Liquid Lithium Lens Pulse Power Supply System for Fermilab Antiproton Source

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CONTENTS

I. Introduction.

For the test studies of the liquid lithium lens at BINP it is necessary to design and manufacture a pulse generator to provide such tests at a frequency of *2 Hz* with a load current of no less than *650 kA*. These tests are assumed to be done with the use of the pulse transformer produced at Budker INP for the test studies of lithium lens at CERN. This transformer is planned to be operated with the transformation coefficient *8:1*, thus the current pulse in its primary circuit, will be with an amplitude of no less than *81 kA*. Let us estimate the load parameters in terms of the transformer primary circuit. It is known that the FNAL lens inductance recalculated to the transformer primary circuit with the transformation coefficient *8:1* together with the transformer parasitic parameters is $2.45 \cdot 10^{-6}\ H$. Let us find out the load active resistance. The lithium rod of *2 cm* in diameter and *15 cm* in length at temperature *230°C* ($\rho = 45.2 \cdot 10^{-6}\ Ohm \cdot cm$) has an active resistance of $2.16 \cdot 10^{-4}\ Ohm$. The lens resistance reduced to the primary circuit of pulse transformer will be $1.38 \cdot 10^{-2}\ Ohm$. Let us take the worse case where an active resistance of the discharge contour is the same and then an active resistance of the contour will be of $2.76 \cdot 10^{-2}\ Ohm$. Thus the generator should be operated at an inductance load of $L = 2.45 \cdot 10^{-6}\ H$ and an active resistance $R = 2.76 \cdot 10^{-2}\ Ohm$. At the Budker INP, the sufficient experience for the construction of such generators have been collected. As an example of such generator is one that was constructed for the tests of CERN lens enabled us to obtain current pulses of *1.5 MA* amplitude in the lithium lens of *4 cm* in diameter [1]. The brief description of the pulse generator produced by the standard scheme: capacitive storage–switch–load is given below. The charge device of the capacitive storage is given in more details. This is unconventional device: it was developed at BINP and to our opinion it fits ideally for charging capacitive storages operated in pulse generators at repetition rates ranging from a few fractions of *Hz* to several tens of *Hz*. Such a charge system was proposed by us for the TESLA collider (DESY, Hamburg) [2] and we want to present it now. This system was offered by us for the TESLA DESY (Hamburg) Project. It was chosen among several variants for realization.

II. General layout of the pulse generator.

Fig.1 shows a simplified schematic diagram of the pulse generator which enables one to obtain in the load the sine currents of *300 mks* duration with an amplitude of over *650 kA* at repetition rate of *2 Hz*. In this case, the capacitor batteries C_1 and C_2 are charged by the charge device of constant power providing their charge of up to *7 kV* at the generator operating frequency of *2 Hz*. Exchange of poles is achieved through diodes D_3, D_4 and the load. Because of the low duty factor of the contour this circumstance does not affect practically the heat release in the lithium lens as seen from diagram in Fig.2 (power) but in this way, we remagnetize the saturation choke L_1 and the pulse transformer Tr_1 . After test shots to the real load one can arrive at the final conclusion on whether an additional demagnetizing system from DC-source B_0 will be necessary or not. The generator discharge contour parameters are given below. Fig.2 shows values of current and voltage in the main points of generator calculated with CAD «NL-2.02» (designed by A. Smirnov). All the values are reduced to the primary winding of transformer Tr_1 .

1.	Load inductance .	$2.45 \cdot 10^{-6}$ *H*
2.	Inductance of buses of capacitor batteries	$0.3 \cdot 10^{-6}$ *H*
3.	Total inductance of two thyristor modules	$0.3 \cdot 10^{-6}$ *H*
4.	Inductance of choke L_1 in saturated state ($\int V dt = 4.5 \cdot 10^{-2} [v \cdot s]$)	$0.26 \cdot 10^{-6}$ *H*
5.	Inductance of feeder line generator–load	$0.2 \cdot 10^{-6}$ *H*
6.	Total inductance of charge contour	$3.51 \cdot 10^{-6}$ *H*
7.	Active resistance of charge contour	$< 3.5 \cdot 10^{-2}$ *Ohm*

