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THREE-PHASE 100W SWITCHING POWER SUPPLY UNIT

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An efficient small dimensions low cost pulsed DC power source with three-phase power supply and four powerful galvanically isolated output channels was developed. The output power of about 114 W was achieved. The power source admits three-wire connection of a standard three-phase industrial powering network, operates at significant nominal deviation of input voltage and at dump of one phase; allows operation at single-phase power supply. A complex of short-circuits, overloading, extra voltage protections is applied.

Keywords: three-phase network, pulsed DC power source, IGBT transistors, PWM controller, magnetic coupling output inductors.

INTRODUCTION

Industrial gear, operating on three-phase alternating quantity mains often requires a supplementary power supply for low steady voltage feeding of analog and digital parts. Examples of such an equipment are industrial controllers, uninterruptible power source systems, electronic flowmeters, etc. Also, switching inverter sources of average and high power, which are used for needs of plasma arc cutting and evaporation, electric welding, X-ray and laser technology demand in the capacity of auxiliary power source a galvanically isolated four-channel DC power source (power supplying of a high side switch, low side switch, analog and digital parts). At least two channels of the source must be high-powered because for power control of superpower switches requires electrical impulses with amplitude 15V - 20V under the current of 2A. Given the fact, that the digital part of such a source, as a rule, includes the ladder, a digital supply channel must be also high-powered.

Industrial power source specification is more rigid than in regular appliance power source. This is reflected not only in the fact that in input of power source operates the high three-phase voltage, but also in the fact that industrial power sources must ensure safe operation under significant deviation of the input voltage of design value, including dips and voltage surges, as well as the disappearance of one or several phases. Industrial equipment is often powered by three-phase electric mains without neutral or with bad quality neutral, so the power source must accept a four-wire as well as three-wire (without neutral) connection. No less important are the following parameters of utility power converter: the operating range of input voltage, the watt consumption in the standby mode, end-to-end dimensions, reliability, electro-magnetic compatibility and working cost.

Industry produces the following power sources. For example, the MeanWell company produces converters of DRT and WRA series with three-phase power source (four-wire connection). Output DC voltage of both series converters is fixed with the possibility of mechanical tweaking:

- 24V, 48V +16%...0% for DRT series
- 12V, 24V, 48V +19%...-6% for WRA series

Devices output power of both series fall in the range Pout = 120 ... 960W. Both series of converters have short circuit, overload, overvoltage and overheating protections. All devices of both series have single-channel output.

Converter's cost varies in the range $100-300, depending on the power supply.

Inasmuch as, industrial prototypes are not always optimized (at the price, power supply, size, number of independent voltage output channels) a development of such devices continues. Not so long ago, engineers of Power Integration have developed technical solution for the power source of three-phase electricity meter based on chips genus TNY-Switch II [1]. In the [2] is described another three-phase source, based on Power Integration PWM controller - budget genus of LinkSwitch-TN. StackFET technology, applied in this device uses a combination of inexpensive low-voltage MOSFET transistor and Power Integration microelectronic circuit, which together give a fairly cheap source of power supply, able to work in a very wide input voltage range.

Both solutions use the same flyback topology, known of sheet-oriented simplicity and low prime cost. The well known disadvantages of herein topology: the flyback power sources, have not very high rates of power density. It does not matter when designing a power source if $P \leq 10W$. However, in the case, if the power source P> 100 W, this topology is not aimed.

Both solutions use a low-voltage MOSFET transistor in both cases is supplemented by integrated into the PWM controller high-powered voltage ($V_{DS} = 450V$) MOSFET transistor which is switched with a frequency f = 132 kHz. Due to the use of the PWM-controller's of related genus, modes of operation, blocking and security is very close. The differences are in the fact that the first device is a dual-channel power source, and the second - a single channel. Moreover, are used PWM controller's of differential powering scheme: in the first case is used a separate transformer winding, in the second case - supplying directly from the DC bus through the high resistive divider. It should be noted that, despite the lower cost and greater sheet-oriented simplicity of the second solution, the first is still preferable because it allows a steady start and reliable operation at reduced input voltage. The general lack of both solutions - low output power ($\leq 3W$), dictated by using PWM controller with integrated low-power MOSFET-switch. Disadvantages also include a small number of a galvanically isolated output voltage channels.

