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DEVELOPMENT OF THE POWER SUPPLY AND CONTROL SYSTEM FOR THE HEMODIALYSIS MACHINE

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Abstract. *The article describes new approaches to creating an autonomous compact system with automatic control for hemodialysis. It is proposed to organize a closed circuit for cleaning the dialysis solution using an electrolytic regenerator as a function of the concentration of urea in it. The functional diagram of the created system is presented and described. To power the regenerator, ensure thermal stabilization of the solution, and power auxiliary electronic and electrical equipment, a multi-channel power supply and control system for the hemodialysis machine based on high-frequency magnetic amplifiers has been developed and researched. The advantages of power switches based on high-frequency magnetic amplifiers in comparison with transistor switches, including in the construction of controlled power sources, are given. The principle of operation of the voltage regulator on high-frequency magnetic amplifiers is described. Theoretical and experimental oscillograms are given. Photographs of the experimental unit as well as an industrial sample of the multi-channel power supply and control system of the hemodialysis machine are provided. Their main technical characteristics are given. Conclusions to the conducted work are formulated. Carrying out the regeneration of the dialysis solution significantly reduces its costs – 2 liters of solution, which is suitable for use for 6 months, is enough for the operation of the device. Existing hemodialysis machines are a stationary open system using a single-use dialysis solution at a rate of up to 35 l/h, which ties the machine to stationary clinical conditions. Introducing feedback on the concentration of urea in the dialysis solution allows you to automate the blood purification procedure, as well as automatically complete hemodialysis at the necessary time, and also eliminates the dependence of the device on the conditions of the hospital.*

Keywords: hemodialysis, power supply and control system, rectangular hysteresis loop, high-frequency magnetic amplifier

ROZWÓJ UKŁADU ZASILANIA I STEROWANIA URZĄDZENIA DO HEMODIALIZY

Streszczenie. *Do zasilania regeneratora, stabilizacji termicznej roztworu oraz zasilania pomocniczych urządzeń elektronicznych i elektrycznych opracowano i zbadano wielokanałowy układ zasilania i sterowania aparatu do hemodializy oparty na wzmacniaczach magnetycznych wysokiej częstotliwości. Przedstawiono zalety wyłączników mocy opartych na wzmacniaczach magnetycznych wysokiej częstotliwości w porównaniu z wyłącznikami tranzystorowymi, w tym w budowie sterowanych źródeł prądu. Opisano zasadę działania regulatora napięcia we wzmacniaczach magnetycznych wysokiej częstotliwości. Podano oscylogramy teoretyczne i eksperymentalne. Przedstawiono fotografie jednostki doświadczalnej oraz próbkę przemysłową wielokanałowego układu zasilania i sterowania aparatu do hemodializy. Podano ich główne parametry techniczne. Sformułowano wnioski z przeprowadzonej pracy. Przeprowadzenie regeneracji płynu do dializy znacząco obniża jego koszty – do pracy urządzenia wystarczają 2 litry płynu, który wystarcza na 6 miesięcy. Istniejące aparaty do hemodializy to stacjonarne systemy otwarte wykorzystujące roztwór do dializy jednorazowego użytku z szybkością do 35 l/h, co wiąże urządzenie ze stacjonarnymi warunkami klinicznymi. Wprowadzenie informacji zwrotnej o stężeniu mocznika w płynie dializacyjnym pozwala zautomatyzować procedurę oczyszczania krwi, a także automatycznie zakończyć hemodializę w wymaganym czasie, a także eliminuje zależność urządzenia od warunków panujących w szpitalu.*

Słowa kluczowe: hemodializa, układ zasilania i sterowania, prostokątna pętla histerezy, wzmacniacz magnetyczny wysokiej częstotliwości