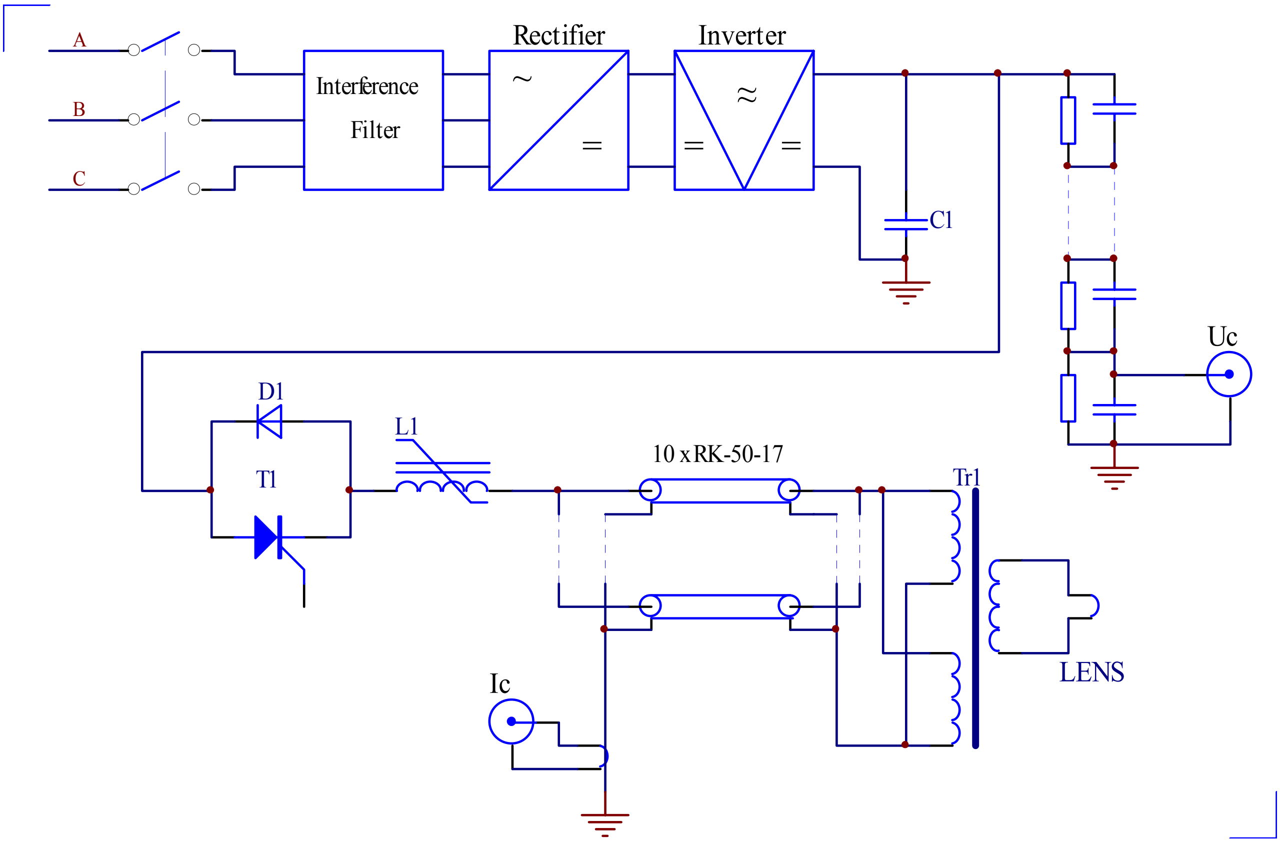

Fig.1. Simplified diagram of the lens power supply

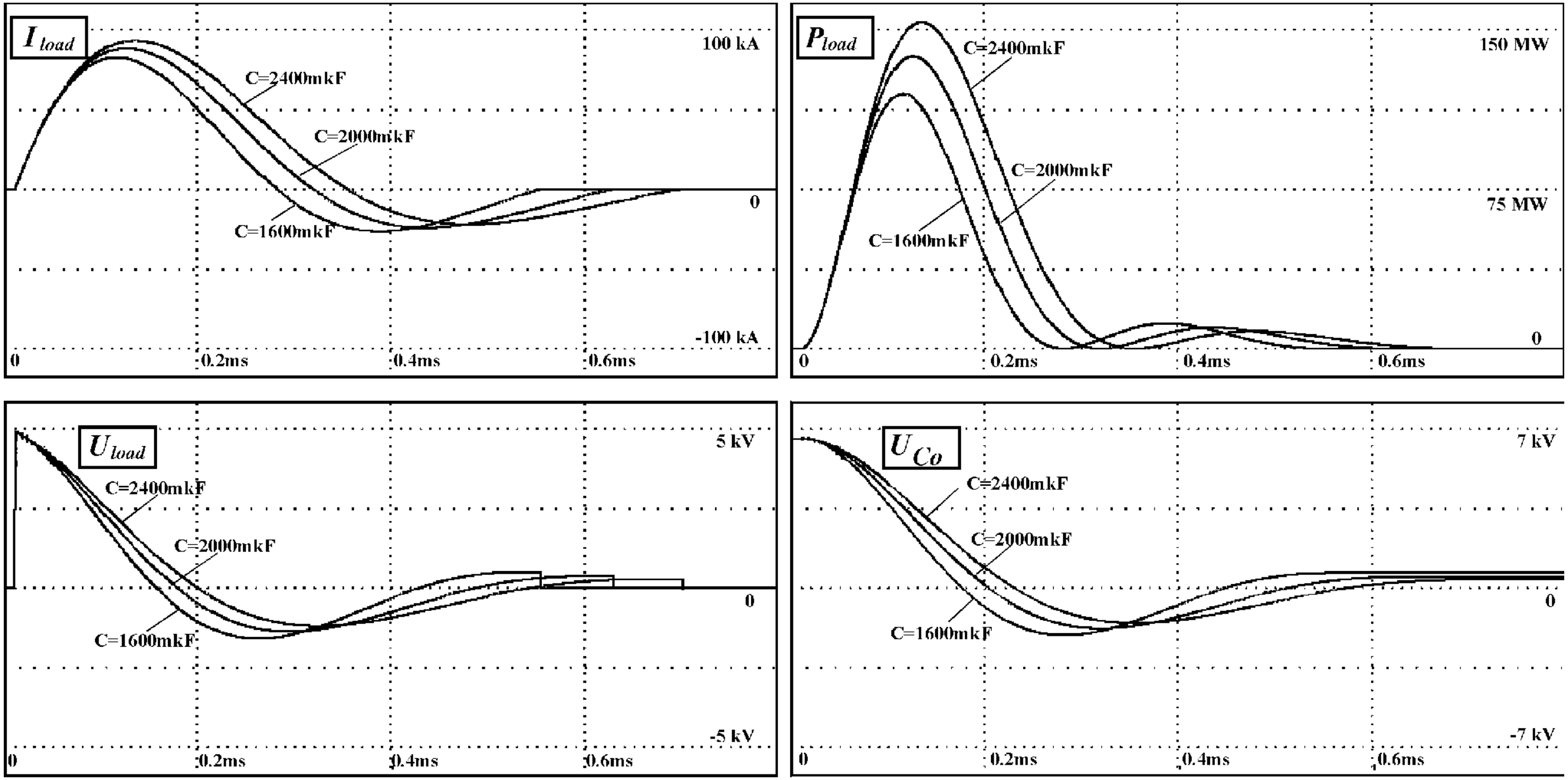

Fig.2.Diagrams of current, power and voltages in the main points of pulse generator.

III. Constant Power Charge Device

1. Conceptual design of a constant power charge device

General requirements to the charge device are mentioned as follows:

1. Maximum efficiency;
2. The mains should be loaded with a constant power with minimum spikes and phase distortions;
3. No breaks in the power consumption during the operation cycle of the modulator;
4. Smooth control of voltage at the capacitance in a wide range (from zero to the maximum value);
5. Turn on of the modulators with a smooth transition to the operation regime;
6. Stabilization of the charge voltage;
7. Variation of the repetition rate of the modulator operation cycles from fractions of a *Hz* up to tens of *Hz* while preserving the condition of constant power consumption from the mains;
8. Obtain a maximum power factor of the rectifier, feeding the charge device by both decreasing the harmonic composition of the consumed current and by the high value of $\cos\varphi$;
9. Maximum correspondence for requirements harmonic control in electrical power systems;
10. Minimum rated power for elements of the charge device.

The proposed charge device, to the opinion of the author, in the maximum measure corresponds to all enumerated requirements.

The analysis of the used methods for charging the capacitors has shown that, as a rule, they can not meet to the full extent all the listed above requirements.

It is known [3] that the maximum efficiency of a charge circuit is provided by charging a capacitance with a constant value of current

$$\eta = \frac{1}{1+2k^2 \cdot \dfrac{RC}{T}},$$

where $k = I_{ef}/I_{av}$ is the charge current form coefficient, (I_{ef} is the effective current value, I_{av} is the average current), R is the active resistance in the charge circuit, C is the capacitance, T is the charge time.

In this context, the optimal system is the one providing the charge of the capacitance from a voltage source with a constant current. The charge of capacitance with a constant current, widely used in the world, is performed by means of a phase control over the mains pulses [4,5] or by means of a pulse–duration modulation of the source [6]. But the conclusion that the converter efficiency is maximal under a condition of a constant charge current is true only if the converter contains a single circuit. Electrical circuits of converters (from voltage sources to current sources) contain no less than two current circuits. When the charge current in the converter output circuit is constant, but the constant current from an input circuit source can not be provided, the condition of minimum relative energy loss can not be met.

A general calculation of the charge device efficiency is given in [3]. Main conclusions of this study are presented below. According to [3], a circuit of the charge device with an ideal converter without loss is given in Fig.3.

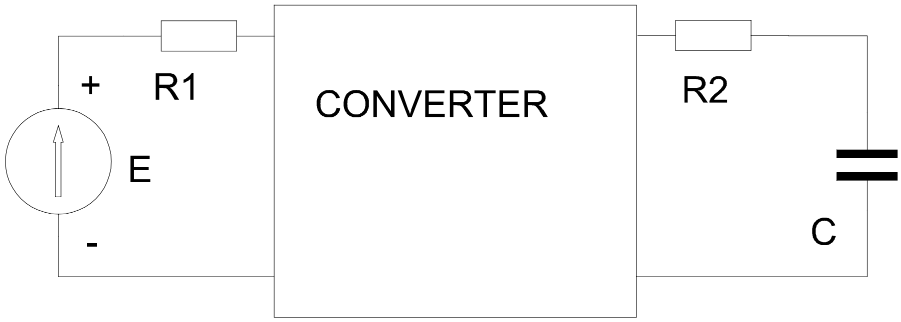

Fig.3. Circuit of charge device with ideal converter without loss.

The input circuit losses are accounted by a resistance R_1 and output circuit losses are accounted by a resistance R_2. The efficiency of the charge device η obviously equals to: $\eta = \eta_1 \backslash \eta_2$, where η_1 is the input circuit efficiency, and η_2 is the output circuit efficiency. As a result the authors obtain the following equation:

$$\eta = \frac{0.5 + \sqrt{0.25 - k_1^2 \left(1 + 2k_2^2 \cdot \frac{R_2 C}{T}\right) \cdot \frac{P}{P_k}}}{1 + 2k_2^2 \cdot \frac{R_2 C}{T}},$$

where k_1 and k_2 are coefficients of the current forms at the converter input and output (charge) circuits, P is the mean charge power on the capacitance C, P_k is the short-circuit power of the collider feeding system. (The effect of P_k on the choice of type of the charge device will be observed further).

