TRANSISTOR POWER SOURCES FOR ELECTRIC ARC WELDING (Review)

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The paper describes the most widely accepted circuits of electric arc transistor power sources. Features of parallel operation of transistors, methods of overvoltage protection and switching path formation, modern drivers, design of high-frequency transformers, power correctors, systems of control of electrode metal melting and transfer are considered.

Keywords: *electric arc welding, power source, transistor, transformer, control system, metal melting and transfer*

Leading manufacturers of welding equipment are mainly producing transistor-type power sources for electric arc welding. Thyristor rectifiers and rectifiers with step voltage switching are manufactured in small quantities. Transistor sources have small weight and overall dimensions, high accuracy of adjustment and fast response. The simplest transistor source is the one based on pulse controller (chopper) (Figure 1). Compared to inverter sources, transistors operate at significantly lower voltages without any through currents, their control circuit is much simpler, and there is no high-frequency transformer. Chopper sources generate relatively low interference and only slightly distort the mains voltage, and their power factor is close to 1. Their large weight is a disadvantage. Chopper source Origo Mig 4002c (ESAB) for 400 A has the weight of 139 kg. Weight of inverter power source Origo Mig 4001i for the same current is equal to 43.5 kg.

One of the first transistor sources, manufactured in Ukraine in 1972 at the Institute of Electrodynamics by the order of the E.O. Paton Electric Welding Institute, was designed for consumable-electrode welding in space. Maximum current was equal to 300 A, at 27 V power supply from the spaceship on-board mains. In 1980s the Institute of Electrodynamics developed chopper sources for 500 A for multi-station semi-automatic welding in shipbuilding [1]. A source for 1000 A was manufactured for investigation of metal transfer in consumable-electrode welding, which lowered metal losses for spattering to 0.5 % in CO_2 welding [2, 3].

Application of two transistors and high-frequency transformer in the chopper enables eliminating the mains transformer (Figure 2). Other names of such a circuit are single-step converter, asymmetrical bridge, and «skew» bridge [4–6]. Application of such a circuit allows eliminating the causes for appearance of through currents and asymmetrical magnetization of high-frequency transformer. Therefore, at the initial period of development of inverter sources «skew» bridges were very popular. Now a considerable portion of the sources are made by this circuit.

Lowering of output voltage ripple and power increase are achieved at operation of two «skew» bridges for one load (Figure 3). The disadvantage of the «skew» bridge — doubled weight of the high-frequency transformer — is eliminated by semi-bridge circuit (Figure 4). Such a circuit is the most often used in sources of several kilowatt power and mains voltage of 220 V. There is, however, a possibility of through current flowing through transistors in it that may lead to inverter malfunction. Another disadvantage is a two-times increased current load on the transistors

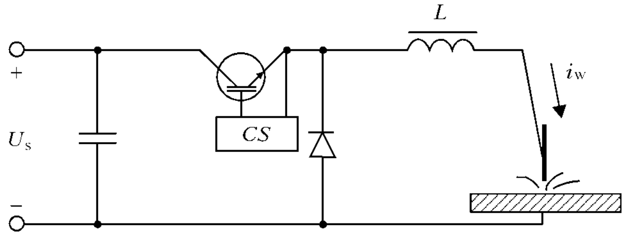

Figure 1. Circuit of reducing pulse controller (chopper)

