IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 27 November 2023, accepted 9 December 2023, date of publication 13 December 2023,
date of current version 19 December 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3342646

TOPICAL REVIEW

Review on the Research Progress of Arc Plasma Power Sources in China

YONG JIN[1], YUE LI[1], CHUAN JIANG[1,2], AND HAILONG YU[1]
[1]School of Petroleum and Natural Gas Engineering, School of Energy, Changzhou University, Changzhou 213164, China
[2]Jiangsu Provincial Key Laboratory of Solar Energy Science and Technology, Southeast University, Nanjing 210096, China

Corresponding author: Yue Li (s21040858002@smail.cczu.edu.cn)

This work was supported in part by the Youth Talent Cultivation Plan of Changzhou University under Grant ZMF22020066; and in part by the Postgraduate Research and Practice Innovation Program of Jiangsu Province under Grant SJCX22_1432, Grant SJCX22_1437, and Grant SJCX22_1438.

ABSTRACT Arc plasma, characterized by its high current density, high energy concentration, and elevated gas enthalpy, is widely utilized in fields such as metallurgy, chemical industry, energy and environmental protection, as well as aerospace. Plasma treatment of solid waste is one of the advanced environmental protection technologies at the international forefront. The rapid development of plasma technology has led to continuous updates and upgrades of arc plasma power sources. This paper provides a comprehensive review of the research progress in arc plasma technology in China, with a particular focus on two key aspects: structure and control methods. The objective is to provide a novel perspective and insights for the international academic community, thereby driving further development in the field of arc plasma power sources. Furthermore, it discusses and analyzes the future development of arc plasma power sources with a focus on achieving higher system reliability, increased power output, environmentally friendly solutions, and intelligent operation.

INDEX TERMS Arc plasma power source, control strategy, gas plasma discharge, digital control.

I. INTRODUCTION

Plasma is the fourth state of matter, in addition to solid, liquid, and gas. It is a gaseous mixture composed of positively and negatively charged ions formed by the ionization of atoms and atomic clusters when some of the electrons are stripped away [1]. There are various classification methods for plasma, and based on their thermal equilibrium state, they can be broadly categorized into two main types: high-temperature plasma and low-temperature plasma [2]. In low-temperature plasma, which is formed in dense gases (at atmospheric or high pressure), when both the electron excitation temperature and particle temperature are high and approximately equal, it is referred to as thermal plasma [2], [3]. Arc plasma is a typical example of thermal plasma, and due to its high temperature, concentrated energy, and high current density characteristics, it has been widely used in various fields including solid waste treatment (municipal solid waste, medical and electronic hazardous waste, sewage sludge, and other industrial hazardous waste), mechanical processing (welding, cutting, spraying, etc.), metallurgy (metal melting, insulation, etc.), energy and chemical industries (ignition and combustion assistance in coal-fired power plant boilers, etc.), aerospace, materials preparation, and even as a light source.

The arc plasma power source system primarily consists of a power supply system, a control system, discharge electrodes, and the load (plasma arc). The role of the power supply is to acquire electrical energy from the grid and perform secondary transformations to convert it into the required form of electrical energy for the arc plasma system [4]. The process of electrical energy transfer in arc plasma is roughly illustrated in Fig. 1.

The power supply system, as an important component in the energy transfer process, deserves the attention of researchers. The development of AC power sources has gone through the transition from single-phase AC to multi-phase AC, characterized by its simple structure, low cost, and ease of maintenance. The development of DC power sources has

The associate editor coordinating the review of this manuscript and approving it for publication was Ton Duc Do.

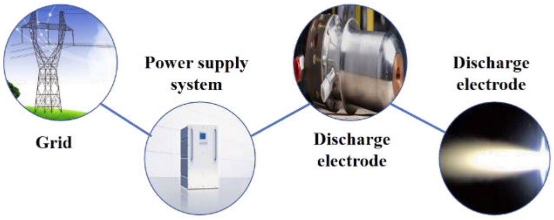

FIGURE 1. Energy transfer process of arc plasma electrical device.

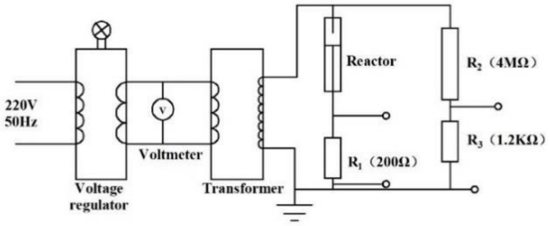

FIGURE 2. Schematic diagram of atmospheric pressure anomalous glow discharge experimental power supply.

advanced from silicon rectifier power supplies with saturable reactors for voltage regulation to thyristor-controlled rectifier power supplies, and finally to switch-mode power supplies [5]. The control of power sources has also gradually shifted from analog control to digital control technology, and control strategies are increasingly moving towards intelligent development.

In recent years, China has made significant advancements and innovations in the field of arc plasma power source technology. However, due to factors such as language barriers and cultural differences, some of China's research achievements have not been fully recognized by the international academic community. This article elucidates the development status of China's arc plasma power source technology, focusing on two key aspects: the structure and control methods of arc plasma power sources. Simultaneously, it discusses and analyzes the future development of arc plasma power sources, with a particular emphasis on achieving higher system reliability, increased power output, environmentally friendly solutions, and intelligent operation. This article aims to promote international cooperation and knowledge sharing, especially in the field of solid waste treatment, contributing to the advancement of environmental technology development on a global scale and addressing global challenges collectively.

