doi.org/10.15407/tpwj2016.04.06

STATE-OF-THE-ART INVERTER POWER SOURCES WITH INCREASED POWER FACTOR

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The paper proposes circuit design of high-frequency transformer-isolated converter and three-phase input without intermediate rectification of input voltage. A system was built using modular approach, i.e. each phase contains identical high-frequency AC/DC transformer-isolated converters, the outputs of these converters have series connection. Application of principle of direct conversion allows reducing amount of elements in the source power circuit, thus, reducing energy loss. Besides, high-frequency energy transformation allows significant improvement of weight-dimension characteristics of the system. Application of special algorithm of power key control provides for the possibility of active correction of input power factor and neutralization of circuit frequency harmonics in source output voltage that significantly reduces the requirements to output filter. The developed source has fast response and can be used for welding processes requiring high rates of change of arc current. 14 Ref., 3 Tables, 4 Figures.

Keywords: *power source, welding inverter, power factor corrector, direct converter, direct conversion, power quality, galvanic isolation*

Modern inverter power sources usually use double energy conversion, namely alternating voltage of supply mains is rectified and smoothed, after what it is supplied to DC/DC converter providing set output parameters of electric energy and transformer isolation from the mains.

A converter of mains alternating voltage in direct one determines power factor (PF) of the source. Usually this problem is solved with the help of a diode bridge with high-value filtering capacitor [1, 2] connected to its output. The disadvantage of such conversion method is low PF of around 0.5–0.7 and large distortions of shape of consumed current curve.

PF can be increased by means of installation of active power factor rectifier-corrector [3–7] or using direct energy conversion method.

Work [8] proposes a variant of single-phase welding source, in which function of input voltage rectification is eliminated due to application of four-transistor chopper of alternating voltage and low-frequency (50 Hz) transformer with low dissipation. The source has good results on efficiency and PF, but application of LF transformer leads to deterioration of weight-dimension characteristics of the device using similar control principle. Besides, necessity in DC welding requires application of energy stores for single-phase sources. These stores provide arcing at zero circuit voltage. This can be a filter capacitor or output chokes.

Attention is also to be given to circuit design with PF correction [9, 10]. It uses three-phase step-down mains frequency transformer, and its secondary windings have loading on three step-down DC/DC converters with series outputs (Figure 1).

Diodes VD1–VD6 form three full-wave rectifiers and elements C1VT1VD7, C2VT2VD8, C3VT3VD9 — three step-down converters operating with common HF smoothing choke L1. Capacitors C1–C3 have small capacity and designed for limitation of pulse surges appearing at power transistor closing. At that, their effect on circuit current formation can be neglected.

Close to one PF is achieved by means of setting VT1–VT3 control pulse relative duration proportional to modules of momentary values of corresponding phase voltages. Mains frequency harmonics are supressed at the output in supply from symmetrical mains that allows using choke L1 with low inductance.

Work [8] outlines a perspective problem of development of three-phase sources with isolating HF transformer and direct conversion and proposes a scheme of single-phase source with direct conversion and HF transformer isolation. The source is designed based on forward converter with transformer. The disadvantages of scheme proposed in [8] are improper application of magnetic mains of pulse transformer due to contact with magnetic flow constant component and impossibility of arc current keeping at zero mains voltage.

Use of source transformers can be improved due to application of push-pull operation. This problem was solved in modular source [11], Figure 2 shows mains design of its power part.