Introduction

In medicine, there is a problem of ensuring the functioning of the body in case of complete or partial failure of vital organs. Kidney functions in such extreme situations in clinical institutions are performed by a biotechnical system that provides artificial hemodialysis – an "artificial kidney" device. Hemodialysis treatment of patients with acute or chronic renal failure had a dramatic effect on reducing the mortality rate of these patients. The main component of the hemodialysis machine is the dialyzer. The dialyzer contains semipermeable membranes that filter the blood. In the process of hemodialysis, the blood is cleaned from metabolic products due to their diffusion into the dialysis solution. At the same time, the patient's blood (up to 3 litres) enters the dialyzer, which is separated by a special membrane. A flowing dialysis solution enters the second section of the dialyzer. By means of a biochemical reaction, there is a transition of metabolic products from the patient's blood into the dialysis solution through the membrane – a transition from an environment with a higher concentration to an environment with a lower one. Contaminated dialysis solution requires appropriate disposal. Although there are known cases of its direct discharge into the sewer.

In addition, the hemodialysis procedure itself is a complex biotechnical system, the functioning of which requires solving a number of difficult problems. Despite the progress made, this membrane therapy is still an incomplete renal replacement, as the mortality and morbidity rates remain unacceptably high. An important characteristic of the membrane is its pore size, porosity and thickness. Further research is underway to improve the mechanical behavior of thin membranes [10]. The solution to the problem of patient safety, in particular electrical safety, requires further improvement [3]. Hemodialysis machines are devices with a risk of infection. Disinfection and sterilization are the main parts of injection control in hemodialysis units [12]. During a hemodialysis cycle, which can last several hours (up to 6 hours in critically ill patients), the actual dialysis machine does not display the water displacement ratio. Therefore, another problem that is currently being solved is obtaining information about excessive hydration or dehydration of patients [16].

But the main drawback of the existing hemodialysis machines, which are widely used today in clinical practice, is that they are a stationary open system. Quality control is carried out indirectly according to the patient's condition, and the use of a single-use dialysis solution (and in large quantities – up to 35 l/h) ties the device to stationary clinical conditions.

1. Formulation of the problem

Thus, the disadvantages of existing systems for hemodialysis are:

- their use only in hospital conditions, which significantly limits the number of operating places;
- large consumption of dialysis solution;
- the need for the used dialysis solution disposal;
- lack of automatic control of the hemodialysis process.

Taking into account these shortcomings, the task of creating an autonomous compact system with automatic control for hemodialysis arises.

Its solution became possible with the appearance of a sensor for the concentration of urine in the dialysis solution. The next step is the organization of the regeneration process of this solution. For this purpose, it is necessary to create a closed loop of circulation of the dialysate solution, in which the regenerator is sequentially switched on. The regenerator works from the applied power as a function of the concentration of urine in the dialysis solution. In this way, it is possible to obtain a closed system of regulation and control of the concentration of urine in the dialysis solution. However, at the same time, the problem of creating a controlled power source for the regenerator arises. The use of existing methods of building pulse power sources based on modern semiconductor elements is limited by a number of factors:

- inability to implement multi-channel sources with equivalent and independent output channels;
- semiconductor commutation elements can switch only constant voltage [5, 1];
- the complexity of the switch control system, which also requires its own power supply;
- impossibility power source and control functions implementation in one converter on the same switch.

To achieve this goal, it is proposed to use the methods developed by the authors for building sources and power supply systems based on high-frequency magnetic amplifiers (MagAmp). The magnetic cores of MagAmps are made of an amorphous alloy with a rectangular hysteresis loop [9, 11, 14].

2. Principles of MagAmp operation

In the controllable power supplies it is suggested to use high-frequency magnetic amplifiers (MagAmps) as the switching elements [1, 2, 4, 6-8, 15, 17-20].

MagAmp switch is just a coil wound on a core with a relatively square B-H characteristic as shown in Fig. 1. The MagAmp is operated in two operating regions, either along the steep or along the shallow slopes of the B-H curve [19]. In the vicinity of operating point R the MagAmp core is unsaturated. Here, the high permeability of the core causes the MagAmp winding to present a high inductance to the circuit, which allows only a trace current to flow. MagAmp requires a certain volt-sec, which is the integral of voltage over time, to be applied to its terminals for the magnetic flux to build up in the core and reach the saturation level. The stronger the reset field, the more volt-secs the MagAmp can withstand until saturated. Once saturated, MagAmp operating point shifts to L, see Fig. 1. Here, the permeability of the core is very low and the inductance of the MagAmp coil has only a negligible value, which allows a large current flowing in the circuit [18].