Based on the foregoing, it is interesting to develop high-efficiency (coefficient of efficiency is max than 90%) of small dimensions pulsed DC power source, with an power supply is max than 120 watts, with three-phase

power supply and a large number (at least 4) powerful (the output current is max than 2A) galvanically isolated output voltage channels. Very desirable that such a converter is permitted three-wire connection of standard three-phase network, could confidently work with a substantial deviation of the input voltage from the nominal value, and the dropout of one phase, allows operation with a single phase power supply. It must be implement complex protection against short circuit, overload, overvoltage.

1. TOPOLOGY AND COMPONENTS SELECTION

Design of the pulsed power source for a wide input voltage range - is a non-obvious problem, because of the high cost of power MOSFET or IGBT transistors and limitations, connected with the operation of the PWM controller in the dynamic range.

Topology selection

Development of the element basis has led to the fact, that prime cost of pulsed DC power sources is now almost completely determined by the price of power supply switches and winding elements. Based on the economic efficiency, the use of two-switch and four-switch schemes for low-power converter is not aimed, because the problem can be solved by using a cheaper single-switch scheme.

The choice between a forward and flyback topologies are not so straightforward. The advantages of a forward scheme in comparison to flyback are as follows:

- longer duration of engaged condition switch according to off condition state;
- higher average voltage in the secondary winding;
- higher output load of current;
- low noise level;
- heightened efficiency at low output voltage.

A forward topology has its shortcomings. Foremost among them - the inability to ensure the group channels stabilization in the multichannel converter, witch results

in different values of output voltage at the output of the equivalent channels at different loads on them. The solution significantly reduces the impact of this effect, allow to use a forward topology when designing early described converter.

To improve the group stabilization of channels author offered to use inductors with magnetic coupling in the output circuits of each channel. The efficiency testing of such scheme was made by means of the modeling package LTspiceIV. The model was a three-channel forward converter with single-switch inverter. To determine the effect of magnetic coupling output stage chokes, the modeling was performed for two different schemes – with no magnetic coupling chokes and with magnetic coupling. While modeling analysis is used a real pulsing transformer with a ferro-magnetic core, as described in [5].

The model of forward converter with no magnetic coupling inductors is in figure 1 presented. In figure 3 is shown the model of forward converter with magnetically coupled output chokes.

The input stage (power filter, rectifier) is modeled by a constant voltage source V1, which is connected directly to the DC - bus. The role of the PWM controller performs generator V5, generating pulses with relative pulse duration of 0.5. Resistors R2, R3, R4 - load three galvanically isolated channels.

The result of the modeling analysis - the time dependence of the output voltage of all channels - is shown in Figure 3. The voltage V (n005), V (n009), V (n014) in all figures - the voltage across the load resistor R2, R3, R4, respectively. Figure 2a shows the result of simulation with a little same load for all channels (R2 = R3 = R4 = Rload = 100 ohms). Figure 2b shows the result of modeling analysis with different loads on the channels (R2 = R4 = 100 ohm, R3 = 8 ohms). Well seen that in the case of substantial differences in channels load skewed output voltage of the second channel according to the first and the third.
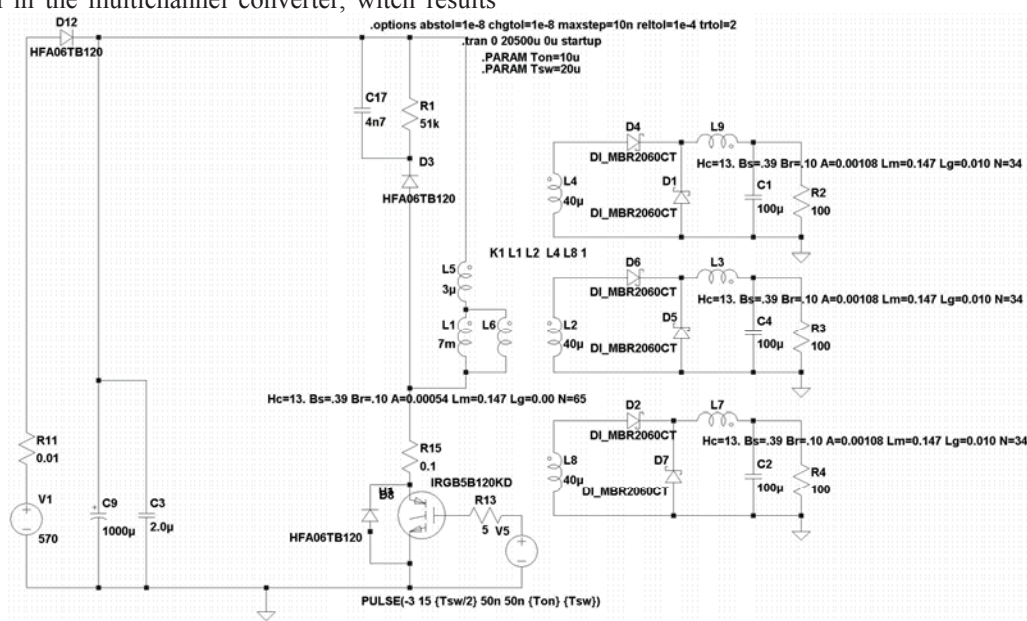