Imagine the charge device, where the capacitance periodic charge is produced from a constant voltage source via an ideal voltage-current converter. The converter contains a device providing relative duration of charge current pulses, or a device for the phase control of mains pulses, and is used for keeping the time independent charge current. It is obvious that then the capacitance voltage and instantaneous power after the conversion will be linearly increased in time. As our converter does not contain a energy storage, comparable with the energy of the modulator capacitor, the instantaneous power at the converter input repeats the instantaneous power form after the converter. The conclusion is the following: the charge system with a time-constant current in the capacitor charge circuit, loads the power system from the saw law, when the power consumed (inside the charge interval) starts from zero and ends with a doubled value with respect to the mean charge power.

The input current form factor for this device is $k_I=1.16$, the efficiency of the charge device is decreased, but there exists a more important factor, which can make it impossible in principle to connect the device to the power system without special measures taken. This concerns the energy consumers whose mean power makes hundreds of MW.

An over two–fold "attack" on the power system with respect to the mean power caused by the DC charge will lead to a contradiction with the electro-technical standard for the electrical energy quality [7].

The value of the charge device efficiency and its optimal interaction with the power system is basically determined by a feasibility to transfer the energy to the converter at a constant power [8] Such a system does not have the above shortcomings and has the following advantages:

1. A higher source utilization factor – this allows to decrease its mass;
2. Minimum possible losses in the converter input/output circuits;
3. Low-frequency "shocks" upon the power system (with lens repetition rate), hampering the operation of other consumers, are eliminated;
4. Meets criteria for charge devices, listed at the beginning of this chapter.

2. The choice of scheme of the power charge device.

BINP has successfully tested a charge system consuming a constant power of *300 kW* from the mains, which consists of three *100 kW* modules. The basic part of the module is a thyristor inverter converting the input voltage into current pulses at a high repetition rate, charging in portions the capacitor up to the required voltage through the step–up transformer. The module operation is described in more detail in [9]. Below in this paper will be also described the module operation in its application to our task. A sketch diagram of the device is given in Fig.4.

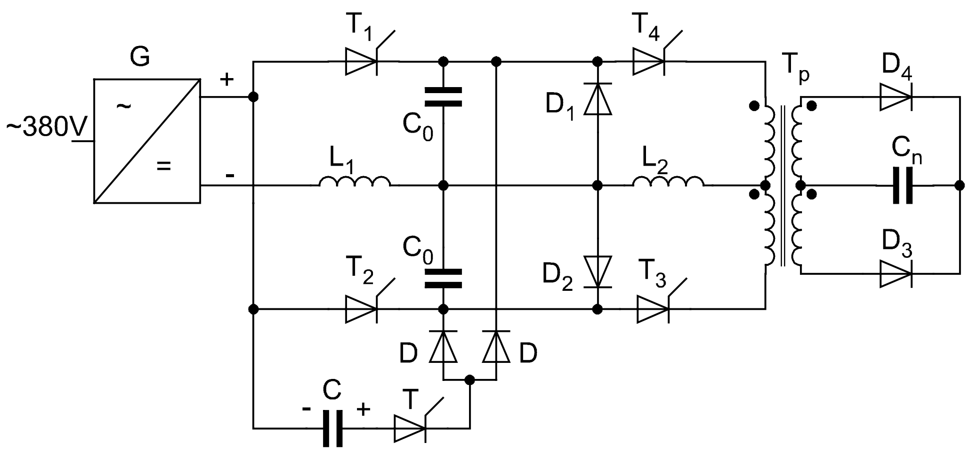

Fig.4. Simplified circuit diagram of a charge device with an electron protection.

The inverter consists of two loops. The first loop consist of a mains rectifier G, thyristors T_1 and T_2, a choke L_1 and dosing capacitors C_0, the second loop includes capacitors C_0, thyristors T_3 and T_4, diodes D_1 and D_4 and a storage capacitor C_n. The step-up transformer T_p used only to transform the inverter output voltage.

The inverter works in the following way. Capacitors C_0 are charged in succession from a low–voltage mains rectifier G up to its two-fold voltage by switching on thyristors T_1 and T_2 through the inductance L_1. Every half–period of the inverter operation they transfer their energy to the capacitor C_n, being discharged by switching thyristors T_3 and T_4 through the inductance L_2 to the primary winding of the transformer T_p. For a complete energy transfer from C_0 to C_n they are shunted by diodes D_1 and D_2. Owing to these diodes there is no over-charging of the capacitors C_0, the energy is completely transferred to capacitor C_n and there are provided initial conditions for the next charge cycle. The last process is the most principle one in the inverter operation. We have the situation, when the rectifier inside the charge interval works to dosing capacitors with zero initial conditions: $U_{Co}=0$.

But the capacitors C_0 are discharged completely with a full energy transfer to the storage capacitor C_n only to the value $U_{Cn} = U_G{\cdot}n$ ($U_G = 500\ V$ is the voltage at the rectifier, n is the transformation ratio of the transformer T_p). With a further increase in the voltage on C_n, the capacitors C_0 do not discharge completely, which leads to a reduction in the average value of the consumed current and a violation of the constant power consumption from the mains. The capacitor charging is finished at $U_{Cn} \approx (1.05 \div 1.1)\cdot U_G{\cdot}n$, which is the maximum tolerable over-voltage in the circuit. Thus, the range $0 < U_{Cn} \leq U_G{\cdot}n$ is the condition for the optimal operation at a constant power consumption.

The control of the charge voltage level is performed by varying the pulse repetition rate of the inverter. The maximum repetition rate corresponds to the continuous inverter operation and the maximum charge voltage. The voltage decreases with the pulse repetition rate. The thyristors T_1, T_3 and T_2, T_4 are triggered by means of a functional "voltage-frequency" converter which is controlled by means of a variable reference voltage. In case it is necessary to compensate parametric instabilities of the modulator elements, it is possible to compare the signals from the gauges with the reference voltage.

As is known from [8], the operation of a single charging device, provided the mean power consumed from the mains is constant, is characterized by ripples with drops to zero in the intervals between the charge pulses. At a maximum inverter repetition rate the phase shift between the sine charge pulse of the current is equal to π. In this case, the efficiency coefficient $k_{ef} = I_{av}/I_{max}$ (I_{max} -

maximum value of current) is equal to *0.637* and decreases with the increase in the phase shift during the voltage drop in the process of control. The multi phase design of the charge system decreases fluctuations (rippling) and makes the efficiency coefficient equal to $k_{ef} = 0.9$ in the two–phase variant for the phase shift by $\pi/2$, *0.95* and *0.97* in the three – and four – phase variants, respectively. Hence, it capacitor charge device can operate consuming a constant power from the mains in a wide interval of voltage adjustment, or variation in pulse repetition rate of the modulator operation cycles. Such a mode of the liquid lithium lens operation is probably needed for adjustment, preventive maintenance and other work.

The problem of smoothly switching on the load into the mains (as well as its switching off) and of a slow growth (drop) of the consumed power is solved by applying the reference voltage to the functional "voltage – frequency" converter through a timer circuit.

The inverter does not require an insulating mains transformer in the rectifier *G*. Either one, or a number ($10 \div 20$) of inverters can operate from one high-current rectifier. Between the rectifier and the inverter an electron switch is used. It works together with emergency switches which are of a comparatively slow action.

