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辅助变压器式 FB-ZVZCS-PWM逆变弧焊电源

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摘 要：现有 FB-ZVZCS-PWM软开关弧焊逆变电源采用阻断电容衰减原边环流电流所需的时间与占空比有关，占空比很小(电源输出电压很低)时滞后臂难以实现零电流开关。采用原边辅助变压器衰减原边环流电流所需的时间不受占空比影响，而与原边峰值电流成正比。文中介绍了采用原边辅助变压器、有限双极性控制的新型 FB-ZVZCS-PWM软开关弧焊逆变电源实现超前臂零电压开关和滞后臂零电流开关的工作原理。计算机仿真和试验结果表明，根据最大峰值电流值设计适当的辅助变压器变比，可以在各种负载条件下实现软开关。

关键词：软开关；逆变；弧焊；电源
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0 序 言

逆变弧焊电源采用软开关技术可以减少功率开关器件的损耗和提高工作可靠性。FB-ZVS-PWM软开关技术由于兼有PWM控制和谐振开关的优点并可克服各自缺点，被应用于逆变弧焊电源。但目前逆变弧焊电源广泛使用的IGBT存在较大拖尾电流，使其在FB-ZVS-PWM变换器中仍存在较大的关断损耗和开关应力。FB-ZVZCS-PWM技术超前臂采用零电压开关，滞后臂采用零电流开关，可以克服FB-ZVS-PWM技术的上述缺点，因而更适合于大功率软开关弧焊电源。然而，现有逆变弧焊电源FB-ZVZCS-PWM技术采用阻断电容衰减原边环流电流所需的时间与占空比有关，占空比很小(电源输出电压很低)时滞后臂难以实现零电流开关。作者研制的逆变弧焊电源采用原边辅助变压器和有限双极性控制的FB-ZVZCS-PWM软开关技术，可在各种负载条件下实现超前臂零电压开关和滞后臂零电流开关。

1 现有 FB-ZVZCS-PWM变换器占空比对滞后臂软开关的影响

1.1 变换器组成

逆变弧焊电源常用的FB-ZVZCS-PWM变换器主要有如图1、2所示的两种电路结构形式，图1所示变换器采用阻断电容C_b衰减环流电流，采用饱和电感L_r阻断电流反向增加。U_{in}为输入直流电压源；Q_1~Q_4为IGBT；D_1~D_4分别为与Q_1~Q_4反向并联的二极管；C_1~C_4分别为Q_1~Q_4的输出电容和外接电容之和；L_k为变压器T_1的漏感；DR_1和DR_2为输出整流二极管；L_f为输出滤波电感；R为电弧等效电阻。

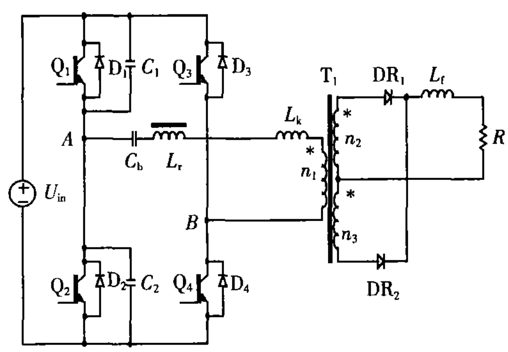

图 1 饱和电感式 FB-ZVZCS-PWM变换器主电路原理图
Fig. 1 Scheme of FB-ZVZCS-PWM converter with saturable inductor

图2所示变换器采用阻断电容C_b衰减环流电流，采用二极管阻止环流电流反向增加。图2与图1相比，去掉了饱和电感L_r，增加了阻断二极管D_5和D_6。

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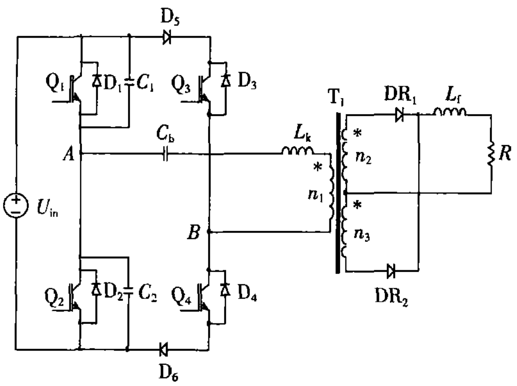

图 2 阻断二极管式 FB-ZVZCS-PWM 变换器主电路原理图

Fig. 2 Scheme of FB-ZVZCS-PWM converter with block diodes

1.2 零电流开关实现原理及条件

上述两种 FB－ZVZCS－PWM 变换器都可以采用移相控制或有限双极性控制，原边环流电流的衰减都是依靠电容 C_b 实现的。采用有限双极性控制，超前臂可并联较大电容，从而减小超前臂的关断损耗[1]。现以图 1 电路为例说明滞后臂零电流开关实现的原理及条件。