II. CURRENT DEVELOPMENT STATUS OF ARC PLASMA POWER SOURCE STRUCTURES

In recent years, due to the rapid development of plasma technology, the power sources responsible for generating arc plasma have been continuously updated and upgraded. The arc plasma power source directly provides electrical energy to the electrodes at both ends of the discharge gas, playing a crucial role in gas discharge. So far, the development of arc plasma power source structures both domestically and internationally has gone through several stages, including generators, AC transformers, rectifiers, inverter-based discharge power sources, arc welding machine power sources, and the current stage of switch-mode power supplies. According to the type of output current, the structural design of power sources that generate arc plasma can be broadly categorized into two main types: AC power sources and DC power sources.

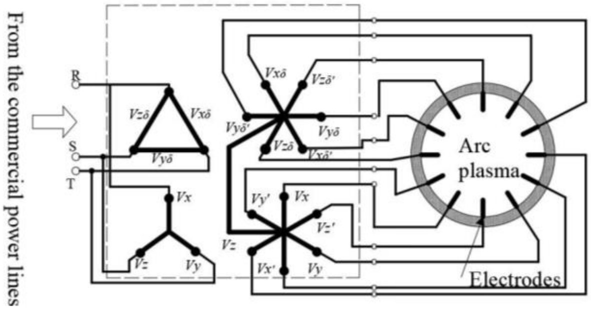

FIGURE 3. Circuit diagram of 12-phase plasma generator.

FIGURE 4. Arcing diagram of 12-phase AC generator.

A. RESEARCH PROGRESS IN AC ARC PLASMA POWER SOURCES

In 2008, Professor Yongxiang Yin from the Institute of Nuclear Physics and Chemistry at the Southwest Institute of Nuclear Industry [6] used the power source as shown in Fig. 2 in their research on atmospheric pressure abnormal glow discharge. Its structure consists of a regulator, a transformer, and high-voltage electrodes for the plasma reactor. A single-phase AC power supply with 220 V and 50 Hz is regulated by the voltage regulator and then boosted by a 1:500 step-up transformer before being inputted into the high-voltage electrode of the plasma reactor to complete the discharge. However, this type of power source generates a low discharge current, only from 10 mA to 110 mA, making it suitable for glow discharge rather than arc discharge. Glow discharge produces minimal heat and has a low current density, limiting its applicability to short-term research experiments.

It’s worth noting that single-phase AC power sources may exhibit unstable discharges with short arcs. During the discharge process, intermittent discharge characteristics may occur. This means that when supplied with sinusoidal AC power, the discharge current may extinguish or arc-breaking can occur during zero crossings. Researchers like Wantanabe from Kyushu University in Japan [7] utilized 12 single-phase AC arc welding power sources to generate multiphase AC plasma jets based on single-phase AC discharge [8], [9], [10]. This system includes 12 electrodes, an arc discharge chamber, and AC power sources. The 12 electrodes are evenly spaced at 30-degree intervals and are arranged in two layers, with six electrodes in each layer, one above the other. The 12-phase AC arc power source employs two transformers, one using an extended delta or angular winding on the primary side and the other using a star winding on the primary side. This configuration introduces a phase shift of 30 degrees on the primary side of each transformer, resulting in a 12-phase setup. The discharge coils are also connected with a phase difference of 30 degrees, as shown in Fig. 3. The 12-phase AC arc discharge generates a 12-phase AC arc jet, as shown in Fig. 4.

Compared to single-phase AC arc discharge, the 12-phase AC arc generator exhibits minimal voltage fluctuations [11], which facilitates the generation of a sustained and stable arc plasma jet. However, the length of the plasma jet is insufficient for the treatment of highly contaminated pollutants. In 2016, researchers like Yunbo Su and Zhixing Sun from the North China University of Science and Technology [12] introduced a six-phase AC arc discharge power source that builds upon both single-phase and 12-phase AC discharges. The six-phase AC arc discharge power source is designed with the same structure and principles as the 12-phase plasma generator. The main power supply system of this device consists of six single-phase AC arc welding power sources, an isolation transformer (iron core AC arc welding transformer), and a plasma generator. This setup is capable of generating an extended plasma jet by utilizing features such as water-cooled confinement tubes. Furthermore, it achieves a high energy utilization rate and is widely employed in various industries for the treatment of high-risk solid waste materials. The configuration of the power supply system is illustrated in Fig. 5. To achieve this, the device employs a six-phase isolation transformer to convert three-phase AC power into six-phase AC power, introducing phase differences between them. The phase difference between any two phases is 60 degrees.

While single-phase AC arc welding power sources have the advantages of simplicity in construction, ease of operation, and maintenance, they often suffer from unstable discharge processes. In single-phase AC arc welding, the current periodically fluctuates and often crosses through the zero point. When the current crosses the zero point, due to the phase difference between current and voltage as well as the influence of resistive loads, the voltage may sharply spike to a peak, potentially causing the arc to extinguish at that moment. In contrast, multiphase AC arc welding power sources, such as six-phase or 12-phase systems, demonstrate minimal voltage fluctuations during the discharge process. This characteristic enables the generation of sustained and stable arc plasma jets. Additionally, these multiphase systems are capable of producing larger and hotter plasma jets. However, it’s worth noting that they may not be able to make the thyristors operate optimally at a control angle of zero degrees, which can lead to certain harmonic issues and challenges like reduced efficiency, increased size, a notable impact on the electrical grid, and less favorable dynamic characteristics.

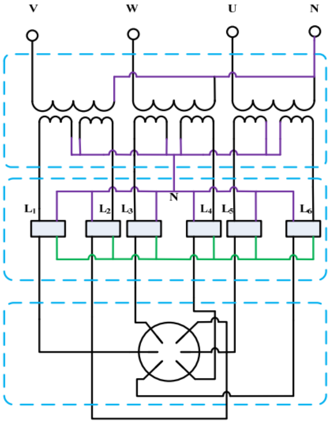

FIGURE 5. Circuit connection diagram of 6-phase AC arc discharge power system.