The protection circuit (see Fig.4) operates as follows: the capacitor *C*, charged from the low power rectifier ($50 \div 100\ W$) in the indicated polarity, is in a waiting mode. During the alarm situation, for example, when the operation fails or the inverter sticks, the rectifier current feeding the inverter goes out of the design mode. In this moment, when it reaches the determined level, the thyristor *T* is switched on by a comparator signal, and the reverse voltage from the capacitor *C* is applied to the inverter thyristors T_1 and T_2, at the same time the trigger pulses are taken off. The thyristor which was switched on at that moment (T_1 or T_2), switches off, the inverter alarm current is taken over by the circuit: the capacitor *C*, thyristor *T*, and one of diodes *D*. After the polarity reversal of the capacitor *C*, the thyristor *T* is switched off, and the protection circuit is restored.

Note one more feature of the proposed charge device - it is powered from a non-controlled diode rectifier. As discussed above, many of charge devices [4,5] (the charge system from Fermilab is among them [10]) are based on thyristor rectifiers, where the capacitor charge mode is preset by a thyristor switch phase. As a rule, the thyristor switch phase is close to π at the beginning of the charge interval, and as the capacitor is being charged, it decreases, approaching at best the value of the mains phase, i.e. $\pi/3$. This fact impairs the harmonic composition of the consumed current and leads to a change of $\cos\varphi$ (shift of voltage and current vectors) inside the charge interval. The conclusion is that for a charging device based on rectifiers with thyristor regulators:

- there is no compensating odd harmonics, because the relationship between their amplitudes constantly varies;
- there is no completely compensating *cos* φ.

The charge systems with thyristor regulators reduces the rectifier power factor. It is known [11] that the rectifier power factor χ depends on the shift factor *cos* φ as well as on the distortion factor ν:

$$\chi = \nu \cdot \cos \varphi.$$

Both the factors ν and *cos* φ are notably reduced when coming to a deep regulation - this is a significant disadvantage of the charge systems based on the rectifiers regulated by means of a line voltage angle α.

An our constant power charge device for capacitors operate from a non-controlled diode rectifier.

Note some disadvantages of the charge system described:

1. the charge device is based on the inverter, that is, as a powerful frequency converter, a source of radio interference voltage. That is why it is necessary to connect an interference filter at its input. The industry produces a great number of interference filters for different currents and voltages with a working damping of *60, 80* and *100 dB*;
2. the inverter is a source of noises of the sound range; the main sources of noise are the chokes L_1 and L_2, and transformer T_p. We partially decrease this disadvantage placing these elements in a tank filled with transformer oil.

In conclusion note, that it is no good using serial inverters produced by different manufacturers for industrial purposes in the charging device. This inverters can not provide the constant power consumption mode, as these are one-circuit systems (they are based on a IGBT transistor or thyristor bridge). The device suggested here has two circuits, and the circuit connected to the mains operates so, that while transmitting the energy to the modulator capacitance, the dosing capacitors C_0 discharge to zero inside the charge interval at each cycle of the inverter operation, and their initial conditions are not changed.

3. Choice of the inverter operation frequency

The operation frequency of the inverter was chosen taking into account most uncostly electronics and electro-technical components, the optimization of the inverter elements by the mass – size parameters, and the method of the voltage stabilization on the capacitance.

The maximum frequency of the inverter operation is determined by the characteristics of the thyristors used, in particular by the time of their switch off. The analysis made at BINP shows that at acceptable energy parameters of the choke L_2, to be optimized by its mass minimum and the efficient value of the current transmitted to the capacitance, the switch off time t_{off} may make $10 \div 15\ \%$ of the duration of the charge current half - sinusoid. The industry produces comparatively cheap inverter thyristors with a switch off time of $10 \div 15\ \mu s$. Thus, the availability of parts makes it possible to choose the duration of the inverter frequency half – period up to $100\ \mu s$. The upper limit for the frequency may be defined by the choice of the ferromagnetic for electro-technical components of the inverter. The main factor will be the idea to use inexpensive electrical cold - rolled steel. These steels up to frequencies of *3 kHz* are beyond competition compared to Permalloy. We have chosen the frequency value *2.5 kHz*. Fig.6 shows the current and voltage diagrams on basic components of inverter. The charge device efficiency is *0.93*.

4. Charging device inverter components and its technical realization

The charging device inverter is based on fast thyristor modules of TT180F type produced by EUPEC. Their technical data is given in EUPEC Datasheet. Each module T_1-T_4 contains two thyristors connected in series. The maximum operational voltage of each thyristor is 1300 V, thus the each arm of inverter can operate under forward and reverse voltage on it not less than 2 kV. The capacitors 2x50 μF (produced by NWL) for 1 kV are planned to be used as dosaging capacitors. (This capacitors are from Fermilab supply). The inductance of L_1 choke is $L_1=2.5\cdot10^{-4}$ H, and the L_2 choke inductance is $L_2=3.8\cdot10^{-3}$ H. There is possibility of inverter operation with 100 or 50 μF dosaging capacitors. At that time the duration of charging half sine pulse will be 500 μs with first and 350 μs with the second capacity mentioned above. Physically the thyristor modules T_1-T_4 together with thyristors of protective module T, diodes D (see Fig. 4) and diodes of three-phase mains bridge supplying inverter are placed on the common water-cooled heatsink and are shown in Photo 6.

The step-up transformer of charging device Tr (Fig. 4) has two sections of primary winding with 30 turns in each one and two sections of secondary winding with 475 turns in each one. Transformer Tr and choke L_1 are placed into water-cooled tank filled with transformer oil. This tank is shown in Photos 2 and 3. The L_2 choke is placed outside the tank and s water-cooled also. The S4KW12KA-3 diodes (Fermilab supply) are used as high voltage rectifiers D_3, D_4.

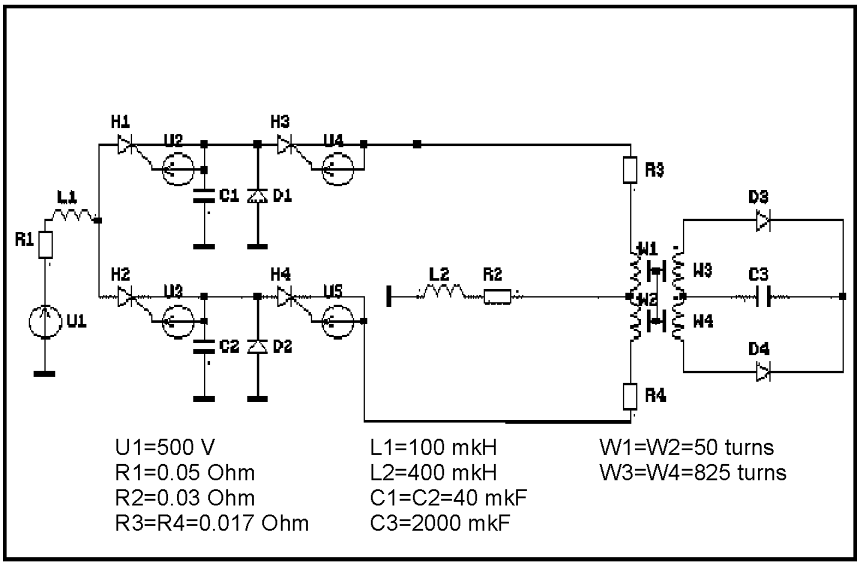

Fig.5a. Scheme of the charge device for calculations.

