A POWER SUPPLY FOR ONE-SECOND SOURCE OF HIGHLY-STABLE MAGNETIC FIELD

D. M. Grishin, V. P. Gubanov, A. V. Gunin, S. D. Korovin, A. S. Stepchenko
Institute of High Current Electronics SD RAS
4 Akademichesky Ave., Tomsk 634055, Russia
tel. 7(3822)258391, fax 7(3822)259134, e-mail dmitry@dpe.spectr.ru

Abstract

Generation of high-power microwave (HPM) pulses at high pulse rates requires strong magnetic fields, which are commonly produced in superconductive cryomagnets [1]. Batch operation of HPM sources allows the use of quasi-stable magnetic field produced in a solenoid powered from a bank of capacitors. Modern capacitors (such as molecular ones) possess energy storing density ~3.8 J/cm^3.

This paper presents a fully controlled power source for a one-second solenoid. The energy store consists of 32 molecular capacitors connected in series in four stages. The total capacity of the store is 9.2 F, the output voltage is 600 V, and the stored energy is 1.6 MJ.

The capacitive store is charged from four independent 20-Ampere DC sources. The charging takes less than 5 min. To produce the magnetic field, the solenoid is switched onto the capacitive store via switching current regulator assembled from Isolated-Gate Bipolar transistors (IGBT's) [2]. Controlling the transistor switch with PWM-controller allows a decrease in the solenoid current less than 5% while the voltage across the capacitive store drops from 600 to 300 V. The solenoid maximum current is 1.2 kA.

I. INTRODUCTION

When operating an HPM source in batch regime, recharge of the energy store from a low-power source may be made in the pause between the batches. The power consumed from the energy store during the time of magnetic field production is much higher than the power of the charging source.

To produce the magnetic field, the solenoid was switched onto a energy capacitive store for a required period of time.

As the capacitive store discharges and its voltage drops, the solenoid current decreases as well. Reducing this decrease and improving the magnetic field constancy, is usually made by increasing the store capacity.

If the discharge if the capacity is small then the efficiency of using stored energy (ratio between power consumed by the load and stored energy) is

$$\eta \approx \frac{2 \cdot \Delta U_C}{U_{C01}}.$$

Application of such a scheme for production of highly-stable magnetic fields during the batch is economically unprofitable since the cost of the stability is the high capacity of the store. At that, the stored energy using efficiency η is very low.

Modern semiconductor switches such as IGBT's can switch currents of few kA at pulse repetition rates up to few kHz. Using such elements allows producing a switching regulator, which provides constant current level in the solenoid even at large variation of voltage across the capacitive store.

II. FEEDING THE SOLENOID FROM CAPACITIVE STORE VIA SWITCHING REGULATOR

The block diagram of the solenoid power supply from a capacitive store via switching regulator of current is depicted in Fig. 1.

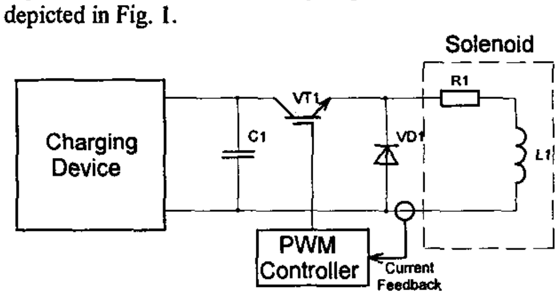

Figure 1. Solenoid power supply with switching regulator of current

The value of initial voltage, to which the capacitive store C1 is charged, is such that, with continuously open switch VT1, the current flowing through solenoid is higher than is required. Since the load of the switching regulator (the solenoid) is inductive with time constant much greater than the period of VT1 switch operation, then the following processes will occur in the circuit (see Fig. 2).

When opening the transistor, the voltage of the capacitor bank U_{C1} is applied to the solenoid, and the solenoid current grows (at that, the diode VD1 is closed).

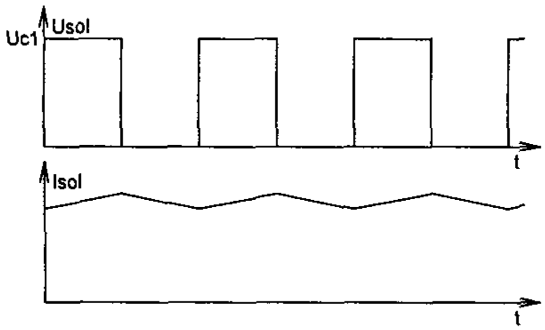

Figure 2. Operation of the switching regulator at initial level of voltage across the capacitor bank

After closing the transistor switch, the diode VD1 opens and the solenoid current continues flowing through the diode (which is accompanied with a decrease in the current). The amplitude of current pulsation depends on the ratio between solenoid time constant and the period of VT1 switch operation.