B. RESEARCH PROGRESS IN DC ARC PLASMA POWER SOURCES

1) RECTIFIER POWER SUPPLIES WITH SATURABLE REACTOR VOLTAGE REGULATION

The rectifier power supply with saturable reactor voltage regulation typically refers to adding a saturable reactor between the transformer and the rectifier circuit of the rectifying tube. By manipulating the AC reactance of the saturable reactor, it effectively adjusts the AC input voltage supplied to the rectifier circuit, consequently leading to a modification in the DC output.

In the 1970s, the Harbin Institute of Technology produced a plasma-cutting power source suitable for use in the Harbin Oxygen Machine Factory using high-leakage-reactance transformers and rectifier power supplies [13]. This power source had a relatively simple structure, adjustable current, good performance, and easy maintenance and operation. However, due to the use of high-leakage-reactance transformers in the circuit, the overall efficiency of the power source was low, making it unsuitable for continuous long-term operation. The high-load sustainability rate typically ranged from 65% to 75%. Additionally, because of its unstable working voltage, it couldn’t be effectively integrated with

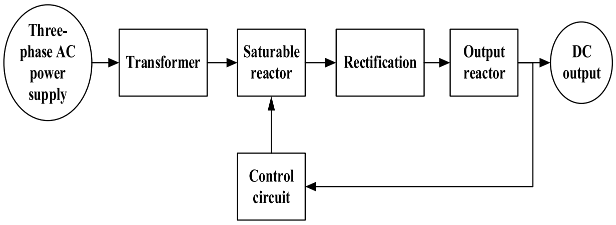

FIGURE 6. Structure diagram of saturation reactor voltage regulation rectifier power supply.

the more commonly used digital control systems in modern applications.

2) SCR RECTIFIER POWER SUPPLY

Since General Electric introduced the thyristor in the United States in 1957 [14], continuous efforts have been made to improve the current capacity of the rectified output. In 1996, Huang Jia and colleagues introduced a three-phase bridge-series same-direction reverse-parallel rectifier circuit [15], which allowed for a single-cabinet output current capacity of up to 30kA. However, this approach resulted in uneven current distribution. Therefore, in order to improve this situation, Xueru Wang and others proposed a solution in 2004 by using the same drive circuit to control the thyristors, effectively reducing the output impedance of the drive circuit [16]. In 2007, Jiaxin Zhu and collaborators suggested improving the current balance within the rectifier circuit by incorporating balancing reactors [17]. In the same year, Mahajan Vasundhara proposed a method for controlling line impedance by introducing thyristor-controlled capacitors in series with the transmission lines [18]. In 2017, an approach was put forward to utilize open-loop voltage control in voltage control mode to compensate for control errors, thereby enabling voltage regulation under all load conditions [19]. These measures have produced favorable outcomes in the advancement and utilization of thyristor rectifier power supplies, contributing to an expansion in the rectifier cabinet's output current capacity and further reductions in losses.

Thyristor rectifier power supplies are primarily composed of structures such as rectification transformers, current transformers, thyristor rectifier circuits, output reactors, etc., as shown in Fig. 7. This type of power supply utilizes the principle of a constant-voltage transformer with compensation. Based on the magnitude of the DC output, it modulates the firing angle of the thyristors to achieve a consistent current operation of the power supply system. This adjustment significantly enhances the overall efficiency of gas discharge power supplies, rendering them suitable for continuous and prolonged operation. As a result, they have consistently been the preferred choice for high-power supply devices both domestically and internationally. However, these types of power supplies typically require the use of line-frequency transformers for voltage transformation and isolation in the later stage rectification process. As a result, these power supplies tend to have large physical dimensions, high weight, and high manufacturing costs. Additionally, they often exhibit a low power factor and can introduce significant harmonic pollution to the electrical grid.

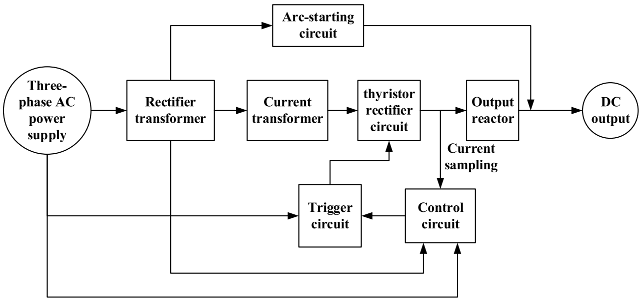

FIGURE 7. Structure diagram of thyristors rectifier power supply.

3) ARC WELDING MACHINE POWER SUPPLY

An arc welding machine power supply plays a crucial role in welding by facilitating the stable ignition and sustenance of an electric arc between electrodes, which is fundamental to welding processes. The evolution of arc welding power supplies has advanced through different stages, encompassing arc welding generators, AC arc welding transformers, arc welding rectifiers, and inverter arc welding power sources [20], contributing to the development of welding technology. Common inverter arc welding power sources can also be categorized based on the type of output current they provide. These categories include DC arc welding power supplies, pulse arc welding power supplies (low frequency, medium frequency, high frequency), and inverter AC square wave arc welding power sources [21]. The operating principle of an arc welding machine power supply involves the conversion of 50Hz AC electricity into stable DC electricity through a rectification module (UR_1) and a low-pass filtering circuit comprising components like L1 and C1. The resulting DC electricity then passes through an inverter circuit (U1) to become the DC power needed for welding between the welding electrodes. The basic schematic diagram is shown in Fig. 8.