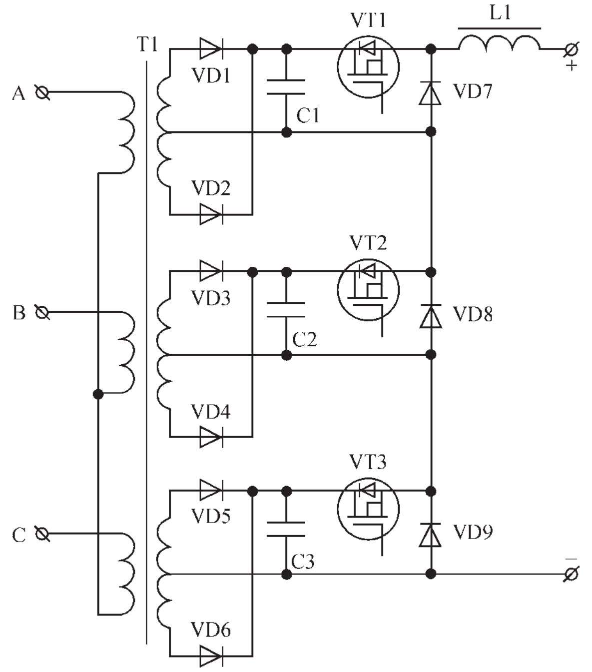

Figure 1. Scheme of hybrid source with LF transformer

Each phase of the source have connected HF transformer, the primary windings of which are switched on in such a way that magnetizing current has different polarity depending on switched on key (for phase A it is transformer T1 and keys S1 and S2). Two capacitors (C1, C2) are designed for power surge limitation in keys change. The transformer output winding is connected to two full-wave rectifier (diodes VD1, VD2). The outputs of rectifiers of all phases have series accordant connection and switched to the source output via smoothing choke L1.

Let's study the processes taking place in the elements, connected with phase A, since the processes in all other phases are similar. The same series of assumptions as in earlier described source is taken for analysis simplification.

Closure of key S1 provides for connection of the primary transformer winding to the input voltage. EMF of the output winding opens one of the output diodes (VD1 or VD2) and closes the second depending on the sign of input voltage. The current of primary winding of the transformer (and key S1) at that equals given load current. The voltages on capacitors C1, C2 are equal between themselves and to output voltage.

Closure of S1 promotes for cut of output winding voltage, load current is uniformly distributed between the output diodes. Key S1 current (it is magnetizing current T1) is flipped to capacitor C2.

S2 opening provokes for the same processes, but they are differ by the fact that a derivative of transformer linkage has opposite sign. It allows preventing saturation of magnetic core and providing push-pull operation mode.

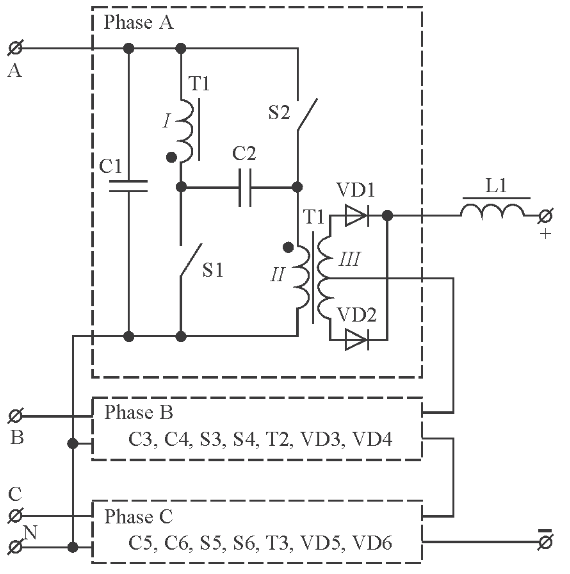

Figure 2. Power part of source with push-pull mode of transformer operation

It should be noted that keys S1, S2 should be designed for voltage not less than double amplitude of output phase voltage.

If power switches of phase A are switched with relative duration $D_a(t)$, the local average values of input current and output voltage for switching period (i.e. the average for the period of PWM carrier frequency) can be calculated. At that, maximum relative pulse duration makes $D_{max} = 0.5$ (at larger relative durations both keys will be switched simultaneously, that results in input short circuit). For better visualization Figure 3 shows equivalent network for local averages.