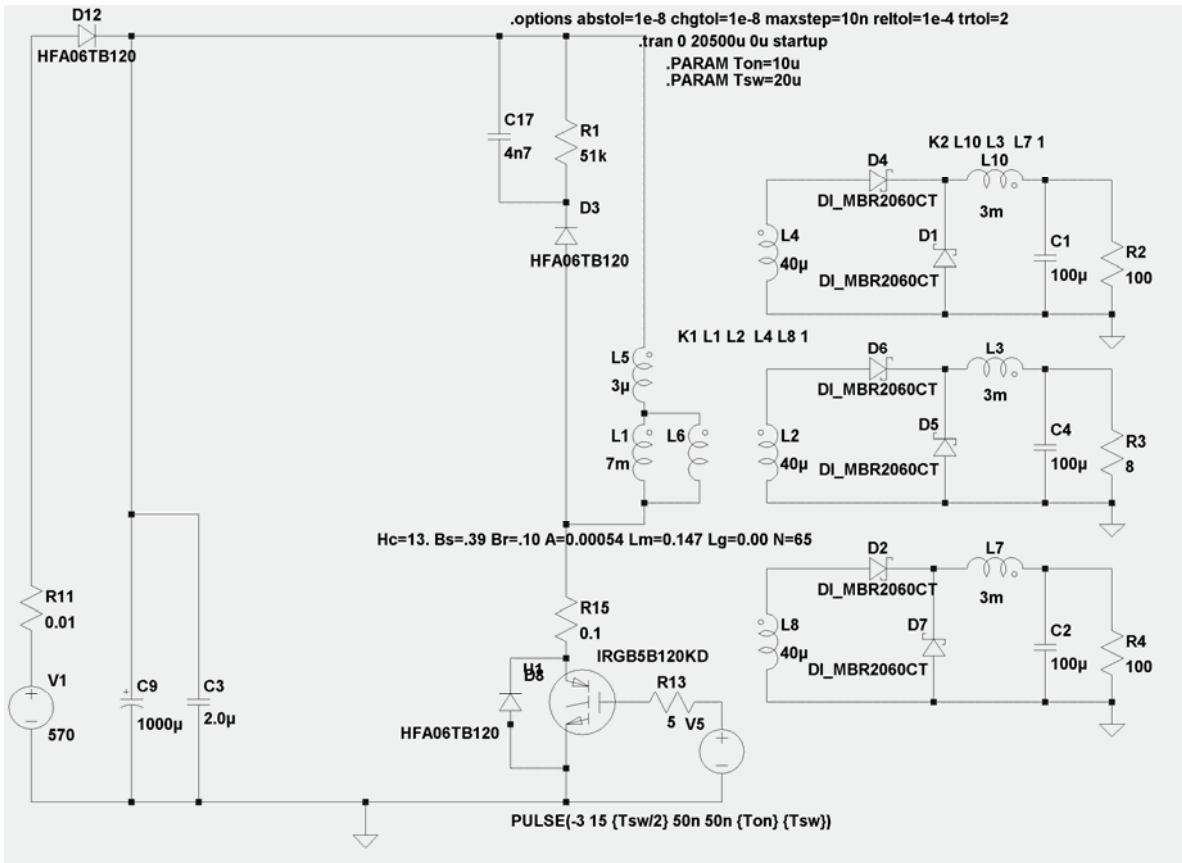Fig. 1. Model of forward converter with no magnetic coupling chokes

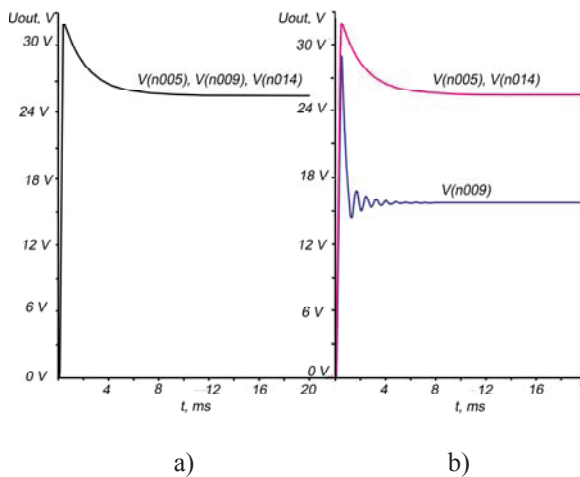Fig. 2. The model of forward converter with magnetic coupling output chokes

a)   b)

Fig. 3. The result of the simulation scheme without magnetic coupling output chokes

a) - the same small load on all channels (R2 = R3 = R4 = Rload = 100 ohms).

b) - the different load on all channels (R2 = R4 = 100 Ohms, R3 = 8 ohms).