The United States first introduced a 300A thyristor inverter arc welding machine in 1978 and then developed a transistor-type inverter arc welding machine based on it in 1981. Subsequently, companies like ESAM and ELTRON in Sweden, as well as Powcon, Miller, and Lincoln in the United States, all developed inverter arc welding power supply products [22]. In 1993, Finland's Kemppi company took the lead in digitally designing its products, creating a significant impact in the industry at that time [23]. In 1998, the Austrian company Fronius gained a significant position in the market with its use of microprocessor control, inverter technology, and the subsequent TPS series of fully digital inverter arc welding power supplies [24]. The Japanese company OTC achieved good experimental results by using IGBTs as the power control devices for their newly developed GMAW (Gas

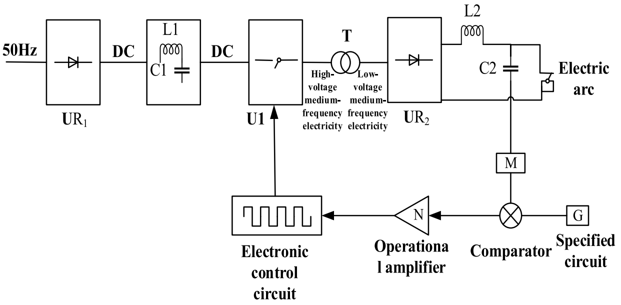

FIGURE 8. Structure diagram of inverter arc welding machine power supply.

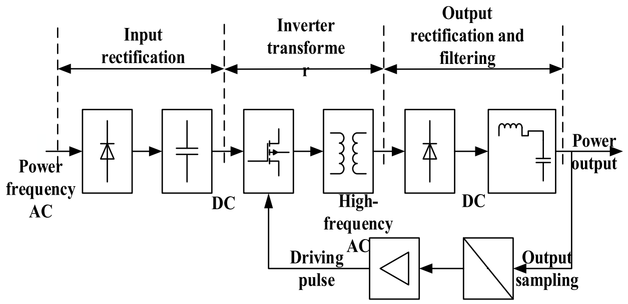

FIGURE 9. Structure diagram of switching power supply.

Metal Arc Welding) pulse welding power source. They also utilized a microcomputer for welding program control and parameter preprocessing, which allowed for constant current characteristics with out-of-droop control and control of the open-circuit voltage waveform, resulting in a more stable arc [25].

In China, several universities and institutions, such as Hebei University of Technology, South China University of Technology, Tianjin University, Shandong University, and many others, have conducted research on digital inverter arc welding power supplies. At Tianjin University, Guixi Jia and colleagues designed a fuzzy controller capable of controlling the constant current characteristic of the power supply. They also developed a prototype of a fuzzy control inverter arc welding power source, which performed well in external characteristic tests [26]. At Shandong University, Bin Duan and others proposed a fully digital intelligent pulse arc welding power source. They employed a main control system software design method based on VHDL for welding process timing and welding arc stability control. The welding quality was found to be satisfactory [27]. At the South China University of Technology, Xiaoming Lu and his team designed a complete software and hardware system using DSP and developed a digital MIG welding power source. They successfully conducted welding experiments, achieving excellent results [28]. At Hebei University of Technology, Lijun Yang and his team addressed the stability of the arc, which plays a crucial role in welding productivity and quality. They combined a strong nonlinear control loop with a weak PID loop to process feedback signals. The primary circuit employed a hybrid modulation technique involving PWM and PFM, with PFM frequency modulation specifically used during the arc ignition phase. This approach led to enhanced arc stability [29]. Xianzheng Li and his team were the first to apply current-mode PWM controllers and current-mode control techniques, using the UC2846 in full-bridge and half-bridge inverter arc welding power supplies with current ratings below 400A [30]. Xian Gao and his team employed the AT89C52 microcontroller as the core of the control system to govern their self-designed half-bridge IGBT inverter welding machine. This approach met energy efficiency and automation requirements effectively [31]. These research efforts have significantly contributed to the development of digital inverter arc welding power supplies in China, advancing welding technology and improving welding efficiency and quality.

4) SWITCHING POWER SUPPLY

In recent years, significant progress has been made in the development of new materials and advanced power electronic devices. Emerging power electronic devices such as Fast Switching Thyristors (FSCR), Gate Turn-off Thyristors (GTR), Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFET), and Insulated Gate Bipolar Transistors (IGBT) have gained prominence. These power electronic devices, characterized by their high output power and wide operating frequency range, have propelled switching power supplies to the forefront and represent a prevailing trend in the development of arc and plasma power sources. The basic principle block diagram is illustrated in Fig. 9.

In 1955, the invention of the self-oscillating push-pull transistor DC converter with a single transformer by American engineer Royer marked the beginning of high-frequency switching control circuits. Subsequently, international research on switch-mode power supplies ventured into more profound levels, yielding notable advancements across various technologies. This progress has spanned from the 1950s with the emergence of Silicon-Controlled Rectifiers (SCRs) to the development and application of technologies like Insulated Gate Bipolar Transistors (IGBTs), Power MOSFETs, and Integrated Gate-Commutated Thyristors (IGCTs). The evolution has also encompassed the shift from switching frequencies in the kilohertz range to today's megahertz frequencies. Furthermore, it has progressed from the early hard-switching DC/DC power conversion techniques, which emerged and were applied in the 1960s, to the adoption of soft-switching techniques in the 1980s, including quasi-resonant and multi-resonant converters. This journey culminated in the introduction of zero-voltage switching PWM converters in the early 1990s. The development of switch-mode power supplies has indeed advanced at an extraordinary pace.