The local average input current equals

$$\hat{i}_a(t) = 2I_L \operatorname{sign}(u_a(t)) D_a(t). \qquad (1)$$

Factor 2 appears because of the fact that the current is used 2 times during one switching period (one time at switched on S1 and the second at switched on S2). The sign of input current always matches with the voltage sign due to effect of output rectifier. The output voltage is respectively:

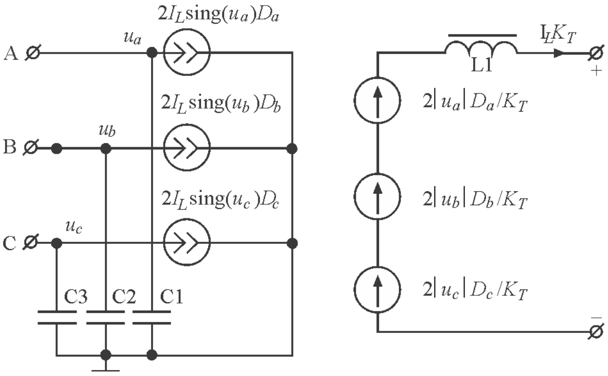

Figure 3. Equivalent network of Figure 2 source for local averages

$$\hat{e}_a(t) = 2\frac{|u_a(t)|}{K_T} D_a(t). \tag{2}$$

The voltage is taken by modulo due to output rectifier.

The condition of close to one input power factor is $D_a(t) = v|u_a(t)|$, where v is the proportionality factor.

The output voltage of three phases of power source if supplied from three-phase symmetrical mains is

$$\hat{e}_a(t) + \hat{e}_b(t) + \hat{e}_c(t) = 2\frac{|u_a(t)|}{K_T} v|u_a(t)| + $$
$$+ 2\frac{|u_b(t)|}{K_T} v|u_b(t)| + 2\frac{|u_c(t)|}{K_T} v|u_c(t)| = \tag{3}$$
$$= 2\frac{v}{K_T}\left(u_a^2(t) + u_b^2(t) + u_c^2(t)\right) = 3\frac{v}{K_T}U_m^2.$$

As can be seen from obtained expression, the output voltage does not include the components with mains frequency or its harmonics, that allows reducing inductance of output choke L1.

Control of output voltage is carried out by violation of parameter v at keeping the condition of relative duration limitation $D_a(t) \le D_{max}$. The following is received by substitution of the corresponding expressions:

$$v|u_a(t)| \le D_{max}; \tag{4}$$

$$v \le \frac{1}{2U_m}. \tag{5}$$

Therefore, the maximum output voltage of the source is

$$\left[\hat{e}_a(t) + \hat{e}_b(t) + \hat{e}_c(t)\right]_{max} = \frac{3}{2}\frac{U_m}{K_T}. \tag{6}$$