As the capacitor store discharges, the PWM-controller (supplied with solenoid current feedback) changes the duty factor of VT1 operation (increasing the switch open state time) so that the solenoid current stays constant. The waveforms of solenoid current and voltage at decreased U_{C1} are in Fig. 3.

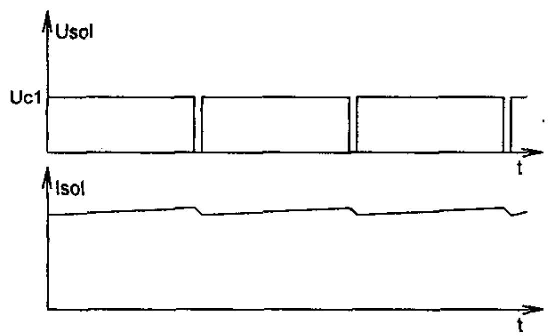

Figure 3. Operation of the switching regulator after partial discharge of the capacitor bank

To estimate the characteristics of the capacitive energy store, consider the process of discharge of the store through the switching regulator. The equivalent scheme of the discharge circuit is in Fig. 4.

This system is described by differential equation

$$C \cdot \frac{dU_C(t)}{dt} \cdot U_C(t) - R_C \cdot I \cdot C \cdot \frac{dU_C(t)}{dt} + I^2 \cdot R_{Sol} = 0$$

Solving the equation results the time dependence of capacitor bank voltage during its discharge through switching regulator:

$$U_C(t) = R_C \cdot I + \sqrt{(U_0 - R_C \cdot I)^2 - \frac{2}{C} \cdot I^2 \cdot R_{Sol} \cdot t}\,, \quad (1)$$

here U_0 is the initial voltage of the bank.

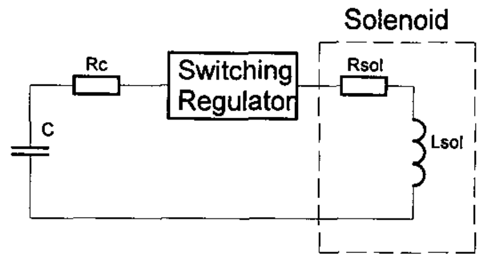

Figure 4. Equivalent scheme of discharge of capacitive store through switching regulator: C – capacity of molecular capacitor bank, R_C – its resistance, R_{SOL} – resistance of solenoid, L_{SOL} – its inductance.

The switching regulator is capable of stabilizing the solenoid current during the time while the output voltage of the capacitor bank exceeds the load voltage ($I \cdot R_{Sol}$).

Starting with this condition and using (1) we get an expression for this time:

$$\tau = \frac{C}{2 \cdot I^2 \cdot R_{Sol}} \cdot \left[(U_0 - R_C \cdot I)^2 - I^2 \cdot R_{Sol}^2 \right] \quad (2)$$

At that, the stored energy use efficiency is

$$\eta = 1 - \frac{U_{C1l}^2}{U_{C0l}^2} = 1 - \left[\frac{I \cdot (R_{Sol} + R_C)}{U_0} \right]^2.$$

III. DESIGN OF THE SOLENOID POWER SUPPLY

The solenoid to be powered from the power source described has two sections. The currents in the sections are 400 A and 800 A, respectively, and the solenoid drop of voltage is 300 V. The magnetic field pulse width is 1 s.

A. Switching regulator

The energy store uses Russian molecular capacitors MNE-4.6/160. Their maximum voltage is 160 V, rated capacity 4.6 F, inner resistance 0.18 Ω. The weight of each capacitor is 32 kg. The bank as assembled by way of serial-parallel connection of the capacitors.

Minimizing the number of capacitors in the bank using (2) for the required solenoid currents and the pulse width gives 32 capacitors connected in 4 stages, 8 capacitors in each stage.