At the end of the 20th century, various active filtering and compensation solutions emerged, along with multiple methods for correcting power factors. These significant

TABLE 1. The main parameters of the power control chip.

Chip Model	TPS62095	TPS62067	Reference [45]	Reference [46]	TPS62135	Reference [48]
Control Mode	PWM/PFM	PWM/PFM	PWM/ABM	PWM/PFM/MSPWM	PWM/PFM	PWM/PFM
Input Voltage / （V）	2.5-5.5	2.9-6	2.5-5.5	2-3	3-17	3.6-5.4
Output Voltage / （V）	0.8-Vin	0.8-Vin	/	1.2	0.8-12	3.3
Maximum Output Current / （A）	4	2	5	0.2	4	0.1
Static Current / （μA）	20	18	/	/	18	/
Peak Efficiency	97%	98%	91%	91%	98%	95.7%
Operating Frequency / （MHz）	1.4	3	3	7.4	2.5	1

advancements laid the cornerstone for the eco-friendly transformation of switch-mode power supplies, systematically tackling issues including low power factor in grid-measured current, irregular power factor patterns, and the prevalence of substantial harmonic components. Hence, the introduction of Power Factor Correction (PFC) technology into switch-mode power supplies became another hot topic in the field of power electronics [32]. In the 21st century, with the rapid development of electromagnetic compatibility (EMC) technology and the continuous improvement of power supply integration, increasing attention has been directed toward modulation methods for switch-mode power supplies. In 2011, Xiaoguang Li and colleagues introduced a cost-effective and space-saving software implementation method based on the DSP chip TMS320F2812 for PWM modulation. This approach not only demonstrated excellent noise immunity but also proved to be efficient [33]. In 2020, Xinyan Zhao and others introduced a PFM-type primary-side feedback switch power control chip for flyback-type switch-mode power supplies. This chip adjusted the duty cycle by fixing the pulse width and changing the switching frequency. While it exhibited low static power consumption, it had certain limitations, such as stability issues and the absence of current limiting functionality [34].

Currently, switch-mode power supplies have been extensively utilized, especially in terminal devices and communication equipment, within the domain of power electronics components. These power supplies are undergoing a gradual evolution, with a focus on achieving higher efficiency, superior performance, and increased reliability. To further enhance these attributes and simultaneously reduce size and cost, countries worldwide are continuously innovating in various areas such as soft-switching techniques, synchronous rectification technology, and digital control, among others. By incorporating these technologies, there exists the potential not only to enhance the performance of switch-mode power supplies but also to enable remote control and fault diagnosis capabilities for these power supplies. This ongoing innovation and advancement in switch-mode power supplies contribute to their versatility and efficiency across a wide range of applications.

III. CURRENT STATUS OF DEVELOPMENT IN ARC AND PLASMA POWER SOURCE CONTROL

A. RESEARCH PROGRESS IN CONTROL METHODS

1) ANALOG CONTROL METHODS

Voltage-mode PWM was one of the earliest analog control methods. It is characterized by its simplicity in structure and strong resistance to interference. Nevertheless, its response speed is relatively slow, and it can solely detect and offer feedback on external disruptions when alterations occur in the output voltage [35], [36]. Building upon this foundation, Redl, R., and others introduced voltage-mode PFM control. By adjusting the conduction or switching times of the switching transistor, they controlled the signal frequency, thus achieving voltage regulation [37]. The PFM control mode minimizes switching losses at low loads, resulting in enhanced conversion efficiency and quicker response times. However, it operates at an unstable frequency, which can pose challenges for subsequent filter circuit design, resulting in poor output voltage waveform quality [38]. In 1978, Deisch, C.W., and others proposed a current-mode control system by incorporating inductor current into the control loop, which improved the system's transient response speed [39]. However, it requires complex current sensing circuits and harmonic compensation circuits, leading to high design costs and lower efficiency. In 2008, Wan, R.L., and others designed a dual-mode control buck converter [40]. It operates in PWM control mode during heavy loads and switches to PFM control mode under light loads, significantly improving the conversion efficiency.

In recent years, analog control methods for arc and plasma power sources have been gradually evolving towards multi-mode control [41], [42]. In 2014, Texas Instruments (TI) introduced the TPS62095 high-efficiency buck converter, which utilizes a dual-mode control with both PWM and PFM modes. Under heavy loads, it operates in PWM control mode at a switching frequency of 1.4MHz, offering relatively good overall performance and finding wide applications. However, it has relatively low chip integration [43]. In 2017, TI made improvements and introduced the TPS62067 buck converter based on the previous model. It also utilizes dual-mode control with PWM and PFM. Under

TABLE 2. Comparison of the advantages and disadvantages of common digital control implementation methods.

Implementation method	Advantages	Disadvantages
Microcontroller	Compact in size, easy to program, reliable performance, versatile applicability, and straightforward implementation.	Low clock frequency, requires separate ADC and DAC modules to be configured.
DSP	Good performance, prominent data calculation and processing capabilities, and comes with built-in ADC and DAC modules.	The chip has a complex structure, programming is challenging, the development cycle is long, and the cost is relatively high.
FPGA	It can perform on-the-fly programming for chips in operation, achieve high-frequency sampling, and offer advantages such as high speed, low power consumption, and high reliability	The chip is expensive and requires a separate configuration of the ADC module.