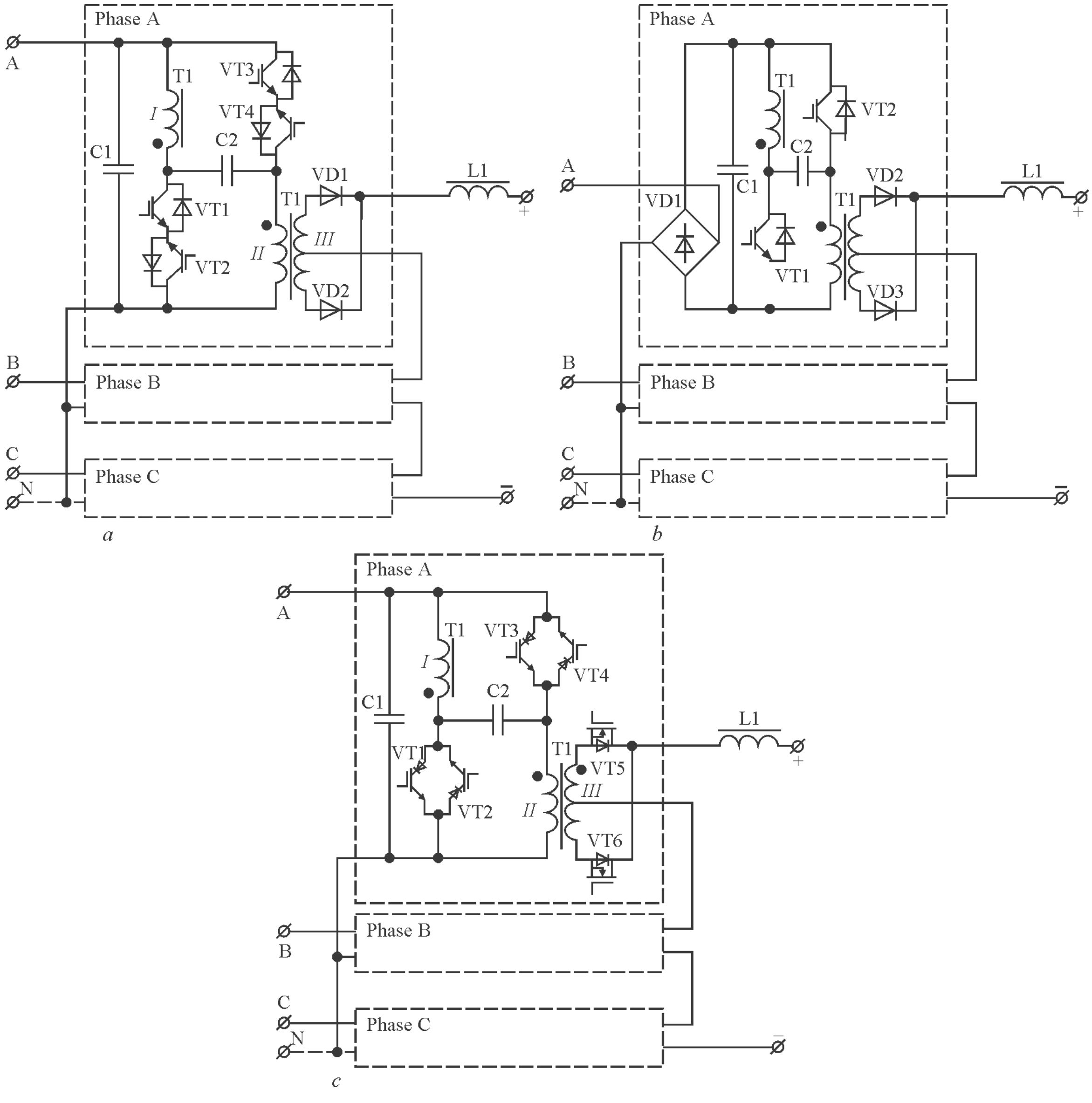

Figure 4. Variants of source power part in Figure 2 (for description see the text)

The maximum output voltage makes around 70 V with U_m = 350 V at practical implementation of three-phase source.

Amount of transformer winds is also determined from the condition of maximum inductance B_m in magnetic core. Let's determine amount of primary winds W_1 by equation of its maximum linkage, which take place at transfer of phase voltage through the maximum at set maximum output voltage. Taking into account push-pull mode of transformer operation (alternating magnetization from $-B_m$ to B_m) it can be written:

$$\frac{U_m D_{\max}}{f} = 2B_m S W_I; \quad (7)$$

$$W_I = \frac{U_m D_{\max}}{2B_m S f}, \quad (8)$$

where S is the section of magnetic core, m^2.

The variants of practical implementation of the source with power part based on Figure 2 can be different. Figure 4 shows several variants.

Figure 4, *a* shows bi-directional keys made in form of two back-to-back-series IGBT transistors with bypass diodes.

Variant, given in Figure 4, *b*, contains a diode bridge in the input of each phase modulus, that allows 2 times reduction of amount of power transistors and simplify control system. The price for simplification is reduced efficiency due to increase of number of semi-conductor elements in power mains (two diode bridges and transistor).

In variant in Figure 4, *c* the keys are made of two back-to-back parallel RB IGBT transistors capable to withstand reverse voltage. This solution allows reducing number of semi-conductor elements in the power mains to one, thus increasing efficiency. Besides, synchronous rectifier based on MOSFET transistors with low channel resistance is used for decrease of output energy loss.