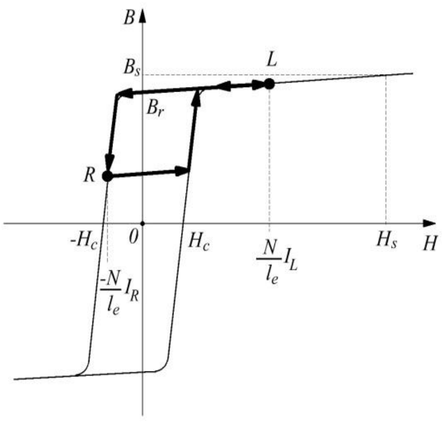

Fig. 1. MagAmp switching trajectory in B-H plain [12]

A MagAmp can be used as a semi-controlled switch that can block and delay the applied voltage. However, MagAmp cannot interrupt the current once started. Hence, MagAmps are used in pulse circuits where they are assisted by diode rectifiers, which cut off the current as the applied voltage changes polarity [18].

Here, the MagAmp post-regulator is implemented as a push-pull full-wave circuit at the secondary of the power transformer, T, as shown in Fig. 2.

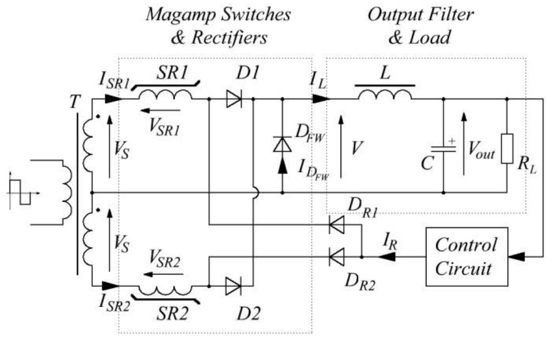

Fig. 2. Push-pull MagAmp regulator circuit [12]

The post-regulator is comprised of a pair of the MagAmp switches SR1 and SR2; power rectifier diodes D1-D2; a free-wheeling diode D_{FW} and a second order LC output filter. As compared to a single ended MagAmp circuit, the push-pull MagAmp configuration has the advantages of the symmetrical operation and doubled dc output voltage.

Such MagAmp switch combined with a rectifying diode and demagnetizing circuit forms a synchronous rectifier, whose control circuit contains just 1-2 active components. Power-width modulation in such switch is achieved through the regulation of the ratio of the time the core is in saturated state to the time the core is unsaturated. This regulation is achieved due to the change of the core demagnetization depth that is a function of the controlled parameters or the regulation algorithm.

Here, both MagAmp switches operate with current reset. The reset current I_R, is provided by the controller. The steering diodes D_{R1} and D_{R2} naturally steer the reset current I_R, towards the device to be reset.

Idealized waveforms of the push-pull MagAmp postregulator are illustrated in Fig. 3.

The upper trace is the transformer secondary winding voltage, V_S. The second and third traces show the MagAmp voltages, V_{SR1}, V_{SR2}. The positive portion of the MagAmp waveform represents the volt-secs blocked by the MagAmp, whereas the negative portion of the waveform is due to the reset process. As a result of the MagAmp blocking, the MagAmp output voltage, V, the upper trace is the transformer secondary winding voltage, V_S. the second and third traces show the MagAmp voltages, V_{SR1}, V_{SR2}. The positive portion of the MagAmp waveform represents the volt-secs blocked by the MagAmp, whereas the negative portion of the waveform is due to the reset process. As a result of the MagAmp blocking, the MagAmp output voltage, V, has a reduced duty cycle and, therefore, has a reduced average value. Fig. 6 also shows the output filter inductor current, I_L, and the currents of the MagAmp switches, I_{SR1} and I_{SR2}. The MagAmp blocking state current is drawn out of proportion for illustration purposes. The free-wheeling diode current, $I_{D_{FW}}$, provides the conduction path for inductor current when the MagAmps are in the blocking state.