heavy loads, it operates in PWM control mode at a higher switching frequency of 3MHz, achieving a maximum efficiency of 98% [44]. The increase in switching frequency also results in improved loop response speed. In 2019, Yuan and Liu proposed an advanced burst mode (ABM) combined with PWM control for a buck converter based on counter-switching. Under heavy loads, it regulates the duty cycle in PWM mode at 3MHz. When the load is light, it switches to ABM mode. Additionally, they introduced an adaptive power switch circuit to significantly reduce both conduction and switching losses of the switching transistor [45]. In 2020, Hong and Lee proposed a buck converter with three operating modes: PWM, PFM, and Multi-Sawtooth PWM (MSPWM). Under a load current of 100mA, it operates in PWM mode at 7.4MHz. As the load current decreases, the converter switches to PFM mode, and when it enters super-light load conditions, it uses MSPWM mode. Compared to other similar chip converters, it provides higher-quality power output and can be used as a buck converter for specific applications [46]. In 2021, TI introduced the TPS62135 buck converter with PWM/ PFM dual-mode control. In PFM mode, the conduction time can adapt to changes in input and output voltage, making it highly adaptable to external voltage fluctuations. As a result, it can be applied in a variety of working environments [47]. In the same year, Kim and Kim proposed a buck converter with PWM/ PFM dual-mode control. Its adaptive PFM mode continuously adjusts based on the peak inductance and output voltage ripple, resulting in high conversion efficiency under light loads. However, it has a limited supported load range and may not be suitable for a wide range of applications [48]. The main performance specifications of the power control chips mentioned above are summarized in Tab. 1.

2) DIGITAL CONTROL METHODS

Control chips composed of analog components have complex peripheral structures, require more components, have larger volumes, and are more affected by temperature. With the rapid development of Very Large Scale Integration (VLSI) and chip manufacturing processes, digital control technology has also seen significant improvements. Utilizing high-performance digital control chips can enhance the overall performance of power supplies and increase reliability. The common digital control methods include three types of digital devices: microcontrollers, Digital Signal Processor (DSP) microprocessors, and Field-Programmable Gate Array (FPGA) integrated circuit chips. Their advantages and disadvantages are as shown in Tab. 2.

China's research in the field of digital power supplies started relatively late and is still in the exploratory stage. Therefore, there are not many research achievements in the field of digital power supplies, and much of the reference material comes from high-level universities.

In 2007, Shiming Zhang from Nanjing University of Aeronautics and Astronautics designed a bidirectional DC/DC converter using DSP control [49]. The digital circuit system employed a dual-loop control strategy, achieving bidirectional power flow control. Hardware design and experimental analysis were conducted, resulting in high conversion efficiency. In 2009, Hao Zhang from Huazhong University of Science and Technology designed a digital converter based on hybrid DPWM control, with FPGA as the main controller [50]. They verified the stability of the power system by establishing a simulation model, achieving an output voltage ripple of 2.6% and a system response time of approximately 100 ms for load transients. In 2012, Bin Wang from Anhui University of Science and Technology proposed the design of a direct digital frequency synthesizer (DDS) based on FPGA [51]. The article primarily focused on addressing the limitations posed by ROM bottlenecks and proceeded with module design and synthesis using Verilog HDL, followed by simulation verification. This demonstrated that the FPGA-based DDS has advantages such as low power consumption, high resolution, and fast conversion times. In 2014, Xuefei Gao from Southwest Jiaotong University employed DSP and FPGA as the core components for digital regulation. This approach resulted in fast sampling and computation speeds, enhanced system stability, real-time responsiveness, and achieved the objective of adjusting voltage and current [52]. In 2020, Yanwei Qi from Xi'an Shiyou University applied DSP chip TMS320F28335 for digital control of the converter. They developed software programs by selecting suitable sampling frequencies and methods, wrote programs for the ADC, PWM, and SCI modules, and

TABLE 3. **Comparison of characteristics of main control methods.**

Control Mode	Control principle	Transfer functions	Theoretical control effects
PI Control	According to the deviation between the given value and the actual output value, the proportion and the integral of the deviation are combined linearly to form a controlled quantity to control the object under control.	$G_{cv} = K_p + \frac{K_i}{s}$	Differential adjustment
PID Control	The addition of an extra differential link (D) to PI control enables better elimination of static errors, accelerates the control regulation process, reduces overshoot, and overcomes oscillations.	$G_{cv} = \mathrm{K}_p + \frac{K_i}{s}$ $G_{fb} = \frac{1}{K_{fb}}$	Differential adjustment
PR Control	Proportional resonance controller, consisting of a proportional link and a resonance link, for static-free control of sinusoidal quantities.	$G_{cv} = K_p + \frac{2K_r s}{s^2 + \omega^2}$	Non-differential adjustment
QPR Control	Quasi-proportional resonance controller, based on PR control, relieves the gain at the resonance point.	$G_{cv} = K_p + \frac{2K_r \omega_c s}{s^2 + 2\omega_c s + \omega^2}$	Non-differential adjustment

discretized control loop parameters for digital control of the circuit [53].

In order to enhance the network capabilities of the system and meet the requirements for remote control of the power supply system, Changqi Chen and others [54] employed power measurement and control PLC, Siemens 5611-Profibus communication card, and touchscreen TP177B to construct the control system. This setup achieved real-time control of the plasma electrode power supply. Simultaneously, utilizing PLC as the control core facilitated functions such as system status inspection, monitoring, and early warning.

In order to ensure the various parameters of the plasma, Jiao Shi and others [55] developed a microwave power control system based on fiber optic communication technology. The control system in the document is centered around the C8051F500. Research and development were conducted on the digitized and optically signaled measurement and control circuits, utilizing optical fiber as the information transmission medium to achieve the design of the microwave power control system. This not only ensures the reliability of the microwave power control system but also guarantees that the power output can meet the specified parameters of the plasma.