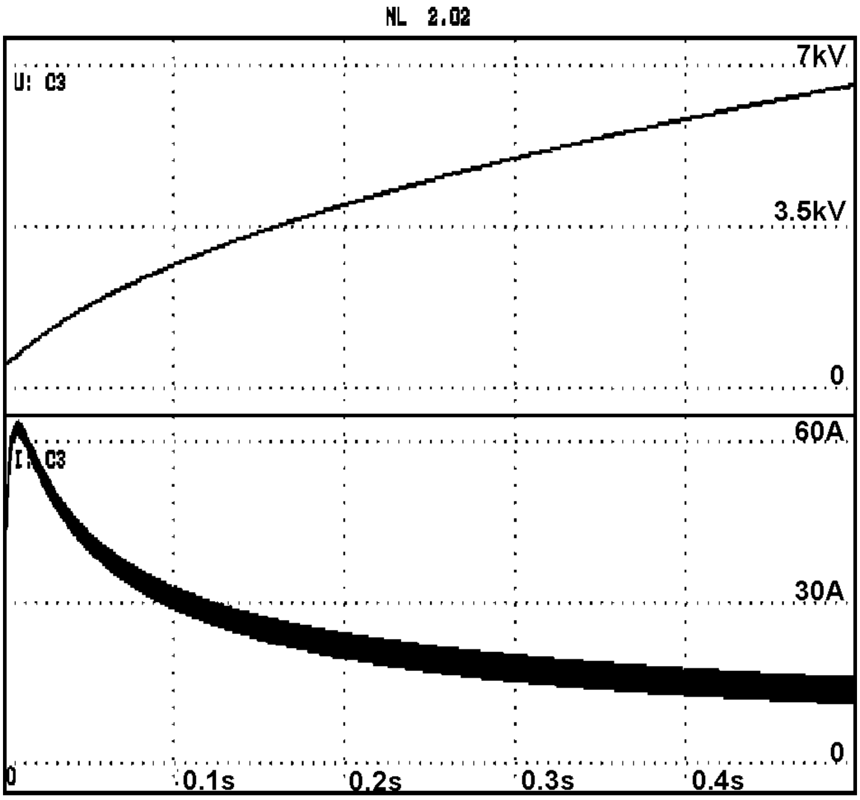

Fig.5b. Diagrams of charging current of the modulator storage capacitor and voltage on it.

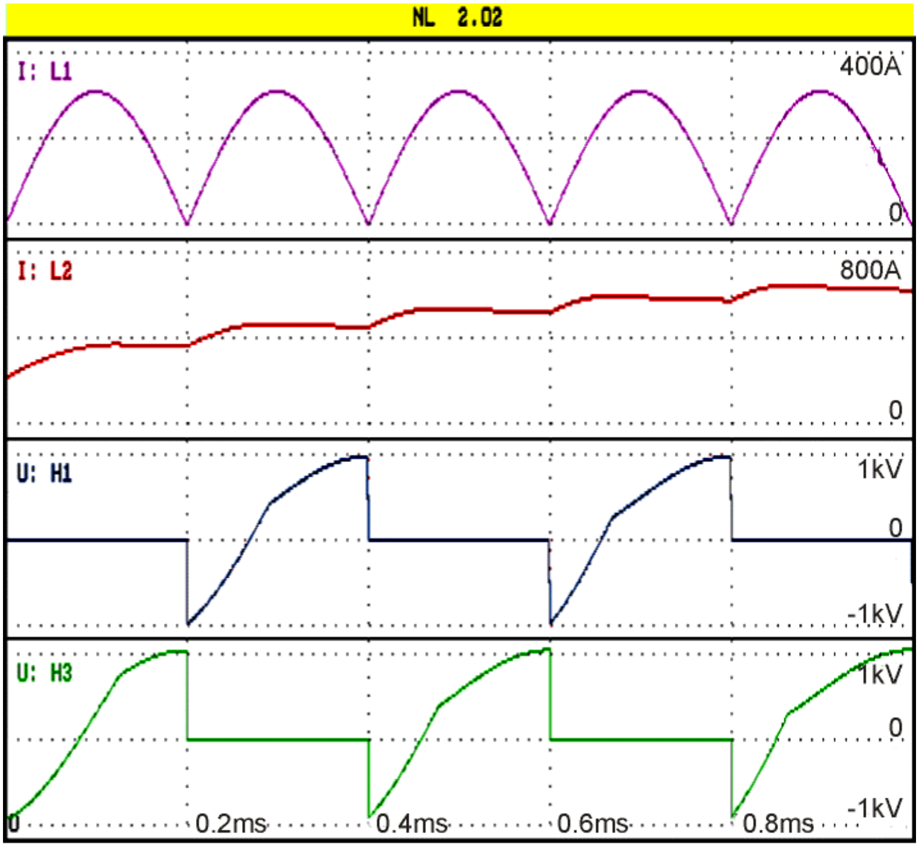

Fig.6a. Diagrams of currents through chokes L_1 and L_2 and voltages on inverter thyristors H_1 and H_3 at beginning of charging.

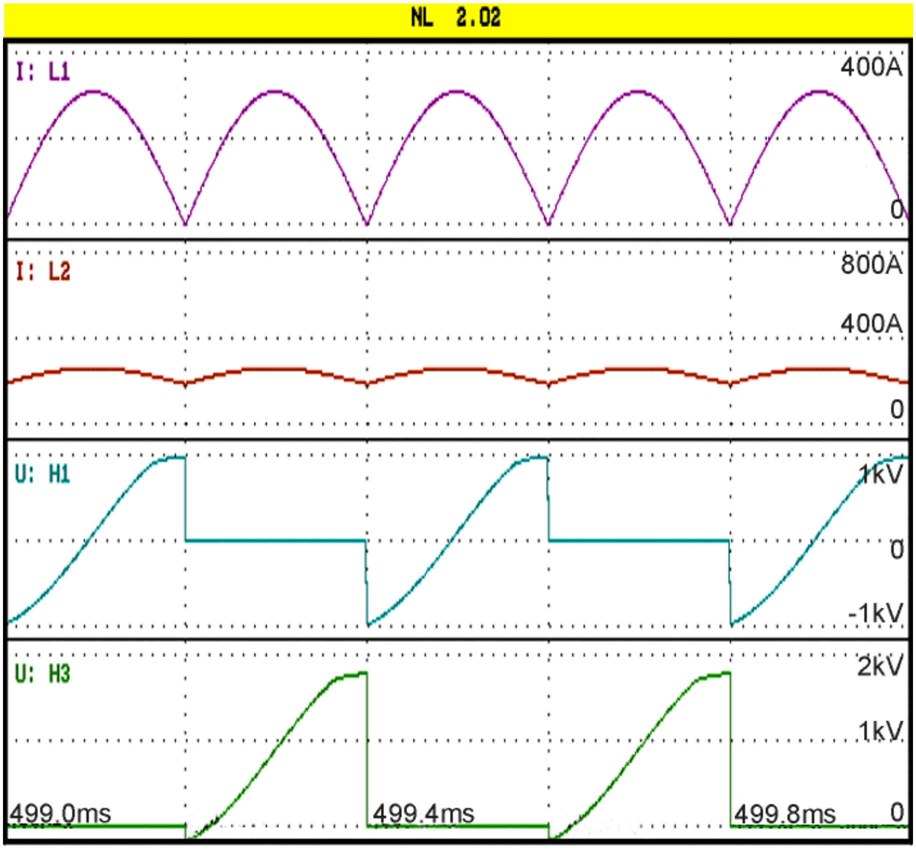

Fig.6b. Diagrams of currents through chokes L_1 and L_2 and voltages on inverter thyristors H_1 and H_3 at end of charging.

IV. Thyristor commutator.

The energy commutation from the capacitive storage to the load is performed by thyristor module shown in Photo 1 and Drawing 1. Module contains 15 thyristors T1101S (manufactured by EUPEC) in five branches located axially symmetrical. Each branch consists of 3 thyristors connected in series. Thyristors are supported in axial direction through the special rocker (10) by means of bolts (2) with force 2.3 *t*. For the branch insulation it is used the insulator (3) designed for an appropriate force and for the compensation of forces at thermal changes the washers of plate kind (9) calibrated by the total force are envisioned. The basic support component of the structure is the power rod (4) designed for the total force not less than 5x2.3 *t* and being the air conduit at the same time. The air applied through the pipe (5) passes into the inner cavity of the power rod (4) and plate radiators (6) are air cooled through the hole in the rod. In the first variant in order to divide current between branches the 5 coils (7) was proposed to be connected between branches. But then it was decided to refuse from coils and use the inductance of RF cables connecting generator with load as such current dividers between brunches of thyristor module. Each thyristor of the module is triggered from the separate pulse ferrite transformer though yoke of which the primary winding wire passes and whose isolation is designed for the total voltage. The dynamic and static division of voltage between thyristors connected in series is traditional. It is placed on separate PCB around module and it's not shown in Drawing 1. The characteristics of T1101 thyristors used in module are given in EUPEC Datasheet.