MagAmp operation principles, analysis of the processes in a regulator based on MagAmp, comparative analysis of MagAmps and transistor switches are described in detail in the following literature [4-8, 15, 17-20].

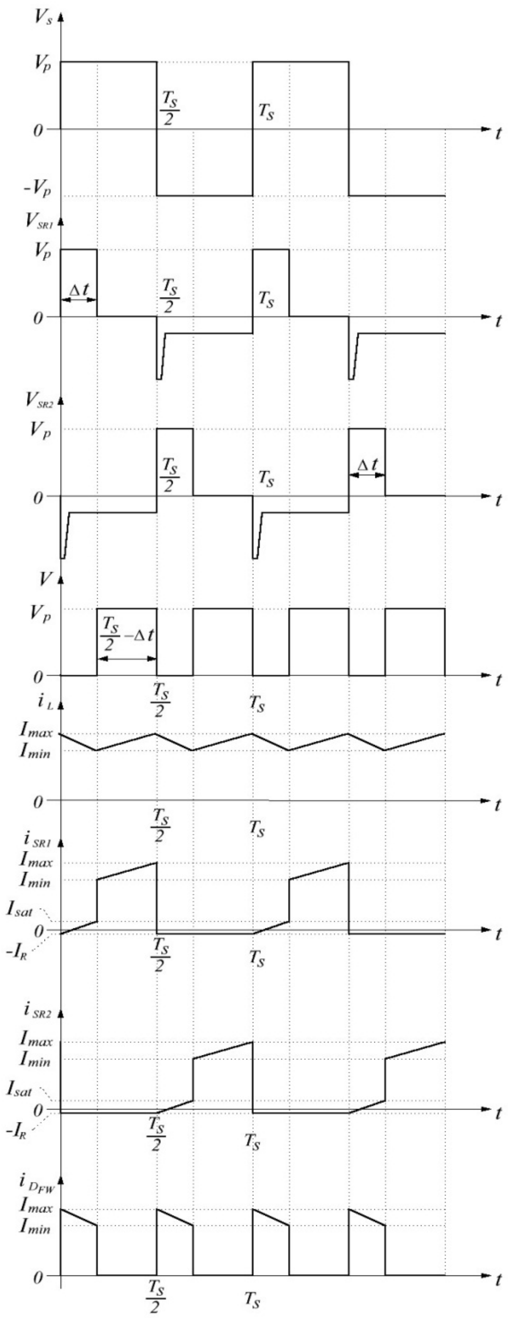

Fig. 3. Theoretical waveforms of a push-pull MagAmp regulator [16]

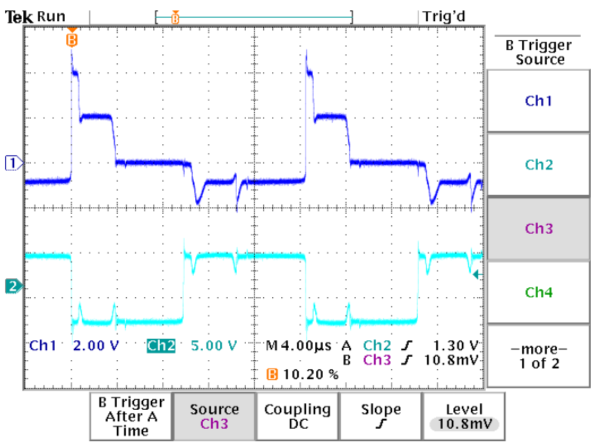

Fig. 4. Real waveforms for the MagAmp voltage regulator (at output parameters 24 V, 4 A): 1 – input voltage; 2 – MagAmp voltage

The real waveforms of the input voltage for the MagAmp voltage regulator (at output parameters 24 V, 4 A) and the voltage directly on the saturation core of MagAmp are presented in Fig. 4.