The modeling results for forward converter with magnetic coupling output chokes is present on Fig 4.

a)   b)

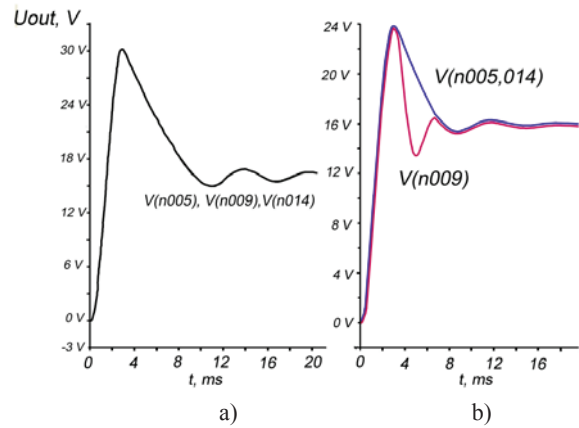Fig. 4. The modeling analysis result for the circuit with magnetic coupling of output chokes

a) - the same small load on all channels (R2 = R3 = R4 = Rload = 100 ohms).

b) - the different load on channels (R2 = R4 = 100 Ohms, R3 = 8 ohms).

In figure 4 is shown the time dependence of all output channels voltage. In figure 4a is shown the result of modeling analysis under the same low load for all channels (R2 = R3 = R4 = Rload = 100 ohms). In figure 4b is shown the result of modeling analysis with different loads on the channels (R2 = R4 = 100 ohm, R3 = 8 ohms). It is easy to see that in the case of essential load differences at the channels in the scheme with a magnetically coupled output chokes, the differences of the

second output voltage channel towards to the first and the third outputs are not observed.

Switch selection.

From the general theory, which is confirmed by modeling analysis (and direct oscillographic voltage testing in the finished device) it is known that over-voltage on the switch in the single switch inverter reaches twice the voltage of the DC bus. Thus it is needed a switch to the permissible voltage of 1200V between the emitter and collector (drain and source). It isn't need a powerful switch at the desired converter power output current consumed by the device (and hence the current through the switch) does not exceed 1A. Given the stock it is needed a switch to limiting current of 5 A.

MOSFET-transistors with required parameters are available in the market - it's transistors fabricated by SiC - technology. However, the cost of such devices is much higher ($30 vs. $3) versus IGBT-transistors with the same parameters. It should be noted that the MOSFET transistors with voltage capability of Vsi = 1200V - a relatively new and find them on the market is problematically. In particular, the author failed to find such transistors on the market of Ukraine. On the other hand, IGBT-transistors with described parameters are widely represented.

In particular, NPT IGBT - transistor IRGB5B120KD satisfy completely herein requirements. Benefits of NPT technology are wide spread [3]: high resistance to short circuit, positive temperature coefficient of voltage saturation and a rectangular area of RBSOA safe operation. Ability of latching in NPT IGBT is excluded for all values of operating current, up to the short circuit current. However, for high resistance ensure to breakdown of the structure should have a wide area of the sublayer as well as relatively large value of voltage saturation. Furthermore, increasing the width of the area of the sublayer increases the parasitic capacitance and impairment of the frequency characteristics of the switch.

Nevertheless International Rectifier was modified NPT technology to obtain IGBT-transistor with low saturation voltage (VCE (on) = T 125 $^\circ$C = 2.75V) and low switching losses. NPT IGBT - transistor IRGB5B120KD successfully combines all aforementioned with a high switching frequency (in the represented device, the switching frequency was increased to 65 kHz), small-outline packages, TO-220, and low cost ($ 2.65).

Selection of PWM controller.