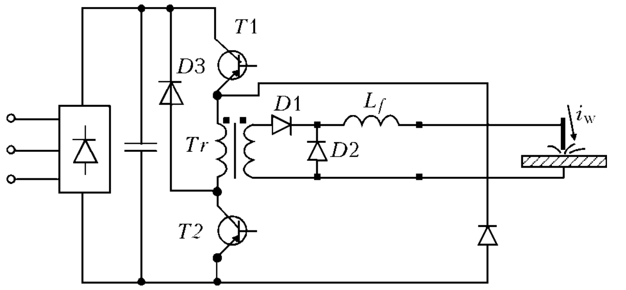

Figure 2. Circuit of asymmetrical («skew») bridge

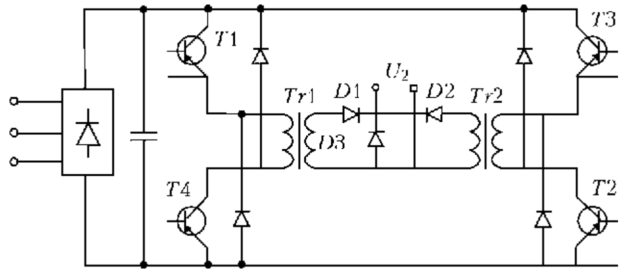

Figure 3. Circuit of power source consisting of two asymmetrical bridges

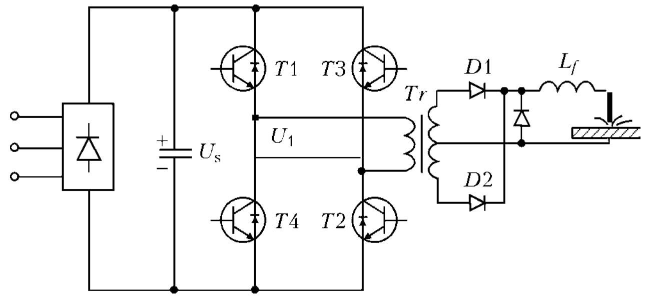

Figure 5. Circuit of bridge inverter

compared to bridge circuit (Figure 5). A pilot sample of bridge welding inverter with power supply from 380 V mains was manufactured in 1982 at the Institute of Electrodynamics. Absence of reliably operating transistors for more than 600 V voltage at that time did not allow introducing it into batch production. This problem is not completely solved even now.

Maximum admissible current of the most popular IGBT transistors at case temperature of 25 °C is 50 A. With temperature increase up to 100 °C, current drops markedly. For reliable operation of the transistors, they should be loaded by not more than 30–50 % of the maximum admissible current. Therefore, parallel connection of transistors, which began to be applied already in 1950s [7], is often used even in sources with power supply from 220 V voltage and welding current of 120 A. Reliability of such a connection can be smaller than that of one transistor, as the quantity of semi-conductor crystals and brazed joints is increased.

In order to improve the reliability of parallel connection rather than lowering it, the Institute of Electrodynamics proposed deep redundancy method. At the start of 1960s this method was used to manufacture a transistor switch for 100 A [8]. One thousand (!) germanium transistors were connected in parallel, each of which with maximum admissible current of 0.4 A. Transistors were first sorted by voltage drop. Transistors with the same voltage drop were connected in parallel that reduced current scatter between the transistors. In addition, fuses were connected into the emitter and base circuit of each transistor. Transistor failure led to fuse blowing and its switching off. Current switched by the failing transistor was redistributed between the remaining transistors. As all the transistors operated at significant underloading even in the case of maximum current switching, current increase by 1/1000 did not lower operation reliability. Theoretical investigations and experiments confirmed the high reliability of such connection. In modern power sources deep redundancy method is not used, so that failure of one transistor can lead to malfunction of the source.

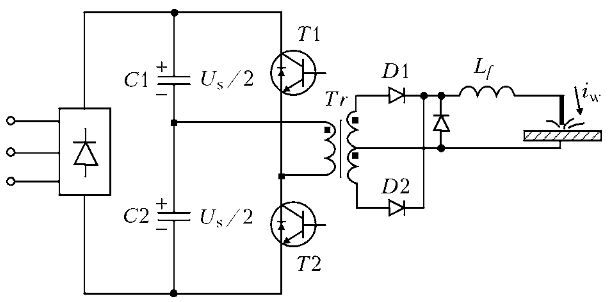

Figure 4. Circuit of semi-bridge inverter

At design of high-frequency power transformers two main problems have to be solved: achievement of minimum leakage inductance, and taking measures for elimination of the influence of surface effect in conductors. Leakage inductance causes pauses in rectified voltage, which lower the source effectiveness [9].

