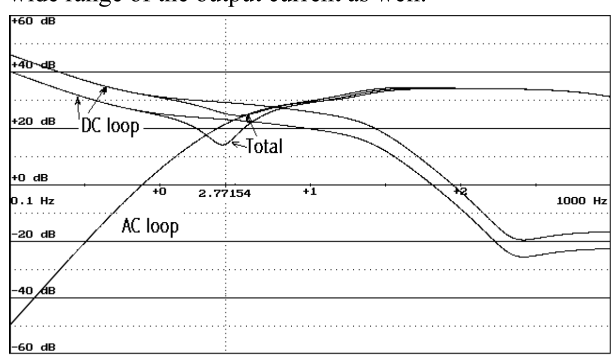

Figure 4: The voltage regulator open loop frequency response.

The current feedback loop includes a DCCT as a current sensor and a precision error amplifier with frequency compensation adjusted for the wiggler electrical parameters. The current regulator is a proportional-integral type. Three Danfysik Ultrastab 860R 5000A DCCT [4] have been acquired to provide required current stability and reproducibility.

INTERLOCKS

A new interlock module has been designed and developed to reduce the numerous mechanical relays in the original design. All interlock sensors and signals (total 9 in use and 3 spare channels) are separated into two categories: one for immediate shutdown such as for an AC or DC over-current, and another for setting zero current such as for an over-heating failure. Any signal sets a flip/flop that latches the interlock until reset by a local or external reset pulse.

TEST RESULTS

Duke FEL standard DC measurements [5] were performed to determine the stability, reproducibility and linearity for each power supply. The stability test covers several levels of current over the operation range: 200 A, 800 A, 1400 A, 2000 A and 2700 A. Each measurement cycle takes about 40 minutes. Fig.5 shows the DC performance of the first Trans-Rex supply powering the OK-4 Wigglers. The current peak-to-peak variation during measurement cycle does not exceed 15 ppm (30mA).

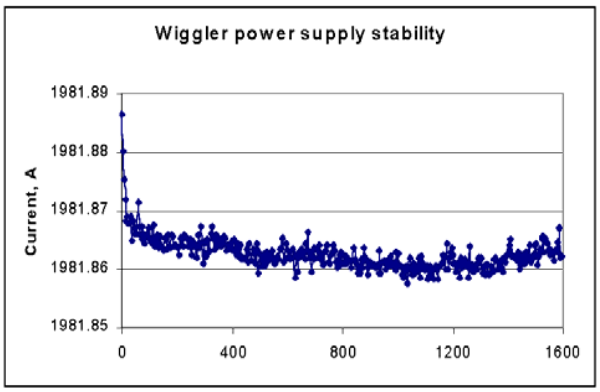

Figure 5: Stability for Trans-Rex OK4.

Fig.6 shows the current stability and reproducibility for a time interval of about 14 hours of actual operation. During this period the current setting was changed several times as shown by breaks in the readback current. Unfortunately, the monitoring ADC does not have sufficient resolution (effectively ≈20 ppm) to show current variation in detail. Peak-to-peak deviation is 30mA (60 ppm).

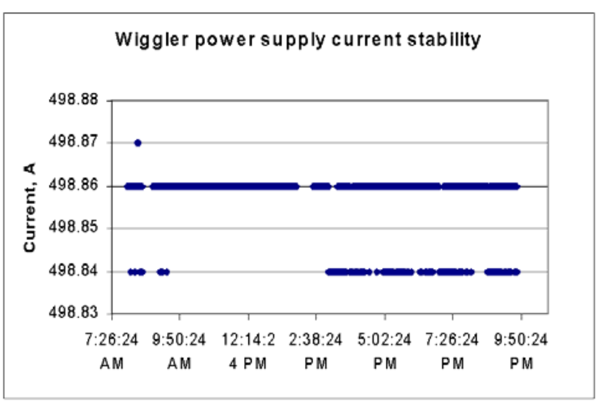

Figure 6: Typical DC performance during one operation day.

AC ripples and noise measurements also were performed. Total peak-to-peak noise over the frequency range of 1 Hz–1 kHz is less than 50 mA. Since the current regulator has narrow band pass, the suppression rate for the line related ripples depends upon the voltage regulator and electrical parameters of wigglers. Comprehensive AC tests need to be performed for the actual magnet configuration.

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