Microelectronic circuit of PWM controller is the key element of momentum off-line supply. The main function of PWM controller is operation of potential triode transistor in primary circuit of momentum transformer and out voltage maintenance on required level using feedback signal. The structure of modern PWM controllers provides additional functions that enhance efficiency and reliability of power supply equipment:

- current and interpulse period limitation in the potential triode transistor drive circuit;

- soft start of converter after supply (Soft Start);

- on-board dynamic power supply equipment from HV voltage input;

- control of the level of input voltage level with removal of «cliffs» and «eruptions»;

- short-circuit protecting in potential transformer circuit and output circuits of outlet box;

- temperature protection of controller and key element;

- converter blocking at reduced and high input voltage;

- control optimization for standby conditions and undercurrent condition in load current (skip cycles or converting underfrequency changeover);

- EMI level optimization.

In [4] modern PWM controllers' survey is presented, comparative results are shown in the table 1. It can be deduced from the comparison that PWM controller NCP1252 is prospective for engineering of intended forward static power supply unit as it possesses more service modes than wide-spread UC3844 one. PWM controller's structure contains logic that plots state engine. Automaton transition chart is realized on comparers, triggers, time registers and elements of logic. Basic states of controller are initial startup of frequency-response generator, process stabilization of operation conditions, adaptive load current tracker and selection of optimum operation, detection of critical activities, fallback, auto-recover after failures.

Other distinctive features of the controller are:

- Regulator with operation on peak current (peak control mode of force multiplier consists in comparison of swelling current of force multiplier with required level which is determined with feedback voltage);

- Protection against current capacity excessing with 10 ms fixed delay (at the moment of switching key on through discharge in high-power diode and winding capacity charge of transformer short power pulse of current shapes and disturb regulator due to which short delay in tracking of actual magnitude of current);

- Overstressing protection on force multiplier's control gate (maximal voltage is internally limited to 15V).

Circuit power supply range is within 9 to 28V with automatically renewable undervoltage protection circuit of supply of inner structures of microelectronic circuit (UVLO). Undervoltage of operation for keys of output stage circuit of controller is dangerous because of triode transistors' transfer to linear condition and thermal overload of chip which leads to failure; that is why all modern drivers on gate-control diode contain UVLO circuit which prevents form such operating mode).

Table 1

Comparison of basic parameters of PWM controllers of various manufacturers.

Type	Topology	Regulation regime	Frequency, kHz	Stand-by regime	Under- and Over- Voltage Protection UVLO, B	Output short circuit protection	Blocking	Soft-start regime
NCL30000	Flyback	current	up to 300	-	-	-	-	-
NCL30001	Flyback	current	up to 150	-	-	-	-	-
NCP1237	Flyback	current	65	-	-	+	+	+
NCP1238	Flyback	current	65	-	-	+	+	+
NCP1288	Flyback	current	65	-	10	+	+	+
NCP1379	Flyback	current	variable	+	9	+	+	+
NCP1380	Flyback	current	variable	+	9	+	+	+
NCP1252	Foward	current	up to 500	+	9-10	+	+	+
NCP1221	Foward	voltage	up to 1000	-	+	-	+	+
CS5124	Flyback	current	400	-	+	-	-	+
MC33025	Push-Pull	current or voltage	1000	-	+	+	-	+
MC33060	Flyback	voltage	200	-	+	-	-	+
MC33067	Flyback	voltage	1000	-	+	+	-	+
MC33364	Flyback	current	variable	+	+	-	-	-
MC34060	multiregime	voltage	200	-	+	-	-	-
MC34067	resonant	voltage	-	-	+	+	-	-
MC44603	Flyback	current or voltage	up to 250	+	9	+	+	+
NCP1200	Flyback	current	100	+	-	+	-	-
NCP1203	Flyback	current	100	+	+	+	-	-
NCP1203	Flyback	current	100	+	+	+	-	-
NCP1207	Flyback	current	up to 1000	+	+	+	-	-
NCP1216	Flyback	current	100	+	-	+	-	+
NCP1217	Flyback	current	100	+	+	+	+	+
NCP1219	Flyback	current	100	+	9,4	+	+	+
NCP1230	Flyback	current	100	+	+	+	+	+
NCP1252	Flyback/Forward	current	up to 500	+	9-10	+	+	+
NCP1271	Flyback	current	100	+	+	+	+	+
NCP1294	Flyback	-	Up to 1000	+	+	+	+	-
NCP1308	Flyback	current	variable	+	+	+	+	+
NCP1337	Flyback	current	variable	+	+	+	+	+
NCP1338	Flyback	current	variable	+	+	+	+	+
NCP1351	Flyback	current	variable	-	-	+	+	-
NCP1377	Flyback	current	variable	+	+	-	+	+
NCP1379	Flyback	current	variable	+	9	+	+	+
NCP1380	Flyback	current	variable	+	9	+	+	+
NCP1381	Flyback	current	variable	+	+	+	+	+
NCP1382	Flyback	current	variable	+	+	-	+	+
NCP1392	Half-Bridge	current	250	-	9	-	-	+
NCP1393	Half-Bridge	current	250	-	9	-	-	+
NCP1395	Push-Pull	voltage	1000	+	+	+	+	+
NCP1396	Push-Pull	voltage	Up to 500	+	+	+	+	+
NCP1397 A/B	Half-Bridge	voltage	50-500	-	9,5/10,5	+	+	+
NCP1562	Flyback	voltage	Up to 500	-	+	+	-	+
NCV3843, UC3843	Flyback	current	52	-	+	+	-	+
UC3842/43/44	Flyback	current	52	-	+	+	-	-
UC3843/44/45	Flyback	current	52	-	+	+	-	-
UC3845	Push-Pull	current	52	-	+	+	-	+