Scheme of Figure 4, *a* is applied at practical implementation of the source. E42/21/20 (EPCOS) cores from N87 material with magnetic core section S = = 234 mm^2 are used for phase transformers; the maximum inductance is taken equal B_m = 0.25 T. Switching frequency f = 20 kHz, U_m = 350 V. Using these data W_1 = 75 winds is obtained.

Power transistors are of STGW30N120KD type. Diodes of output rectifiers are the assemblies of 80CTQ150 type. Transformer ratio of HF transformers equals 7.5 (output winding has 2 sections by 10 winds). Capacitors have capacity of 4.7 μF and operating voltage 400 V. Output choke L1 has inductance 45 μH at 60 A current (43 winds for toroidal core T184-52).

Control scheme is made based on single-crystal microcontroller STM32F100C4T6B (STMicroelectronics), operating at 24 MHz frequency. For each phase the controller forms two impulse relative time signals F_1 and F_2 (for keys S1 and S2). These signals are distributed between transistors depending on sign of phase voltage. Table 1 shows such a distribution for phase A.

Formation of control signals for the transistor power gates is carried out with the help of special optical couplers FOD3120. Computational capabilities of applied microcontroller allows realizing source operation without connection to neutral circuit, at that balancing of input voltages of phase modules is carried out by program using known principle «two out of three» [12, 13], i.e. the correction of relative duration take place in phases with the maximum and minimum voltages that allows controlling displacement of Y-point formed by phase modules.

The source, based on scheme of Figure 4, *c*, can use IXRP15N120 (IXYS) transistors, and in output rectifier — IRFS4115-7P (International Rectifier) transistors. The transformers and capacitors are the same as in the source based on scheme of Figure 4, *a*. Formation of control signals for transistors of phase A is given in Table 2 (exclamatory mark (!) designates logical negation operation NOT).

Pairs of signals (F_1; !F_1) and (F_2; !F_2) are formed with dead time, necessary for corresponding switching of power keys.

Deterioration of the parameters at low loading can be explained by the fact that LF harmonics of rectifiers VD1C1 in Figure 4, *b* start prevailing in input current. In schemes (Figure 4, *a*, *c*) reduction of PF at

Table 1. Distribution of control signals

Phase to earth voltage	VT1	VT2	VT3	VT4
$U_{AN} > 0$	F_1	1	F_2	1
$U_{AN} < 0$	1	F_1	1	F_2

Table 2. Control signals for scheme in Figure 4, *c*

Phase to earth voltage	VT1	VT2	VT3	VT4	VT5	VT6
$U_{AN} > 0$	F_1	1	F_2	1	!F_1	!F_2
$U_{AN} < 0$	1	F_1	1	F_2	!F_2	!F_1

Table 3. Dependence of parameters of source prototype on output current

Output power, kW	0.25	0.5	1	1.8
Power factor	0.95	0.98	0.99	0.99
Mains current harmonics factor, %	28	15	5	4

low loading will take place due to capacitive current passing through input capacitors (C1 in Figure 4, *a*, *c*).

Setting of the relative duration of control pulses of key transistors being proportional to the modules of transient values of corresponding phase voltages is not the single possible algorithm for control of proposed converter. Thus, work [14] provides for a review of methods for formation of input currents in the active three-phase rectifiers under different conditions in supply mains, i.e. unbalance and presence of voltage higher harmonics. Regardless the fact that this network research is made for active current rectifiers and active voltage rectifiers, its results with some limitations can be applied to proposed direct converters since its equivalent network (see Figure 3) corresponds to the active current rectifier. It follows from the conclusions given in work [14] that at mains unbalance the optimum variant is control in order to minimize the output current pulsation, and the method, at which phase currents follow the shape of phase voltage is the best for mains voltage distortions.

Application of the considered converters of three-phase voltage allows eliminating distortions in supply mains voltage, reducing energy loss in the converter, improving its dynamic and weight-dimension characteristics.

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Received 20.05.2015