In addressing complex electromagnetic environments, Jiaqiang Li and others [56] introduced a pulse power control system with the Intel Cyclone IV series FPGA as its core. This control system effectively copes with the strong magnetic field conditions encountered in plasma confinement experiments. Additionally, a Labview monitoring system has been developed on this foundation, with a debugging mode that caters to the specific testing requirements of experimenters. In the design process, logical interlocking functionality between multiple buttons is implemented through interlock commands.

Foreign manufacturers, who initiated their ventures early and possess robust expertise in the digital power sector, have introduced a diverse range of multi-class and multi-functional digital power controllers, asserting their dominance in both domestic and global digital power markets. China started relatively late in the field of digital power and lacks research and development experience. Therefore, most of the digital power supplies commonly used domestically are imported integrated chips from abroad or controlled using microcontrollers and similar control chips [57]. Among the various digital control methods, FPGA chips have become a research hotspot in the field of digital power due to their unique advantages.

B. CONTROL STRATEGY DEVELOPMENT CURRENT STATUS

The mainstream control strategies for arc plasma power sources include proportional-integral (PI) control, proportional-integral-derivative (PID) control, proportional-resonant (PR) control, and quasi-proportional-resonant (QPR) control [58]. Tab. 3 provides a comparison of these four control strategies.

PID control is currently a popular control strategy in the field due to its simplicity, reliability, efficiency, and robustness. Integer-order PID controllers have a straightforward structure, making them easy to implement, and they have found wide applications in inverter control for arc plasma power sources. Bo Hou and his team [59] proposed an adaptive PID control method for voltage-type inverters. This method adds three additional control terms to enhance the system's robustness compared to traditional PID control. However, it increases the complexity of system design and has limited adjustability for system gain. Siddique and his team [60] introduced an adaptive PID control approach incorporating a robust model reference for voltage-type inverters. This innovative method is designed to ensure safe operation across various load conditions, thereby bolstering system stability. While it represents an improvement over conventional integer-order PID control methods and delivers some enhancements to system performance, it's worth noting that due to constraints related to parameter selection, the stability range of the PID controller remains somewhat limited, ultimately affecting the overall performance of the control system. Professor Podlubny was among the earliest proponents of fractional-order PID control, with its general format denoted as $\mathrm{PI}^{\lambda}\mathrm{D}^{\mu}$. This approach introduces fractional-order integration and differentiation, adding two additional tuning parameters to the controller. Consequently, the overall parameter range for control extends from a point-like grid to a more flexible surface, leading to improved control performance [61]. Chaobo Chen and his team [62] introduced an intelligent optimization algorithm based on artificial bee colony in the design of the fractional-order $\mathrm{PI}^{\lambda}\mathrm{D}^{\mu}$ controller. This approach simplifies the controller's structure and significantly enhances the system's control performance. Zeyue Pan and his team [63] conducted an extended study on the PID control algorithm for high-voltage pulse bias power supplies. Building upon the proportional, integral, and derivative control components of the PID control algorithm, the research explores a generalized predictive control structure and deduces the generalized predictive PID control algorithm. This control algorithm incorporates additional predictive time-domain parameters and control time-domain parameters alongside the P, I, and D control parameters of the PID control algorithm. Through FPGA programming, the literature has adjusted and validated the algorithm, resulting in improved system stability and dynamic response characteristics.

Rao et al. [64] compared the transient response control effects of PID controllers, traditional compensators, and SMC controllers for load variations in switch-mode power regulators. Among them, the SMC controller demonstrated optimal performance in terms of undershooting and response time. For the SMC control algorithm, Samantaray [65] and Huerta-Moro [66] implemented the SMC algorithm for controlling Si-type switching devices in low-power DC/DC circuits. The output of the experimental circuit falls into the low-frequency low-power range. It is challenging to ensure a high degree of compatibility between SMC and the peripheral power supply circuit in mid-frequency circuits. Additionally, maintaining a sustained output of clean DC power is difficult to guarantee. Kumar [67] implemented the application of an SMC controller in a Si-based Buck circuit, achieving a control frequency of 200kHz. The study realized an output of 12V, 2A, without achieving high-power output. In applications requiring high power at medium frequencies, Jiao [68] proposed a design model for a Buck/Boost circuit based on GaN devices. The power supply achieved an output of over 100W within the frequency range of 100kHz to 500kHz. During the experimental process, the circuit, when controlled by the SMC algorithm, demonstrated effective performance with low noise and strong anti-interference capabilities.

In order to enhance the dynamic response performance of the system and achieve better anti-interference capabilities, Mao et al. [69], based on the plasma current control system of HL-2A (Chinese Tokamak), proposed a robust adaptive control algorithm to address the issues of large overshoot and slow response associated with PID control algorithms. The introduction of this algorithm is based on Lyapunov stability theory and robust adaptive methods [70]. In comparison to classical PID control algorithms, this approach improves the dynamic response performance of the system.

For low-temperature plasma power sources, their parameter models exhibit nonlinearity, time-varying characteristics, and uncertainties. In addressing such nonlinear and time-varying systems, Zhang et al. [71] proposed a switch power control method based on a fuzzy PID algorithm. The approach involved establishing fuzzy rules with expert experience. The fuzzy adaptive PID control algorithm demonstrated small control errors and high precision, imparting excellent stability to the switch power supply. In comparison with traditional PID control algorithms, the introduction of the fuzzy algorithm resulted in a 0.03s improvement in system dynamic response time and a 10% reduction in overshoot.

Based on the comprehensive research on the current status of arc plasma power control technology, it can be observed that the control structure in China's power control systems has become increasingly stable, with a corresponding improvement in control speed.