The simplest method to suppress leakage inductance is to use it as inductance in the resonance power source. In the other cases, inductance should be lowered by minimizing the distance between the windings and their sectionalization. Frequency from 20 up to 80 kHz is used in modern sources. Transformer magnet cores are made of ferrite. Depth of current penetration into the conductor at such frequencies is from 0.50 up to 0.34 mm. Therefore, it is rational to use wires with not more than 1–2 mm cross-sectional dimensions. In sources of several kilowatt power currents are relatively low, so that primary winding is wound from wire of round section. Parallel connection of wires of round or rectangular section is used in the secondary winding [6, 10, 11].

Another variant of reducing the surface effect is application of RF cable as the conductors, which can be replaced by simultaneous winding with parallel conductors. In high power transformers the primary winding is wound with wire of rectangular cross-section. Secondary winding can be made of insulated copper strip equal to doubled depth of current penetration and width covering the entire primary winding. Shell-core transformer of such a design of 15 kW power

(100 % duty cycle) and 1 kg weight was manufactured in 1982 for inverter power source.

Modern power sources mainly use shell-type transformers as the most manufacturable ones, rather than core-type or ring transformers, although they lower the leakage inductance and improve the cooling conditions. The most manufacturable cable transformers are used even more seldom. For 3 kW source cable transformer magnet core consists of several ferrite rings with cross-sectional area of 8 cm^2, and windings with w_1 = 12 and w_2 = 2 turns [12, 13].

In modern power sources IGBT transistors are mainly used. Field-effect transistors are applied much more seldom. At parallel connection of IGBT transistors the transistor with the lowest saturation voltage, transmits greater current and is heated more [14, 15]. The sign of the temperature coefficient of saturation voltage (TCSV) has the greatest influence on connection reliability. If TCSV has a positive value, then temperature rises and voltage drop becomes greater in the transistor with greater current, thus leading to current decrease. If TCSV value is negative, transistor with higher current is heated more, voltage drop in it decreases, thus leading to an even greater load by current and further heating. In IGBT transistors TCSV sign depends on current. For instance, for transistors of GA100TS60SQ type TCSV is negative at small currents, and positive at high currents [15].

There are several factors promoting equalizing of current between transistors connected in parallel [16]. The first factor is that transistors should have the same temperature that is achieved by mounting them on one radiator. In this case crystal temperatures differ only slightly, that promotes lowering of current disbalance. Line current increase (second factor) leads to greater voltage drop on all the transistors, thus promoting an even more uniform distribution [15]. The third factor is connection of pre-selected transistors with similar voltage drops. This enables achieving a current difference of less than 5 % [17, 18]. If transistors are not selected, then the non-uniformity of current distribution is increased with increase of their number that eventually will lead to failure of one of them. Welding current rectifier diodes are also connected in parallel in power sources. Diodes with the same voltage drop should be used to reduce currents disbalance [18].

In addition to non-uniform current distribution in statics, there exists non-uniform current distribution in dynamics. This is caused by different times of transistor switching on and off and threshold voltages of transistor activation. Selection of transistors with similar dynamic characteristics is practically not used. Therefore, to reduce current disbalance in dynamics, it is rational to connect a resistor into control circuit of each transistor [18]. Non-uniformity of current distribution at transistor switching is caused by inductances of connecting conductors [19]. Application of IGBT modules eliminates the problem of reducing the non-uniform distribution of current between discrete transistors and diodes for the developer [20].

Power source output voltage can be controlled by several methods. The first is variation of inverter supply voltage, for instance, using a chopper. The second method consists in application of controllable welding rectifier of output voltage. The third, most often used method, is inverter regulation [21]. Regulation can be performed by pulse-width modulation (PWM), PWM with a controllable phase shift (PWM-PS), frequency variation (PFM) or combinations of these methods. PWM is the simplest and most often used method. In bridge inverter arm transistors are switched simultaneously at PWM. If arm transistors are switched with a time shift (PWM-PS) dynamic losses and interference can be reduced. At PWM application, variation of pulse duration is possible at constant duration of the pause or at its variation at constant pulse duration. Frequency method is most often used in budget or self-made sources [6, 11].