The advantages of the magnetic switch in comparison with the transistor switch are the following:

- is an AC voltage switch;
- not critical to the form of input voltage;
- gain on a current up to 1000;
- simplicity of the control circuit (1-2 transistors in linear mode);
- does not create electromagnetic interferences;
- is the filter of input interferences (both in non-saturated, and in a saturated condition);
- high efficiency (99 %), the losses do not depend on load current;
- high level of radiation stability and mechanical stability;
- does not require protection (itself serves as a protection device of high-frequency transistor inverter);
- is multifunctional: the power amplifier, power switching device, pulse-width modulator, executes functions of the integrator, comparator, protection device.

It is the advantages of the magnetic switches that determine the advantages of MagAmp power converters compared to traditional transistor power converters. They are the following:

- possibility of implementing multi-channel power converters with equivalent and independent output channels with 100% load current change range;
- allow a wide range of changes in the input voltage;
- high quality of output voltages (no high-frequency peaks and low-frequency component, minimal high-frequency component);
- high level of dynamic characteristics – the disturbance is worked out in a time equal to half a period of a high switching frequency (in the frequency domain, the MagAmp is an inertialess element with a delay of half a period of the operating frequency), the transient process ends when the regulated value (voltage) reaches the first value of its established level [17];
- lower level of electromagnetic interference;
- lower cost;
- a higher level of radiation and mechanical stability;
- a higher level of reliability due to both the physical nature of the MagAmp and the significant simplification of the circuitry;
- high level of the specific power;
- high level of unification – the possibility of using the same standard size of the MagAmp core and the same circuitry solutions to realize of the power converters in a wide range of output parameters.

3. Power supply and control system for the hemodialysis machine

Hemodialysis device, implemented according to the principle of a closed cycle, is intended for cleaning the patient's blood from harmful impurities. The block-diagram of the device is presented in Fig. 5. The essence of its action is reduced to purification by electrochemical decomposition of the dialysate solution, which provides purification of the patient's blood through the appropriate membrane equipment [19].

The patient's blood enters the dialyzer 1, which is separated by a membrane. The second part of it is filled with dialysis solution. In order to clean the dialysis solution from harmful impurities entering it through the membrane from the patient's blood, a closed loop of its circulation is organized. Depending on the concentration of urine in the patient's blood, different levels of direct current are required to maintain the reaction in the electrolyzer at a given speed. Therefore, the power regulator itself is made on the basis of high-frequency magnetic amplifiers. Such a decision made it possible to simply implement a power source with the function of controlling its output power in the 100% range of its change on one element. The output power of this channel is a function of the urine concentration in the patient's blood.

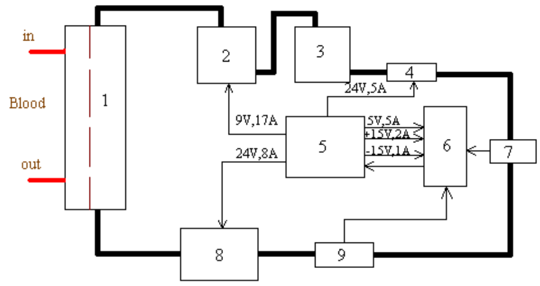

Fig. 5. Block-scheme of the hemodialysis machine (1 – dialyser, 2 – electrochemical regenerator, 3 – block of passive post-cleaning, 4 – pump, 5 – power suply, 6 – control system, 7 – sensor unit of concentration, 8 – heat exchanger, 9 – temperature sensor)

The signal from the urine concentration sensor 7 is sent to the corresponding control system 6, which matches it with the output signal (0–5 V), and also forms a signal for the completion of the hemodialysis procedure. Under the influence of this signal, the MagAmp saturation chokes are remagnetized. The main channel works as follows. When the concentration of urine in the patient's blood increases, the value of the signal sent from the concentration sensor to the control system increases. At the same time, the voltage at its output increases, which leads to a decrease in the demagnetization current. The MagAmp saturation choke is demagnetized to a smaller depth B (Fig. 1). And this corresponds to the mode of operation of the MagAmp saturation choke, in which it will reach its saturation faster in the next working half-cycle. This leads to an increase in the regenerator current. Under its influence, the intensity of decomposition processes increases, and accordingly, the purification of the dialysis solution.