V. Saturating choke.

In the pulse generator under construction the thyristor commutator should be designed for the current growth rate $\frac{di}{dt} \geq 1000\, A/mk\sec$. Ten parallel branches of thyristor commutator enable the operation with such of current growth rate however for higher reliability of the generator we use the conventional way of reducing the current derivative at energizing thyristors – we introduce the saturating choke connected in series to the discharge contour shown in Fig.9. Its design is determined by the purpose to obtain the maximum duty factor, minimum inductance in saturated state and by the possibility to achieve the required time delay of current pulse. On the flat core made of electrotechnical steel *Э3425* with a band thickness of *0.08 mm* two wide copper buses are placed forming two turns. These turns are connected in parallel, the copper thickness exceeds the operating skin layer thus providing the maximum duty factor of the choke. The choke measured inductance in its saturated state is $0.26{\cdot}10^{-6}$ *H*.

VI. Matching pulse transformer.

The test of lithium lens is planned to be performed with use of available at BINP transformer (Fig.10a,b,c) previously produced for the tests of the CERN lithium lens. It was operated over one million cycles with a current of *1 MA* on lens with an inductance $L=4{\cdot}10^{-8}$ *H* at pulse operation *~1.5 mks* and pulse energy of up to *100 kJ*. In the development of the transformer we focussed mainly on providing its reliable operation at large current amplitudes under conditions of high level radiation of antiproton target stations and lowering its parasitic parameters.

The transformer is a thick wall tore of rectangular cross section with an outer diameter of *420 mm* being a secondary turn with a cut on its inner diameter for the lens connection. Inside the tore there is circular magnetoguide of rectangular cross section separated on its inner diameter from the secondary turn by the insulation air gap. The basis of design scheme of the transformer is the principle of equilibrium primary winding each coil of which is placed in the holes in thick walls of the secondary coil with symmetric gaps and it does not interacts with neighboring coils. In such a design the scattering inductance of the secondary winding is equal to zero and the scattering inductance of the primary winding is proportional to the number of its coils and it depends on insulation gaps. Each of 18 primary turns of the transformer (we recommutate the primary winding to two windings connected in parallel by 8 turns) is formed by sections of coaxial lines of rods passing in axial direction through cylindrical holes in the body of the secondary coil by one in the inner diameter and by two in the outer diameter. The rods are connected in radial direction by flat wedge jumpers located in radial grooves on the ends of the secondary turn. The transformer ends are covered by ring copper caps so that over the plane of wedge jumpers there are similar *3 mm* gaps thus providing equal magnetic fields on their surfaces and equilibrium of the winding.

The connection of cylindrical pars of winding by flat jumpers is made by collet clamps. Each jumper is supported by ceramic insulator inserted into cylindrical bores in the bottom of groves in the body of the secondary turn. The massive secondary turn of the transformer is water cooled and the primary winding turns are cooled by air fanned through insulation gaps in axial direction. The temperature of primary winding can reach *100℃* determining the pulse repetition rate. Such a transformer with iron cross section of *180* cm^2 provided a current over *1 MA* at pulse duration of *3 ms*.

VII. Capacitor battery.

The capacitor battery will be assembled from capacitors 150 μFx6 kV (Produced by NWL, Fermilab supply). Three electrotechnical cabinets proposed for capacitor battery allow us to obtain the total capacity up to $5.4 \cdot 10^{-3}$ F

The main characteristics of capacitor battery are mentioned below.

The capacity of single capacitor	150 μF
Maximal operational voltage	6 kV
A number of capacitors in the battery	36
The total parasitic inductance of capacitor battery and its buses	$0.25 \cdot 10^{-6}$ H

The electro-technical cabinets used in BINP for generator tests are shown in Photos 7-9.

VIII. Pulse generator testings

At this time the pulse generator by the scheme in Fig.1 has been assembled. The capacitor battery of generator consists of two sections of $1.2 \cdot 10^{-3}$ *F* capacity, so the total capacity of the battery is $2.4 \cdot 10^{-3}$ *F* and its testing voltage is *8 kV.* Such battery will allow to carry out the lens testings at a voltage up to *6 kV* and *2-3 Hz* frequency. For the experimental turnings on a special dummy lens with electrical parameters close to the proposed lens ones was manufactured. During the testings the current in lens was risen up to *760 kA*; the voltage at the capacitor battery was about *5 kV.* Oscillogram of current is shown in Fig.7.

Testings were made at *0.5 Hz* frequency. The frequency gain was limited by the heat removal possibility from the dummy lens. These testings have proved the normal operation of the pulse generator and possibility to carry out all experiments with the liquid lithium lens with it.

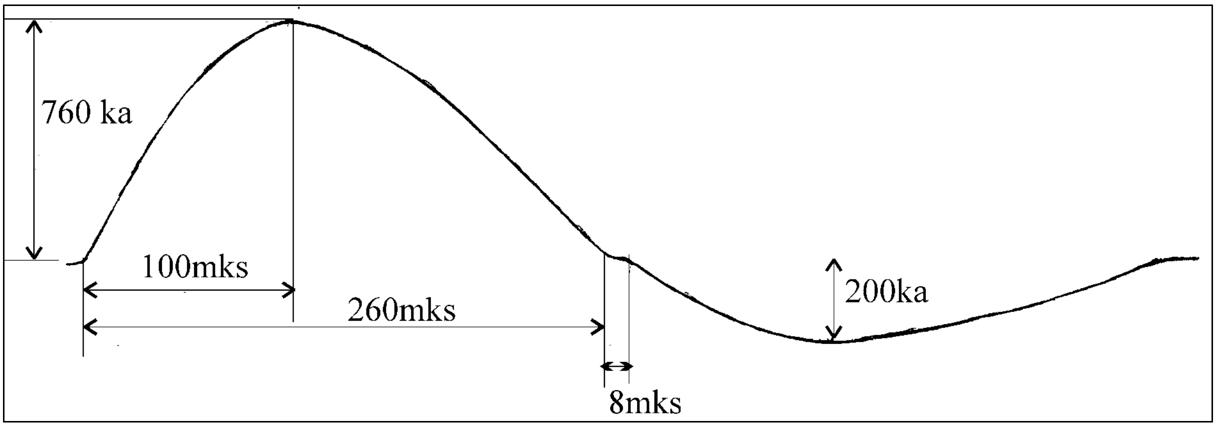

Fig. 7. Oscillogram of lens current

IX. Monitoring and control of the lens power supply source

Monitoring and control of the lens power supply source (Fig.8) consists in the following:

1) voltage stabilization on the storage capacitor at the end of charge interval;
2) control of electric parameters of main components;
3) control and signaling the operation conditions such as air and water supply, conditions of the doors of electromechanical cabinets, etc;
4) lens current stabilizing.