Each section of the solenoid is powered from its individual switching regulator from the common capacitor bank. The block diagram of power supply for a two-sectioned solenoid is in Fig. 5

As switching elements in the regulators, IGBT-modules MTKI-400-12 by Russian company "Electrovipryamitel" (1200 V, 400 A, analogous to FD400R12KF4 by EUPEC) and MTKI-1200-12 (1200 V, 1200 A, analogous FZ1200R12KF4) are used. The module MTKI-400-12 has a built-in diode for 400 A, included as diode VD1 in Fig. 1. The circuit of 800-A regulator on the base of MTKI-

1200-12 uses 10 diodes RHR150100 by Intersil (1000 V, 150 A), connected in parallel. To measure current in the solenoid sections solid-state closed-loop current sensors CSNK591 by Honeywell are used.

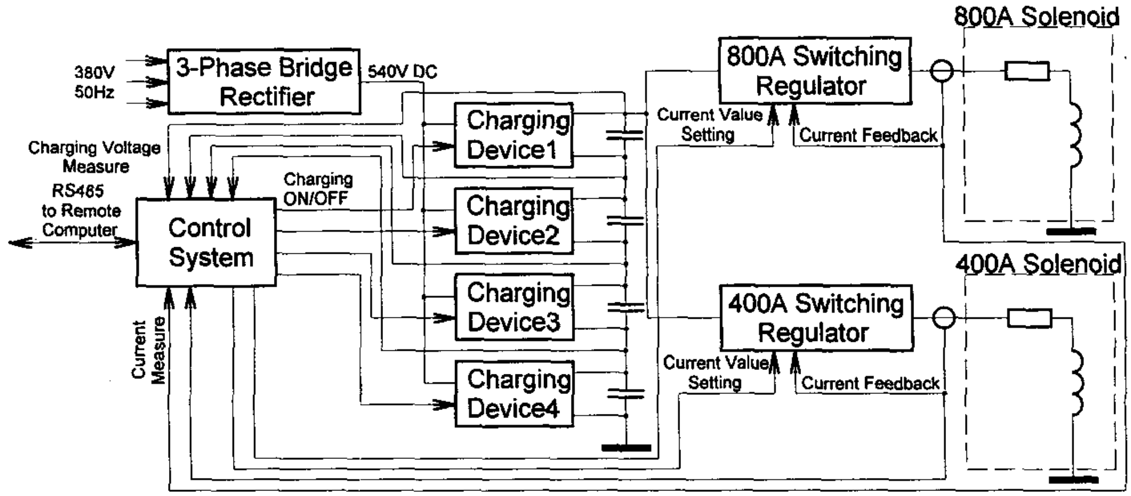

Figure 5. Block diagram of solenoid power supply

B. Charging the molecular capacitor bank

Since the serially connected molecular capacitors have a spread in their capacities and leakage currents, nonuniformity in charging of the stages occurs when charge the bank from a single common power source. To prevent this effect, four independent galvanically uncoupled charging devices are used. Each source charges one stage of the bank with DC current of 20 A up to maximum voltage of 150 V. The charging schematic is shown in Fig. 6.

Each of the four charging devices is a full-bridge transistor converter operating at 20 kHz. As switch elements in the bridge inverter, IRG4PH50UD IGBT's by International Rectifier are used. The PWM controller controls the bridge inverter operation in such a way that constant current flows in the output inductance (behind the rectifier). The charging devices are fed from 3×380V, 50 Hz power mains via 3-phase bridge rectifier. The mains power is 12 kW. The time it takes to charge the bank from zero up to 600 V is less than 5 min.