In series with the regenerator 2, a block of passive post-cleaning 3, filled with a sorbent, is turned on. The speed of circulation of the dialysis solution in the circuit is set by the pump 4. Its operation is provided in two modes – automatic and manual. The output stabilized channel with output parameters of 24 V, 5 A is used to power the pump. It is implemented according to the traditional MagAmp scheme of the voltage stabilizer.

Another responsible element of this circuit is the heat exchanger 8. Its task is to maintain the temperature of the dialysis solution in the circuit at the level of the patient's body temperature. It works as a function of the signal from the temperature sensor 9 according to the same algorithm as the main channel. The executive elements of the heat exchanger are elements that use the Peltier effect. To power the heat exchanger and stabilize the temperature, the system implements the MagAmp controlled output channel with output parameters of 24 V, 12 A.

The remaining three output channels of the power supply are designed to power the microprocessor control system. One of them (5 V, 5 A) is designed as the MagAmp voltage stabilizer, the other two are linear voltage stabilizers in an integrated design.

The developed power supply and control system of the hemodialysis machine also meets electrical safety requirements. First of all, this is a double galvanic isolation. It is provided by the use of optocouplers in the control channel and the implementation of the high-frequency power transformer. In addition, the high-frequency power transformer has twice the insulation breakdown voltage value between the primary and secondary windings – instead of 2 MV, 4 MV is provided.

The functional diagram of the main channel of the power supply and control system of the hemodialysis machine is presented in Fig. 6. The method of uniform distribution of the load current between the diodes of the high-frequency rectifier was proposed and investigated, which allows to significantly reduce the time of existence of the short circuit in the circuit of the rectifier diodes during two-stroke rectification at the beginning of each half-cycle. This provides higher efficiency and improves the quality of the output voltage. At the same time, each diode VD3...VD5 (VD6...VD8) is connected to its secondary half-winding of the power high-frequency transformer TV through its MagAmp winding of the saturation choke TS1 (TS2).

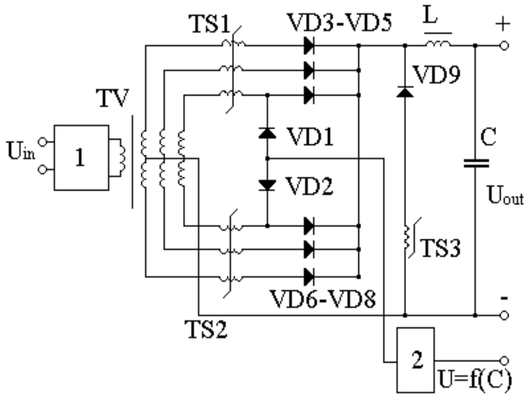

Fig. 6. Main channel of the power supply and control system (1 – nonregulated high frequency transistor inverter, 2 – MagAmp control circuit, C – concentration of the urea)

The uniformity of the distribution of the load current between the rectifier diodes at their parallel operation is determined by the technological spread of the diode parameters, namely the direct voltage drop and its frequency characteristics. The recovery time of the valve properties in the arm of the rectifier is determined by the diodes through which the largest current flows and which have the worst frequency characteristics. In addition, at the beginning of each half-cycle with push-pull rectification, there is a mode in which a short circuit occurs in the circuit of rectifier diodes. This is due to the properties of the p-n junction of the diode, namely: the closing time of the diode is longer than the opening time. The time of existence of a short-circuited circuit is determined by diode with the worst frequency characteristics and through which the largest current flows. The following experiment was conducted: five 2D213 diodes were connected for parallel operation. At an output current of 30A, short-circuited circuit time was almost 4 µs (at a half-cycle of the working frequency of 10 µs).