Source reliability and energy efficiency are strongly influenced by the processes of transistor switching. At the moments of switching a high power is released in the transistor crystal, which causes accelerated ageing of the crystals. Application of chains of capacitors, diodes and resistors (snubbers) allows directing transistor current to a capacitor at the moments of switching [21, 22]. In the pauses between switching, energy stored in the capacitor dissipates in the resistor, thus increasing the temperature inside the source. At short pauses between switching the capacitor does not have enough time to discharge, and snubber effectiveness decreases. More complicated chains with an additional inductance ensure energy recovery [4, 5, 21]. Efficient snubbers are quite cumbersome. The simplest method to improve transistor switching conditions and their operating safety is switching off supply voltage from the inverter at the moments of switching by an additional transistor. Modern IGBT transistors can briefly transmit maximum admissible current at maximum admissible voltage drop in them. Therefore, no special devices are used in many sources to form the path of transistor switching. Often just one high-frequency capacitor is applied to power the inverter, located as close as possible to the transistors.

Transistor voltage should not exceed the maximum admissible value, even briefly. Switching overvoltages caused by wire inductances may reach hundreds of volts. Overvoltage drop is achieved by reduction of the area of current flowing circuit inside the inverter [20, 21, 23]. Limitation of switching overvoltages is achieved also by designing circuits of minimum area. Application of transistor-diode modules reduces overvoltages.

Another method to lower dynamic losses and overvoltages is application of resonance inverters, in which transistor switching occurs at zero current or voltage [5, 6, 21, 24–27]. High-frequency transformer primary winding is most often connected in series with capacitor C and inductance L. In this case transistor switching occurs at zero current. Capacitor also eliminates the direct component of magnetization current. Circuits with parallel connection of C, L and primary windings are applied less frequently. Inverter should provide a wide range of adjustment of voltage and current at load variation in the range from short-circuiting to open-circuit mode. Under such conditions it is difficult to ensure transistor switching without current in all the modes. Therefore, in some cases dynamic losses of resonance inverter can exceed the losses in regular inverters. Resonance inverters are the most often applied in sources with power supply from 220 V mains. Current is regulated by frequency method. Transistor switching at zero current occurs at maximum welding current and minimum frequency. At frequency increase circuit impedance rises, and welding current decreases. Capacitor voltage during the resonance can reach several kilovolts [6, 11]. Investigation and design of a resonance source by analytical methods is a challenge, it is more convenient to model it using MatLab, MicroCap and other packages [26].

Current consumed from the mains by welding inverter has a pulsed component, which is due to input capacitor charge. Pulsed currents are particularly significant at power supply from single-phase mains. This increases the mean-root-square value of the consumed current and distorts the mains voltage. Application of power factor correctors (PFC) reduces the mean-root-square current, and allows increasing the welding current at the same mains voltage. This is particularly urgent for power sources connected to a low-power network [4]. A simple enough and effectively operating PFC can be constructed by converter circuit with voltage increase (Figure 6). PFC output voltage is 400 V that allows application of current transformation coefficient 5/1 and reducing transistor current. The same circuit can be applied at power supply from three-phase mains. Further reduction of mains distortions requires more sophisticated control algorithms and circuits [4, 28]. Power correctors on the whole make the power source more complicated and increase the cost. Therefore, despite the advantages, they are seldom used.

For a good ignition of the arc and prevention of its extinction, source open-circuit voltage should be 60–80 V. At 200 A current arc voltage is not more than 24 V. If transformer transformation coefficient ensuring smooth voltage adjustment in the range from 0 up to 80 V is used, transistors will transmit higher current by short pulses in the operating mode. This increases energy losses and necessitates application of transistors with higher admissible current. Therefore, it is advantageous to apply transformers, in which maximum secondary voltage is equal to nominal arc voltage, and apply an additional low-power source with a steep-falling characteristic to increase the open-circuit voltage. To avoid using a separate inverter, increased voltage for low-power rectifier can be obtained from an additional winding of the main transformer. Another method is application of secondary voltage multiplier [6]. Pilot current in the arc will be maintained all the time that lowers the requirements to smoothing choke inductance.