IV. DEVELOPMENT TRENDS IN ARC PLASMA POWER SOURCES

Arc plasma technology is widely used in various fields, including industry, daily life, and healthcare, and it has garnered increasing attention from both domestic and international communities. As the power source is a critical component for arc plasma discharge, designing a stable, efficient, cost-effective, and environmentally friendly arc plasma power source is a significant and non-trivial challenge. From the current research and application standpoint, arc plasma power sources still face challenges such as complex structure, significant temperature rise, strong electromagnetic interference, and poor system reliability. Therefore, the future of arc plasma power sources should focus on improving system reliability, increasing power capacity, achieving environmental sustainability, and embracing intelligent solutions.

A. THE DEMAND FOR SYSTEM RELIABILITY IS STEADILY INCREASING

Due to the unique negative impedance characteristics of arc loads and the harsh operating conditions of power supplies in this context, the demand for reliability is increasing. Currently, there are several main reasons for the low reliability of arc plasma power sources:

① In the inverter circuit, the heat generated by switching devices increases with higher switching frequencies, which can lead to reduced safety margins for these devices and increased design complexity.

② During the plasma discharge process, the arc load undergoes complex variations, making the design of protection and monitoring systems for power sources challenging.

③ Arc plasma power sources operate for extended periods under high voltage and high current conditions, resulting in significant electromagnetic interference.

B. THE TREND IS TOWARDS HIGHER POWER LEVELS IN THE SYSTEM

To expand the scope of plasma technology applications, the output power of arc plasma power sources is crucial. In order to improve efficiency, it is generally required that the power output of the power source should reach several hundred kilowatts to even tens of megawatts. Currently, overseas, semi-controlled rectifier discharge power sources can achieve power levels in the megawatt range, with a power efficiency of 80%. Inverter-type discharge power sources abroad can also reach power levels of up to 200 kilowatts. However, in China, although there have been research reports of hard-switching inverter discharge power sources reaching power levels of 300 kilowatts [72], the actual mature, reliable, and highly efficient power sources are only in the 100-kilowatt range [73].

C. THE SYSTEM IS TRANSITIONING TOWARDS GREENING

Currently, most arc plasma power sources operate in a hard-switching mode, causing severe distortion in voltage and current waveforms during operation, along with the presence of high-order harmonics. Furthermore, there is a significant phase difference between high-order harmonic voltage and current, resulting in a decreased power factor and substantial pollution of the power grid. With the growing concern for environmental issues, there is a demand for power sources to achieve ‘‘zero emissions’’ to become truly ‘‘green’’ sources of energy for the power grid.

D. THE SYSTEM IS MOVING TOWARDS INTELLIGENCE

In recent years, the emergence of new algorithms such as neural networks, genetic algorithms, and particle swarm optimization has led to improvements in both the precision of control and response speed in digital control systems. This has made arc plasma power sources more ‘‘intelligent,’’ not only capable of providing electrical power but also being user-friendly and easy to maintain, transforming them into truly ‘‘plug-and-play’’ power sources.

V. CONCLUSION

Arc plasma power sources are devices used to generate high-temperature plasma and find wide applications in industrial, scientific research, and medical fields. With the advancement of technology, arc plasma power sources have undergone several stages of evolution and improvement. This article primarily discussed the current state of development of arc plasma power sources from two aspects: structure and control methods.

In terms of structure, power supplies can be primarily divided into two major categories based on the type of output current: AC power supplies and DC power supplies. The development of AC power supplies has evolved from single-phase AC to multi-phase AC, resulting in increasingly stable electric arcs. The development of DC power supplies has gone through various stages, including silicon rectifier power supplies with saturation reactors for voltage regulation, thyristor-controlled rectifier power supplies, and switch-mode power supplies, gradually advancing towards high efficiency, high performance, and high reliability.

In terms of control, with the rapid advancement of ultra-large-scale integrated circuits and chip manufacturing processes, control chips have been continuously updated and upgraded. They are moving towards miniaturization, high speed, low power consumption, and high reliability. Control strategies are also constantly improving to simplify control structures and enhance control performance.

In conclusion, arc plasma power sources have evolved significantly in terms of structure and control methods. However, from the current research and application standpoint, arc and plasma power sources still face challenges such as complex structures, significant temperature rise, strong electromagnetic interference, and poor system reliability. Therefore, the future development of arc and plasma power sources needs to focus on improving system reliability, increasing power output, making them more environmentally friendly, and enhancing their intelligence.

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YONG JIN received the B.S. and Ph.D. degrees from the Nanjing University of Science and Technology, Nanjing, China, in 2008 and 2014, respectively. He is currently a Lecturer with the School of Petroleum and Natural Gas Engineering, School of Energy, Changzhou University, China. His current research interests include plasma ignition and enhanced combustion technology, and industrial automation.

YUE LI was born in Jiangsu, China, in 1999. She received the B.S. degree in electrical engineering from the North China Institute of Science and Technology, China, in 2021. She is currently pursuing the M.S. degree with the School of Petroleum and Natural Gas Engineering, School of Energy, Changzhou University. Her recent research interest includes plasma power supply.

CHUAN JIANG received the B.S. and Ph.D. degrees from Southeast University, Nanjing, China, in 2013 and 2021, respectively. He is currently a Lecturer with the School of Petroleum and Natural Gas Engineering, School of Energy, Changzhou University, China. His research interests include concentrating solar-thermal energy systems and heat pipe-based heat exchangers.

HAILONG YU was born in 1975. He received the Ph.D. degree from Zhejiang University, in 2004. He is currently a Professor with the School of Petroleum and Natural Gas Engineering, School of Energy, Changzhou University, China. He was selected as an academic and technical leader of Henan Province. His research interest includes solid waste treatment.

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