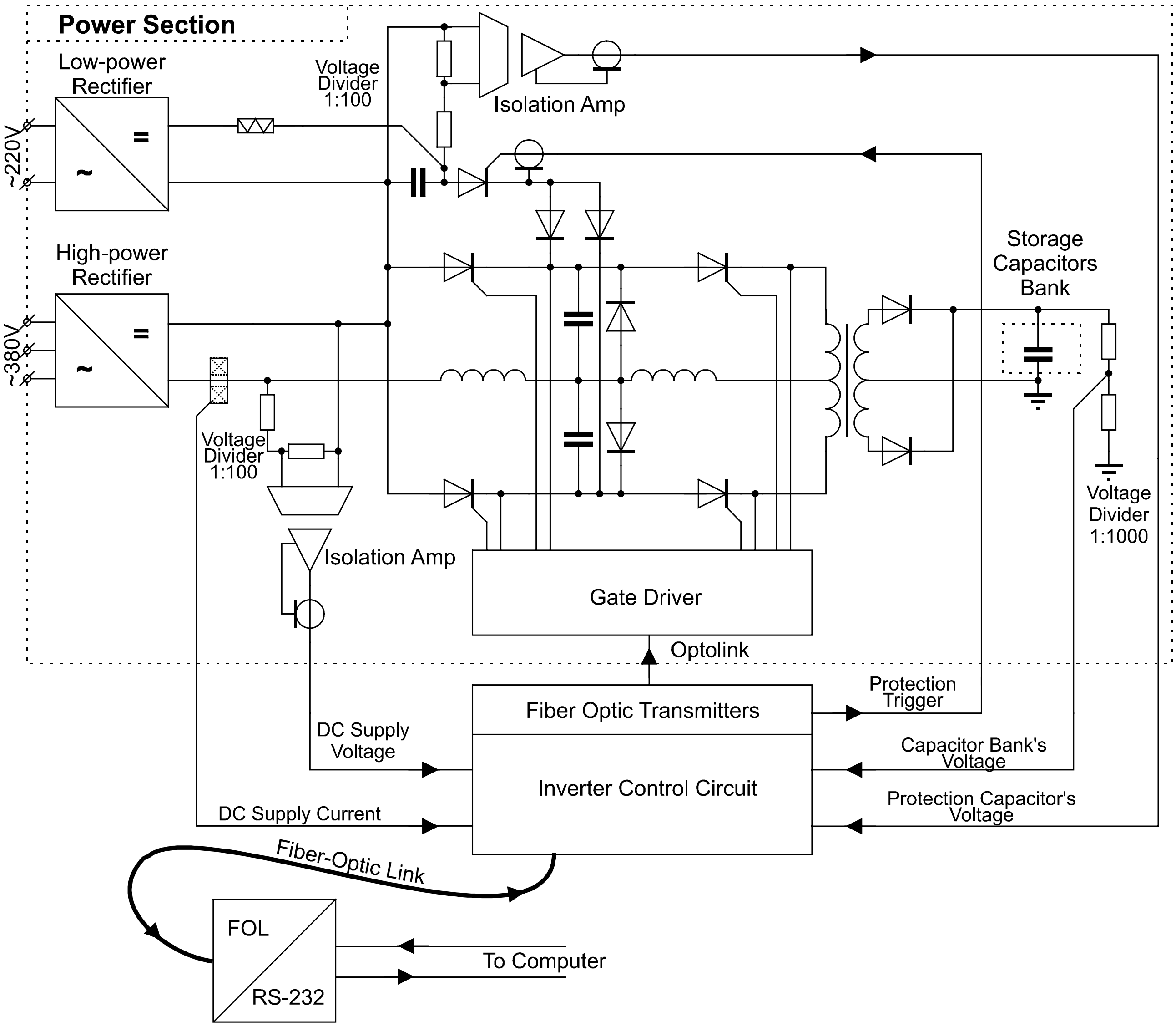

Fig. 8. Monitoring and control of the lens power supply source

1. Apparatus protection system of charge device

For safe operation of the constant power charge device and for avoiding emergency of charge device, in the control system the analog apparatus control is envisaged in the real-time mode of the following parameters:

1. The mains rectifier voltage is U_{rect}. The minimum value $U_{rect.min}$ and maximum value $U_{rect.max}$ are given so to have a possibility of precise stabilization of the storage capacitor voltage within this interval and to avoid the hazard of malfunction of charge device components because of overvoltage. With the U_{rect} over the admissible limits the VFC and a triacs trigger's amplifier (PA) are blocked and the signal **«Overvoltage Rect.»** or **«Undervoltage Rect.»** is sent to the operator. With the return of U_{rect} into the interval of admissible values the system operation is renewed.
2. The mains rectifier current (I_{rect}). Maximum current value of rectifier $I_{rect.max}$ is given. Excess of this value means «overturn» of the inverter (simultaneous opening keys of both inverter branches). With the values I_{rect} over maximum values the triac controlled pulses are blocked and a fast protection system is triggered, the signal **«Overcurrent Rect.»** is sent to the operator.. The inverter's triacs are switched-off and rectifier current I_{rect} becomes zeroth. After this, the system will not renew the operation unless getting an explicit permission signal from the operator (**«Reset Protection»** signal).
3. The capacitance voltage in the electronic system of the inverter protection is U_{pr}. The system of electronic protection operates safely only in the case if the capacitance C_{pr} (Fig.1) is charged up to the required voltage $U_{pr.min.}$ Therefore, the triac control pulses should be blocked while $U_{pr}<U_{pr.min}$. In such a situation, the operator gets the signal **«Undervoltage C_{pr}»**. One has to note that C_{pr} has voltage up to *1 kV* with respect to the inverter ground and U_{pr} is measured with the amplifier with galvanic isolation. Such an amplifier is based on the microcircuit AD202 of the Analog Device production and it has the transformer galvanic isolation at voltages of up to *2.5 kV*.
4. Voltage at the storage capacitance is U_{st}. Lens current will be defined by the voltage on the storage capacitor battery. Overvoltage of capacitor battery will bring about the overcurrent of lens, the effect of this will be destruction of lens. Restriction of maximum voltage on capacitor battery prevents both a destruction of lens, and breakdown to insulation in capacitors. In order to avoid this the apparatus protection system blocks the

inverter operation and in case of $U_{st} < U_{st.max}$ the operator gets the signal **«Overvoltage Storage Capacitance»**.

In addition to all said above, the charge device can be blocked by the signal **«Inhibit»** from CBS (Interlock Chassis) or by the signal from operator. Any operation of the protection system is induced on the control panel of operator by the light signal.

In the protection system the comparators of analog signals CMP04 of the Analog Device production and the basic logic microcircuits of 74LS series are used. For the control of all enumerated parameters the analog probes with current output are used for providing high safety protection of the circuit.

2. Device of blocks and signals (Interlock Chassis)

The constant power charge device is mounted in the electromechanical cabinet of the BINP standard. A simplified diagram of power supply is given in Fig.9.

The control of the operation conditions of the charge device and generator for lithium lens is performed by the following parameters:

1. Water pressure in the water cooling system (binary signal **«Water»**). In the absence of pressure the system operation is prohibited.
2. Air pressure in the air cooling system (binary signal **«Air»**). In the absence of air supply, the system operation is prohibited.
3. Control of temperatures of operational components of charge device (four analog signals **«T_1...T_4»**). At overheating of components the system operation is prohibited.
4. Condition of doors (binary signal **«Doors»**). Doors of the charge device are blocked mechanically with MMB (Manual Mechanical Blocking). The system operation is prohibited if the only door is open.