2. EXPERIMENTAL RESULTS

Circuit engineering of developed source is rather traditional for such class of kits. Tree-phase input is fulfilled three-wire circuit-wise. Single-phasing is also possible. F1-F3 wire fuses protect the kit against extra current of short-circuit. Thermal resistors R2-R4 complete protection against current rush at the moment of switching. Input voltage is filtered with Γ – filter which consists of C2, C3 and L1. Three-phase rectifier consists of diodes VD2 – VD7. Input rectified voltage is filtered with Π-filter which consists of C5, C6, C7 and L2. For excess voltage decay on the key the RCD-damper consisting of C10, R14,

VD10 is applied. Electrical isolation is fulfilled by means of pulsing transformer T1 coiled round the reel hub EE42.

Output rectifier of each channel is organized forward circuit-wise based on matched Shottky barrier diode MBR 20100 (VD12-VD15) with magnetic couple of output stages' dashpots. Dashpots of all the stages are coiled round unique reel hub EE42. Such structural solution makes possible not only provide grouped stabilization of channels but provides more complete converter's board assembly.

Power output driver of PWM controller makes possible directly operate control gate of force transistor key switching frequency of which is given by means of external resistor R13 (f = 65 khz). At that given frequency is called central, the real one changes during operating device through so-called jitter – introduction of low frequency modulation (±5%) in the vicinity of central frequency. Jitter does not affect the operation of converter (as it does not alternate output duty ratio) but makes it possible to «blur» the spectrum of electromagnetic impulse, by means of distribution of their power in wider frequency band which leads to significant decay of disturbances produced by the converter, in other words, it decreases its electromagnetic compatibility.

For soft start mode operating – activity execution delay at switching – external capacitors C12, C13 are plugged into SSTART contact. At converter's power connection the inner time register switches on and keeps fixed time (120 ms). After this the capacitor's loading begins; with the loading of which coefficient of charge (pulse ratio opposite value) of output signal is increasing that leads to soft increasing of effective output current and voltage.

Brown-out mode is meant for converter shutdown at decreasing of input voltage level of electric power supply (Vbulk) below the line. Necessary structural interface (Vbulk(on)) and shutdowns (Vbulk(off)) are given by means of external resistive ratio device R18, R19, R16, R17.

Monitoring of primary current by means of shunt resistor R15 connection to output CS permits maintain effective current constantly under external factors change and organize overloading and short-circuit protection. RC-filter R9, C9 is necessary for filtration of current transducer signal.

For organization of feed-back according the value of output voltage PWM controller tracks the condition of load current by means of secondary winding connection through optoisolator VT1. At load decreasing coefficient of charge also decreases in order to provide constant output voltage. If the load is totally absent, PWM controller switches to a mode of zero coefficient of charge.

For PWM controller power supply separate transformer winding, rectifier on Shottky-barrier diodes VD16 and liner voltage stabilizer DD2 is applied.

Physical configuration and electrical circuit diagram of developed source are shown on Figs. 5 and 6 accordingly.

The operation of the developed device was tested under the three-phase and single-phase powering.