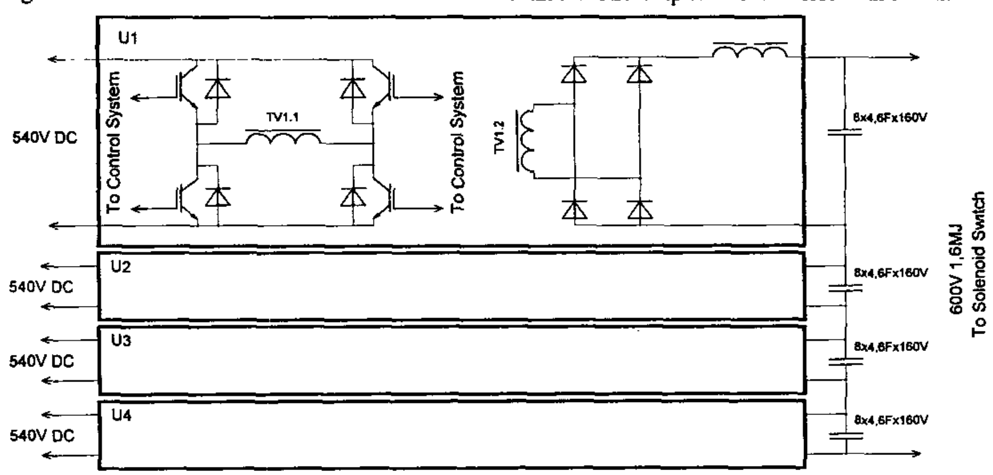

Figure 6. Block diagram of the charging device

C. Control system

The microprocessor control system of embedded type is made on the base of single-chip micro controller AT90S4434 by Amtel. Serial interface RS-485 provides connection of the control system with computer within 1000 m. The block diagram of the solenoid power supply and interaction of its main parts with the control system are represented in Fig. 6.

The control system provides molecular capacitor bank charging and voltage maintenance at required level switching on and off each charging device to keep equal voltages across each serial stages of the bank. The control system gives reference voltages to PWM-controllers thereby setting the required level of current stabilization. This latter can be regulated independently in each of the regulators. At the moment of magnetic field production, the system turns on the regulators for a required period of time, continuously measuring the current. As the rated level of the current is reached, the system generates permission signal to start the HPM generator.

The operating parameters of the source such as voltage the molecular capacitor bank is charged to, values of stabilized currents, and width of magnetic field pulse, are controllable from remote computer. Starting the bank charge and starting the magnetic field pulse is also made by means of this computer. It also displays the values of voltages across each stage of the bank, its charge state, and the present currents in the solenoid sections.

IV. EXPERIMENTAL RESULTS

At present time, the source operates with a single-section solenoid with rated current of 400 A and magnetic pulse width 2 s. In the nearest future, the source will be used to power a double-section solenoid with currents of 400 A and 800 A respectively during one second.

Figure 7 shows the waveforms of solenoid current and molecular capacitor bank voltage in the regime with no current stabilization (the switching regulator is off). The initial voltage at the bank is 435 V and the maximum solenoid current is 400 A. As is seen, the drop of the current during the pulse is about 20%.

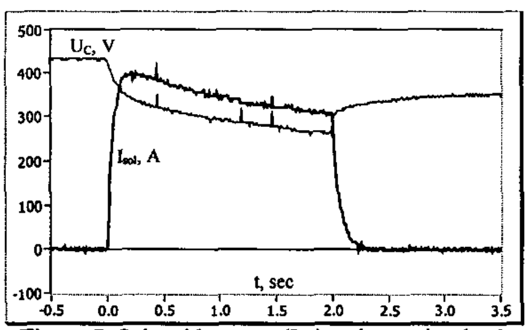

Figure 7. Solenoid current (I_{sol}) and capacitor bank voltage (U_c) with turned-off switching regulator

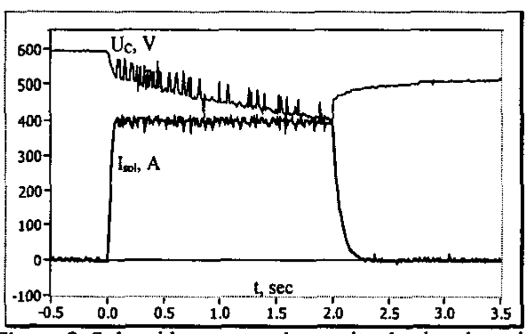

Figure 8. Solenoid current and capacitor bank voltage in the regime of current stabilization

Figure 8 shows the waveforms of solenoid current and molecular capacitor bank voltage in the regime with current stabilization (the switching regulator is on). The initial voltage is 595 V and the stabilized current is 400 A. To the end of the pulse, the voltage at the bank drops for more than 30% but the solenoid current stays constant.

V. CONCLUSIONS

The use of a switching current regulator to power a solenoid from a capacitive energy store allows producing magnetic fields with high stability during a pulse even at considerably dropping voltage at the store. It is important that in this case the energy to be stored in the capacitor bank is much less than that one in the case of feeding the solenoid directly from a bank, to get the same degree of magnetic field constancy.

VI. REFERENCES

[1] Bunkin B. V. et al. "Nanosecond Radar System Based on Repetitive Pulsed Relativistic BWO," Proc. IX Int'l Conf on High-Power Particle Beams (BEAMS-92), v. 1, pp. 192 – 205.

[2] Bees G. L. and Tydeman A. "Capacitor Charging Power Supply Design for High Pulse Repeatability Applications," Proc 12th IEEE Pulsed Power Conference, 1999, pp. 397 – 398.