The following solution was proposed and investigated, which contributes to the uniform distribution of the load current between the diodes of the rectifier and which allows to significantly reduce the time of existence of the short-circuited circuit in the rectifier at the beginning of each half-period of working frquency, and, therefore, to increase the efficiency of the source and improve the quality of the output voltage. For this purpose, the winding of the saturation choke TS and the secondary winding of the power transformer TV of the transistor converter are split. The number of wires of the split winding is equal to the number of diodes in the arm of the rectifier. This method of building an output high-frequency rectifier with an output current of 30 A at an operating frequency of 50 kHz made it possible to reduce the existence time of the short-circuited circuit by several times – it was less than 1 µs. It was this method that was implemented during the construction of output channels with a high level of output current of the power supply and control system of the hemodialysis machine.

As an unregulated transistor inverter the developed power autogenerator with a saturation choke in the positive feedback circuit for the output voltage of the inverter is used (Fig. 7). This inverter was specially created to work with MagAmp voltage regulators (stabilizers). It works as a power generator with feedback from the collector current and the output voltage of the inverter. Its use of bipolar transistors is due to the possibility of controlling their switching processes. The TS saturation choke is made of high-frequency amorphous alloy with a rectangular hysteresis loop.

The working frequency and the switching trajectory of the power transistors VT1 and VT2 of the inverter are determined by the specially created remagnetization modes of the TS saturation choke with a rectangular hysteresis loop in the positive feedback circuit for the output voltage of the inverter. The time of complete remagnetization of the saturation choke TS in the current source mode, which is formed by the voltage of the feedback winding W_U of the high-frequency power transformer TV1 and the internal resistance of the current generator, with the limitation of the speed of its remagnetization determines the half-cycle time of the inverter working frequency. Limiting the speed of magnetization is carried out by the voltage drop on the diodes VD1...VD4 and VD5...VD8 in the base circuits of the power transistors.

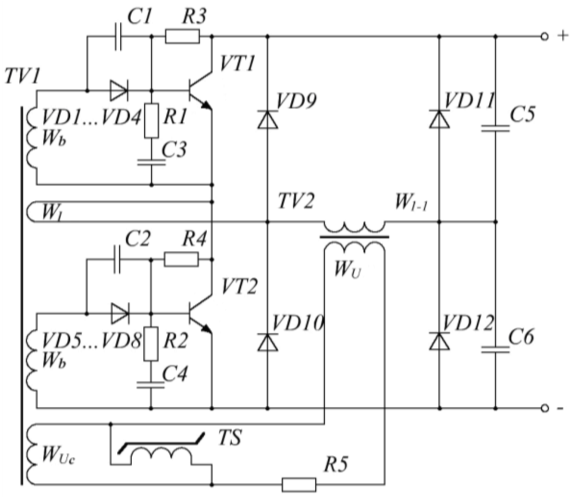

Fig. 7. The unregulated high-frequency transistor inverter

The use of a saturation choke TS with a rectangular hysteresis loop in the positive feedback circuit for the output voltage of the inverter is decisive in the operation of the inverter. Its main functions and advantages of use:

- provides an autogenerator mode of operation of power switches, which significantly simplifies the circuitry of the converter – there is no need for a special control circuit, which, in turn, often requires additional power;
- the moment of saturation of the saturation choke TS determines the moment of re-commutation of the power switches of the autogenerator. Unlike Royer's scheme, this makes it impossible for overcurrents to appear in the power circuit, which ultimately leads to a significant increase in the output power level (up to 500–700 W);
- remagnetization along the full hysteresis loop and the equality of the volt-second integrals of the rectangular hysteresis loop automatically leads to the symmetrization of the power transformer operating modes, and in dynamic modes, the perturbation recovery takes place in half the period of the working frequency;
- the remagnetization time of the saturation choke TS determines the time of the half-cycle of the operating switching frequency;
- ensures the start of the power autogenerator from a high frequency;
- prevents the occurrence of through currents in power switches;
- when the converter is overloaded, only one transistor fails;
- increases the level of electromagnetic compatibility of the converter.