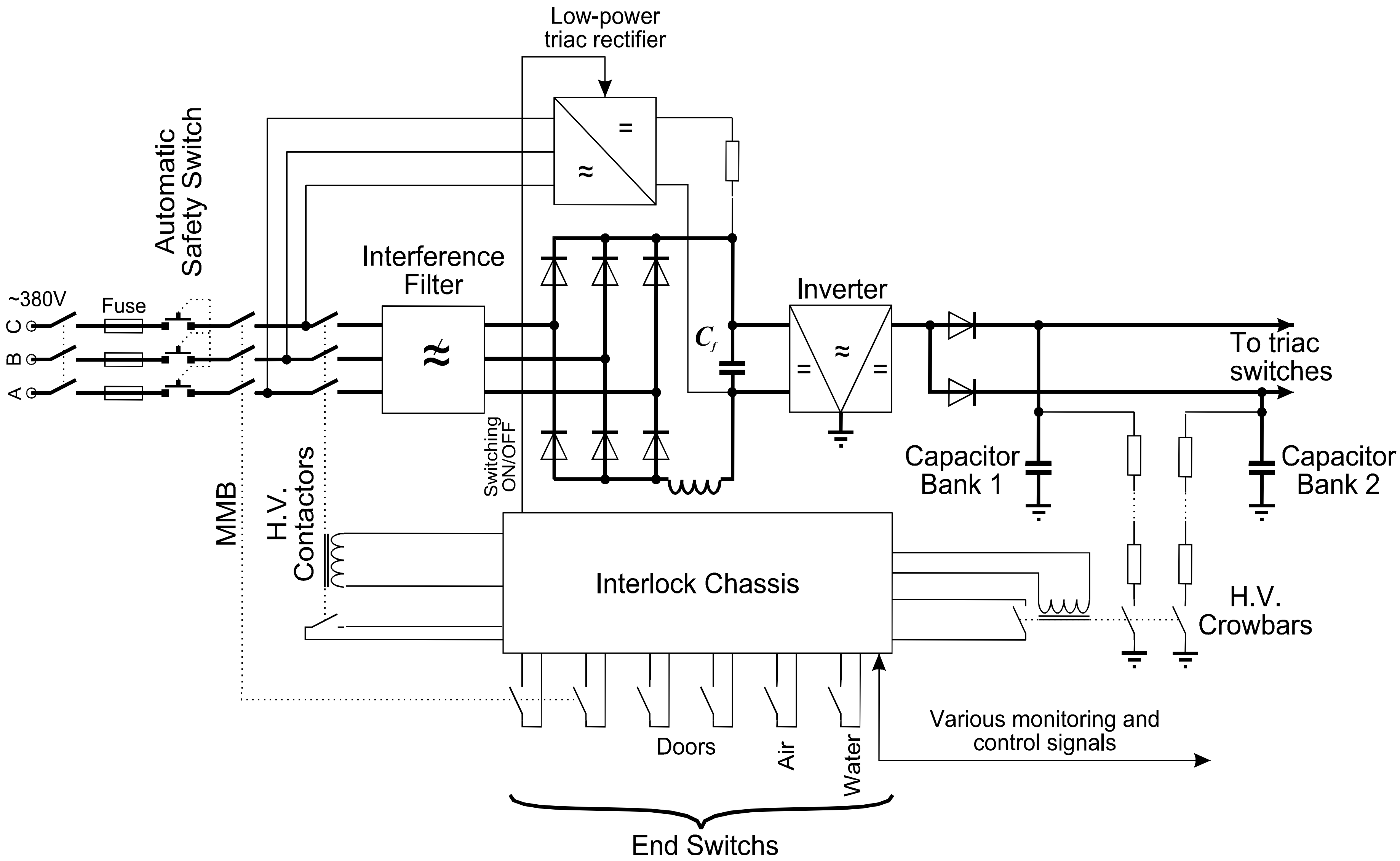

Fig.9. Simplified diagram of constant power charge

5. Condition of MMB. MMB has two ends contacts: fully open (binary signal **«MMB open»**) and fully closed (binary signal **«MMB closed»**). In the condition of fully open, the LED indication is on allowing the operation of the personnel with high voltage elements of the system, the autogrounders are blocked in the lower position, the contactors are blocked if they are not closed and the cabinet doors are de-blocked mechanically. In the fully closed condition, the cabinet doors are mechanically blocked and the closing contactors and elevation of autogrounders are allowed.
6. The condition of autogrounders (binary signal **«AG»**). Autogrounders block the storage capacitance via the ballast resistance to the «ground». Elevation of autogrounders is performed by applying voltage to the winding of the autogrounder winding by the command of the operator.
7. The condition of the High–Voltage Contactors (binary signal **«Power»**). Contactors provide applying 380 V onto the mains rectifier. They can only be triggered at elevated autogrounders. In order to avoid the charge of the filtering capacitor up to double mains voltage at the moment of energizing contactors a two-step switching of the mains voltage is envisaged: first, the low current rectifier charged the filtering capacitance up to the mains voltage; after 5…10 seconds the high current mechanical contactors are switching on. After successful operation of contactors, CBS applies the signal permitting the operation for the apparatus protection unit.

Collection of the binary states of the ends is performed with the optocouples; the control of the electromagnetic triggers and autogrounders is performed through the solid-state relay. This enables one to provide high reliability and antinoise protection of Interlock Chassis.

3. Control of the constant power charge device

The apparatus protection unit for the inverter and Interlock Chassis are linked by the two-directional fiber – optical channel to computer through the monitoring and control circuit described below in the report. The monitoring and control signals are given in Tables 1 – 4.

Table 1. Binary state signals given by protection system and Interlock Chassis.

№	Signal name	Signal description
1	“Power”	State of mains contactors
2	“AG”	State of autogrounders
3	“MMB Open”	MMB state
4	“MMB Close”	MMB state
5	“Doors”	State of doors
6	“Air”	Air cooling
7	“Water”	Water cooling
8	“Overvoltage Rect.”	Mains voltage is higher than its admissible value
9	“Undervoltage Rect.”	Mains voltage is lower than its admissible value
10	“Overcurrent Rect.”	Rectifier current is higher than its admissible value
1	“Undervoltage Cpr”	Voltage at the protective capacitor is lower than its admissible value
12	“OSC”	Overvoltage Storage Capacitance

Table 2. Input analog voltages (10-bit accuracy).

№	Signal	Description
1.	U_{ref}	Reference voltage of VFC
2.	$U_{rect.min}$	Minimum admissible voltage for mains rectifier
3.	$U_{rect.max}$	Maximum admissible voltage for mains rectifier
4.	$I_{rect.max}$	Maximum current of mains rectifier
5.	$U_{pr.min}$	Minimum voltage in the fast protection system’s capacitance.
6.	$U_{st.max}$	Maximum admissible voltage on capacitive storage

Table 3. Output analog voltages (10-bit accuracy).

№	Signal	Description
1.	U_{rect}	Voltage of mains rectifier
2.	I_{rect}	Mains rectifier current
3.	U_{pr}	Capacitance voltage in the electronic protection system
4.	U_{st}	Storage capacitance voltage
5.	T_1	Temperature of charge device components
6.	T_2	
7.	T_3	
8.	T_4	

Table 4. Binary signals controlling the charge device

№	Signal	Description
1	"Switch Power Output"	Switching the thyristor control pulses
2	"Inhibit"	Permission of VFC operation
3	"Reset Protection"	Reset of rectifier current protection flip-flop
4	"AG Up"	Elevation of grounders
5	"High Power On"	Switching mains High–Voltage Contactors

Reference voltages for the apparatus protection unit is given by operator through a multichannel DAC. A multichannel DAC measures the controlled inverter parameters which are further transmitted into computer and displayed on the screen. In addition, by means of DAC the temperatures of charge device components are measured. The data obtained are processed by computer and on this basis the operation of charge device is controlled.

4. Lens current stabilization

Let us define factors affecting the value of lens pulse current. At first approximation, the lens current amplitude is determined by the following expression:

$$i(t) = \frac{U_0}{L \cdot \omega} \cdot e^{-\frac{R}{2L}t} \sin(\omega \cdot t),$$

where R is a circuit active resistance, U_0 is a storage initial voltage, L is lens inductance. It is seen that the main contribution into instability of I is given by an instability U_0. Parameters R and $L \cdot \omega$ can change slowly during the lens operation because of its temperature change which influence also on the lens current stability.

For the compensation of all the factors given above and lens current stabilization the lens current shape pulse detector described below is used. The current amplitude value measured with the detector is processed with computer and on the basis of the data obtained the reference voltage controlling the charge device inverter frequency is corrected. Thus, the current is stabilized from pulse to pulse.

X. References.

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