Transistors and diodes fail at voltage exceeding the above limit values even for a short-time. Therefore, it is extremely important to provide high-speed overvoltage protection. Overvoltages develop during switching processes in the inverter proper, at arc extinction or may come from the mains. Overvoltages are smoothed using damping chains, and maximum value is limited

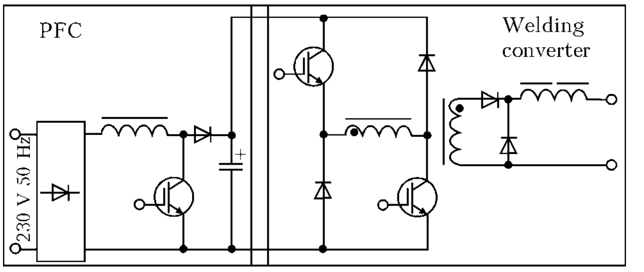

Figure 6. Circuit of source with PFC

by stabistors [21]. Stabistors are the most often used to protect the transistor gate, as voltage can rise uncontrollably at switching because of the capacitance between the gate and collector. Stabistors increase the capacitance of the control circuit that may lead to high-frequency generation. Much more seldom stabistors protect collector-emitter terminals, even though it improves the reliability. Quite often *RC* chains and stabistors protect welding current rectifier diodes [4, 6, 12]. Inverter power capacitors are charged at mains voltage connection. To prevent short-term current rise that may lead to malfunction of input rectifier diodes, a resistor is connected in series, which is shunted by relay contacts after capacitor charging. Such a circuit is used practically in all single-phase power sources.

In addition to overvoltages, exceeding current level, temperature, operation in active mode and high-frequency generations are hazardous for the transistor. It is rational to envisage partial protection from such hazardous impacts using drivers, which can be made in the form of one microcircuit or as a hybrid version. The latter type features greater functional capabilities [29]. One microcircuit case can contain drivers to control the inverter upper and lower arms. To simplify the circuit, upper arm driver is powered from the capacitor, charged from lower driver power source at closed lower transistor. Hybrid version drivers often have a built-in power source of upper arm circuit. Drivers provide a delay between switching on the upper and lower arm transistors, eliminating through currents. To prevent transistor operation in the active region, transistor voltage in off condition is monitored [30]. Driver can have built-in protection from current exceeding the admissible value. A shunt connected into emitter circuit of the lower transistor or additional transistor terminal can be used as current sensor. More advanced drivers can distinguish between a soft and hard short-circuit. Soft short-circuit occurs in the load, connected to inverter by a cable with inductance. Hard short-circuit runs inside the inverter and is much more hazardous. Drivers determine the short-circuit type, while changing the switching-off algorithm. The most functionally complete are drivers based on digital technology, providing adaptation for specific application conditions [31].

Inverter power sources enable controlling electrode metal melting and transfer. Lincoln Electric developed a method of metal transfer in CO_2 welding by surface tension forces (Surface Tension Transfer). Its main advantages are lower spatter, welding process stability, and less fumes. In Russia similar control is applied by Company «Tekhnotron» in welding root welds of pipelines [32]. Investigation of metal transfer by surface tension forces was earlier performed at PWI and Institute of Electrodynamics of the NAS of Ukraine [2, 3, 33].

Fronius Company developed a method to control metal transfer with CMT trademark (Cold Metal Transfer). During short-circuiting the wire is drawn back, current stops flowing, and the drop goes into the pool without spatter. Product heating and harmful substances evolution are reduced. Similar work on acceleration of metal transfer with pulsed wire feed was performed at PWI in 1970s [34]. In CMT Advanced voltage polarity on the electrode is changed during short-circuiting. Negative polarity increases electrode melting rate. At positive polarity controlled precision transfer of metal is ensured. Ratios of positive and negative polarities are determined individually [35].