The main advantages of the inverter include:

- high efficiency;
- high reliability;
- low level of the electromagnetic interference;
- high stability of the switching frequency in a wide range of input voltage change and at 100% range of the load current change;
- simplicity of the topology – no transistor control circuit, no additional power source is required for the control circuit;
- soft start with high switching frequency;
- absence of magnetization asymmetry of the power transformer;
- when overloaded, only one transistor fails;
- low cost.

MagAmp voltage regulators (stabilizers) and integrated stabilizers for powering low-power consumers are connected to the secondary circuits of the high-frequency power transformers of these inverters.

Main technical data of the power supply and control system of the hemodialysis machine:

• output power	500 W
• input voltage	220V, 50–60 Hz
• switching frequency	50 kHz
• main regulated output channel	9 V, 17 A
• stabilized output channel	24 V, 5 A
• regulated output channel	24 V, 8 A
• stabilized output channels:	5 V, 5 A
	+ 15 V, 1.5 A
	- 15 V, 1 A
• efficiency	> 0.85
• specific power	140 W/dm^3

Structurally, the power supply system is made in the form of two boards of exactly the same size, placed in one housing. Each of them has an unregulated transistor inverter. The output channels of the power supply of the regenerator and the pump are placed in the secondary circuits of the first. The remaining power output channels are connected to the second inverter.

An industrial sample of the board of the power supply and control system of the hemodialysis machine, on which the main channel is placed, shown in Fig. 8.

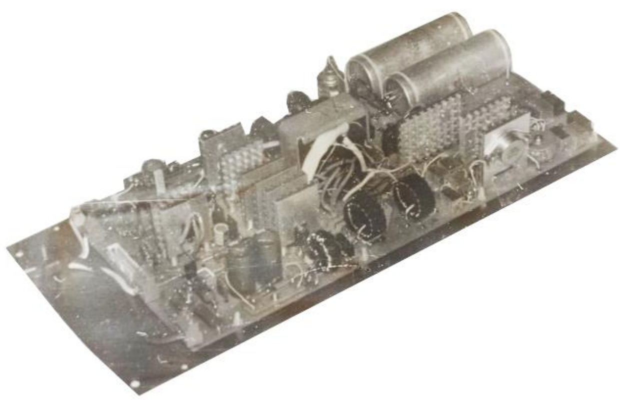

Fig. 8. Industrial sample of the power supply and control system of the hemodialysis machine on the same parameters

The appearance of the experimental prototype of the power supply and control system of the hemodialysis machine, developed and manufactured by the author of the article, is shown in Fig. 9.

Main technical data of the experimental prototype of the power supply and control system of the hemodialysis machine:

- output power 250 W
- input voltage 220V, 50–60 Hz
- switching frequency 50 kHz
- main regulated output channel 12 V, 14 A
- regulated output channel 15 V, 3 A
- stabilized output channels: 5 V, 1.5 A; + 15 V, 1 A; - 15 V, 1 A
- efficiency > 0.85
- specific power 120 W/dm^3

Fig. 9. Experimental prototype of the power supply and control system of the hemodialysis machine

The developed hemodialysis system with dialysis solution regeneration was put into production at the firm "B. Braun – Rolitron" (Budapest, Hungary).

Today, the methods of synchronous rectification in MagAmp power converters proposed by the authors of the article allow creating converters with an efficiency of up to 96% when powered from the industrial frequency network [17, 18].

4. Conclusion

The introduction of feedback on the concentration of urea in the dialysate solution made it possible to automate the blood purification procedure and control the moment of termination of the hemodialysis operation. Carrying out the regeneration of the dialysis solution not only significantly reduces its costs (2 litres of solution, suitable for use for 6 months, is enough for the operation of the device), but also eliminates the dependence of the device on the conditions of the hospital. This made it possible to obtain an autonomous system for hemodialysis, suitable for use even at home.

The use of high-frequency magnetic amplifiers in the role of power switching and regulating elements and methods of building multi-channel power sources based on them with controlled and stabilized output channels made it possible to create a system of power supply and control of a hemodialysis machine with a high level of operational characteristics: a high level of quality of output voltages, dynamic characteristics, efficiency, reliability, low level of electromagnetic interference and price.

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