The output voltage of each channel in the open-circuit operation (three-phase switching), was set to 16 V.
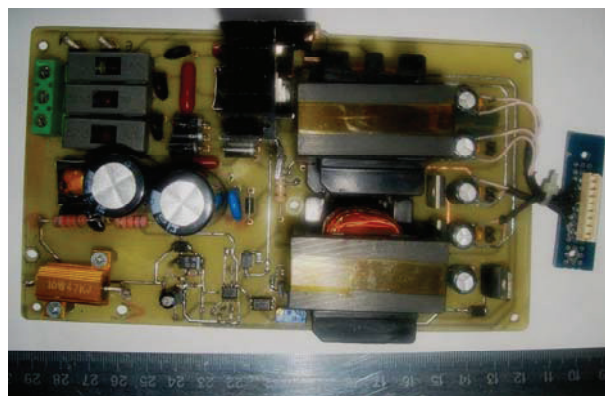

Fig. 5. Physical configuration of developed three-phase switched mode power source DC

A powerful load resistor of Rload = 8 Ohm was connected to the each channel output in the operating mode. The output voltage of each channel was reduced to the level U_{out} = 15.1 V. On the base of the above subscribed experimental data, the output current of each channel was calculated:

$$I_{out} = \frac{U_{out}}{R_{нагр}} = \frac{15.1}{8} = 1.887 A \qquad (1)$$

The output power of the converter was equal:

$$P_{out} = 4 \cdot I_{out} \cdot U_{out} = 4 \cdot 15.1 \cdot 1.887 = 114 W \qquad (2)$$

For an approximate control of the consumed current, an ampermeter installed in the break of the DC bus (between points 1 and 2, see Figure 5) was used. The measured by ampermeter converter input current value was I_{DC} = 263 mA (with a voltage in the DC bus U_{DC} = 543V), which roughly corresponds to the consumed power:

$$P_{IN} = I_{DC} \cdot U_{DC} = 0.263 \cdot 543 = 142.8 W \qquad 3).$$

The converter efficiency:

$$\eta = \frac{P_{out}}{P_{in}} \cdot 100\% = \frac{114}{142.8} \cdot 100\% = 79.8\% \qquad 4).$$

The above described method of the converter's efficiency evaluating is approximate and gives a slightly overvalue result, because does not take into account power losses in the rectifier circuits.

The cost price of the converter is about $ 20.

The converter was tested as a part of a single-phase inverter rectifier of 4 kW power supply in the capacity of the auxiliary power supply.

CONCLUSIONS

Small-size high-efficiency (efficiency factor ~ 79%) pulsed direct-current power supply with output power 114 W and three-phase power supply with four powerful (output current = 2A) voltage output channels is developed. Power source admits three-wire connection to the standard three-phase industrial power network and operates at significant nominal deviation of input voltage and at dump of one phase; admits operation at single-phase power supply. Complex protection of short-circuits, overloading, extra voltage is applied.
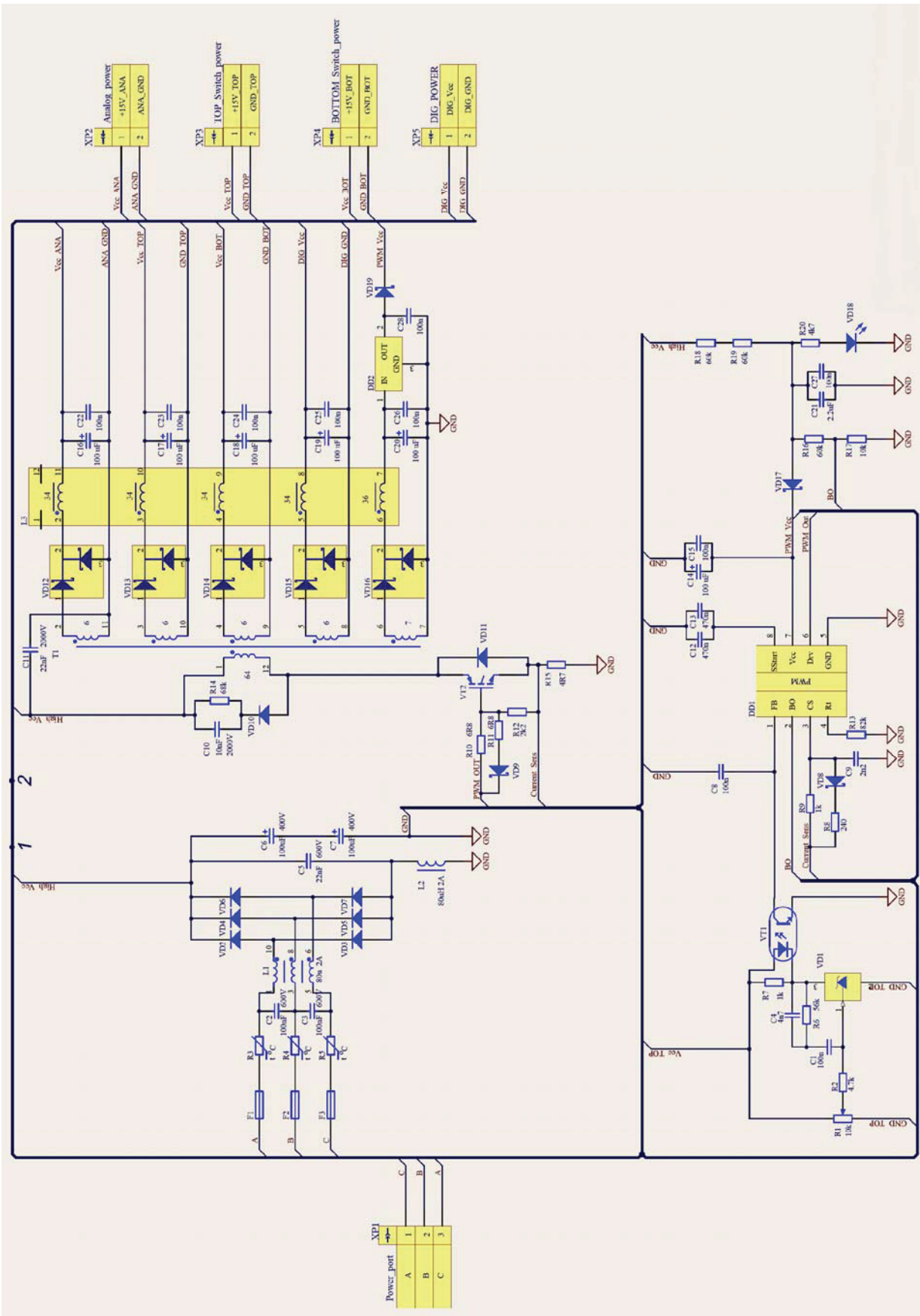
Fig.6. Electrical circuit diagram of developed three-phase momentum direct-current power supply with a capacity of P = 120 W.