Lorch Company combined several control algorithms under a common Speed trademark — SpeedMaster [36]. Compared to regular pulsed-arc welding SpeedPulse reduces drop diameter and increases their number. Metal transfer becomes similar to jet transfer. Penetration and efficiency increase by 48 %. SpeedArc technology is designed for narrow-gap single-pass welding of up to 15 mm thick metal. Increased electrode extension promotes wire preheating and increase of melting rate by 30 %. Similar investigations of automatic control systems in welding with longer extension were begun in 1970s [37, 38]. SpeedUp technology is used for vertical semi-automatic welding. In the hot phase of arcing increased current melts the material. At the cold stage low current ensures precise filling of the groove. A similar method is given in [39]. Holder movement path in vertical semi-automatic welding was studied and algorithms of feed rate control allowing achievement of an even lower spatter and greater efficiency, were proposed in the same work. SpeedRoot technology is designed for welding the weld root with up to 8 mm gap by MIG/MAG processes. Controlled oscillations of weld pool in electrode direction are induced. Drop transfer into the pool occurs at short-circuiting without any current at the moment of pool movement away from the electrode that lowers the metal temperature.

Kemppi Company presents their control algorithms under Wise trademark. Semi-automatic and automatic welding of weld root with a gap is performed by WiseRoot technology with transverse oscillations of the electrode. Control system controls the entire pool volume and periodically switches wire feed off, allowing time for metal cooling down. WiseThin technology allows welding up to 0.6 mm metal.

In [40] it is shown that welder's hand movements may be imposed on the speed of wire movement to item surface, thus increasing metal losses and impairing weld formation. Stabilizing the real rate of wire feed into the arc allows lowering the spatter. A particularly pronounced effect of wire feed rate regulation can be achieved in vertical welding. Such a control technique is not used so far in batch production.

Development of automatic control systems is restrained by absence of more profound information on the welding process. Similar to many years ago, welding current and voltage still remain the main feedback signals. It is convenient to measure arc voltage in the power source case. In reality this signal includes voltage drops on inductances of cables supplying current from the source to the arc, voltage drop at the point of contact of the wire with the tip. At short-circuiting at the final stage of bridge breaking up voltage drop does not exceed several volts and its rapid changes are filled with interferences with a close frequency spectrum. Effective control of welding requires knowledge of instantaneous dimensions of the drop and pool, their temperature and composition of evolving gas. This information could be obtained using video sensors. However, the high temperature of the arc, spattering, portable torch and control system sophistication prevent their application. For control system operation it is necessary to know the speed of wire movement to the arc. Wire feed rate is often measured by motor armature emf. The error of such a measurement is equal to tens of percent. Real speed of wire movement into the arcing zone differs even more, because of elastic deformations of wire in the hose, periodical stopping as a result of electrode welding to the current conducting tip, and welder's hand motions. Not knowing the main welding parameters, it is impossible to make a good control system.

In the control system block-diagram inverter dynamic characteristics can be presented by a link with pure delay $T/2$, equal to half of output voltage period. Microprocessor control system can be also presented by a link with pure delay, the value of which depends on the control algorithm and microprocessor response speed. Choke in the welding circuit is used for smoothing the rectified voltage ripple. For good smoothing of current ripple, time constant of welding circuit should be significantly higher than T. Control system uses current and voltage feedbacks, the signals from which should be filtered with time constants, which are much higher than T. Therefore, the total time of links with pure delay and time constants of the block-diagram is equal to several milliseconds. Final stage of breaking up of the bridge between the electrode and pool proceeds in several milliseconds [2, 33]. Chaotic motions of the drop at electrode tip in MAG welding are in the kilohertz frequency range. Therefore, modern power sources are not capable of reacting to many fast processes in the arc.

Development of transistor power sources began in 1950s with appearance of crystals. During the Soviet period many developments were performed, which were ahead of their time. They are now being put into production by leading companies under various trademarks. As the component base is developed, power source capabilities will be enhanced. Promising directions for improvement are increase of reliability of transistor parallel connection, widening the range of transistor soft switching, reliable protection from all, even rare emergency situations. Dimensions of the drop and pool, their temperature and composition of arc gaseous evolutions with be used for feedbacks. Control algorithms will be introduced for operation in microsecond range. Wire feed rate will be regulated depending on welder's hand motions.

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