References

[1] *Alexei Arbuzov.* Low-power power supplies for industrial automation systems on chips from Power Integrations.// Power Electronics. №3, 2003, pp. 58-59.

[2] *Gennady Bandura.* High voltage switching power supply, made by technology StackFET.// http://www.powerint.ru/SiteFiles/ARTICLES/46/46.htm

[3] *Andrey Kolpakov.* NPT, Trench, SPT ... What now? // Power Electronics. №3, 2003, pp. 14-22.

[4] *Irina Romadina.* Chip PWM controllers for networked power sources.// Components and technologies. №7, 2010, pp. 88-94.

[5] *Volodin V. Ya* LTspice computer simulation of electronic circuits// St. Petersburg "BHV-Petersburg", 2010, pp. 357-369.

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Трехфазный импульсный источник питания мощностью 100Вт / Д.П. Кудрявцев // Прикладная радиоэлектроника: науч. – техн. журнал. – 2017. – Том 16, № 1, 2. – С. 66 – 73.

Разработан высокоэффективный малогабаритный дешёвый импульсный источник постоянного тока с трехфазным питанием и четырьмя мощными гальванически изолированными выходными каналами. Достигнута выходная мощность около 114 Вт. Источник питания допускает трёхпроводное подключение стандартной трехфазной сети, работает при значительном отклонении входного напряжения и потере одной фазы; допускает работу при однофазном питании. Реализован комплекс защит от короткого замыкания, перегрузки, перенапряжения.

Ключевые слова: трёхфазная сеть, импульсный источник постоянного тока, IGBT транзистор, ШИМ контроллер, магнитосвязанные индукторы выходного канала.

Табл.: 01. Ил.: 06. Библиогр.: 05 назв.

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Трифазне імпульсне джерело живлення потужністю 100Вт / Д.П. Кудрявцев // Прикладна радіоелектроніка: наук. – техн. журнал. – 2017. – Том 16, № 1, 2. – С. 66 – 73.

Розроблено високоефективне малогабаритне дешеве імпульсне джерело постійного струму з трифазним живленням і чотирма потужними гальванічно ізольованими вихідними каналами. Досягнута вихідна потужність близько 114 Вт. Джерело допускає живлення за трипровідною схемою підключення до стандартної трифазної мережі, працює при значному відхиленні вхідної напруги і втраті однієї фази; допускає роботу при однофазному живленні. Реалізовано комплексний захист від короткого замикання, перевантаження, перенапруги.

Ключові слова: трифазна мережа, імпульсне джерело постійного струму, IGBT транзистор, ШІМ контролер, магнітозв'язані індуктори вихідного каналу.

Табл.: 01. Іл.: 06. Бібліогр.: 05 найм.