图 3 为 Q_1 ~Q_4 的控制信号（超前臂 Q_1、Q_2 采用 PWM 控制，滞后臂 Q_3、Q_4 采用固定脉宽控制）、两桥臂中点电压 u_{AB}、变压器原边电流 i_p 和阻断电

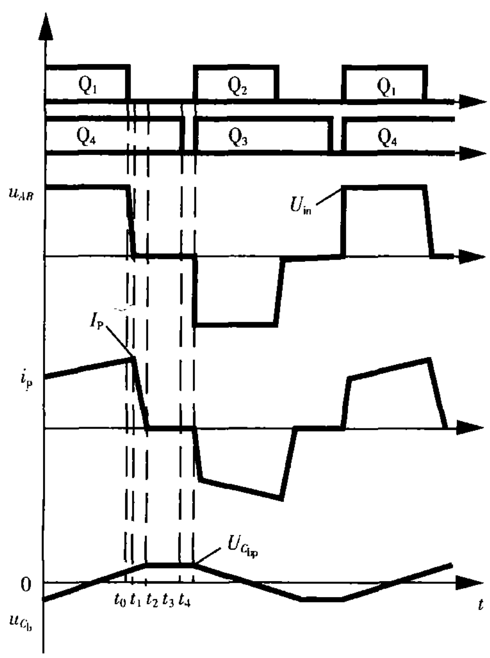

图 3 FB-ZVZCS-PWM 功率器件的控制信号及主电路主要波形示意图

Fig. 3 Control signal of FB-ZVZCS-PWM power devices and key waveforms of main circuit

容 C_b 两端电压 u_{C_b} 的波形示意图。t_0 时刻关断 Q_1，C_1、C_2 开始充放电，t_1 时刻充放电结束，该期间即为超前臂换流所需时间 t_{01}。换流结束后 D_2 导通为 Q_2 创造了零电压开通的条件，原边电流环流开始。此时阻断电容 C_b 的电压 u_{C_b} 全加在变压器的漏感上，原边电流开始衰减，t_2 时刻原边电流衰减到零，饱和电感 L_r 阻断电流反向增加，使原边电流保持为零，这样 Q_4 实现零电流关断。

设 D 为占空比，T 为周期，Q_1 和 Q_4 共同导通时原边电流为 I_p，$U_{C_{bp}}$ 为阻断电容 C_b 的峰值电压。在 Q_1 和 Q_4 共同导通时间内（即 $DT/2$），I_p 对 C_b 充电为

$$I_p = C_b\frac{du_{C_b}}{dt} = C_b\frac{U_{C_{bp}} - (-U_{C_{bp}})}{\frac{DT}{2}} = \frac{4C_bU_{C_{bp}}}{DT}。\tag{1}$$

$$U_{C_{bp}} = \frac{DTI_p}{4C_b}。\tag{2}$$

从 t_1 ~t_2，原边环流电流从 I_p 衰减到零，设 t_1 ~t_2 的时间为 ΔT，在这一时间内电容的电压 $U_{C_{bp}}$ 加在了漏感 L_k 上，即

$$U_{C_{bp}} = -L_k\frac{di_p}{dt} = -L_k\frac{0-I_p}{\Delta T} = L_k\frac{I_p}{\Delta T}。\tag{3}$$

$$\Delta T = \frac{L_kI_p}{U_{C_{bp}}}。\tag{4}$$

将式（2）代入式（4）[2] 可得

$$\Delta T = \frac{4L_kC_b}{DT}。\tag{5}$$

在焊条电弧焊、短路过渡 CO_2 焊等工艺中，逆变弧焊电源经常处于短路状态。由式（5）可知，即输出电压很低（占空比 D 很小）时，ΔT 会很大，这时滞后臂就难以实现软开关。

2 辅助变压器式 FB－ZVZCS－PWM 变换器

2.1 变换器主电路

为了实现滞后臂零电流关断，应在原边电流开始环流后，施加一个与环流电流方向相反的电压，使环流电流迅速衰减到零；然后要阻断环流电流的反向通道，使原边电流保持为零。采用如图 4 所示的原边辅助变压器[3]，可以满足上述两个条件，其中 T_a 为辅助变压器，变比为 $n(n=n_{a_1}/n_{a_2})$。

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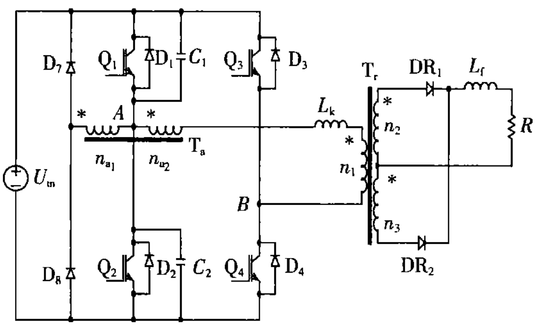

图 4　辅助变压器式 FB-ZVZCS-PWM变换器主电路原理图

Fig. 4　Scheme of FB-ZVZCS-PWM converter with auxiliary transformer

2.2　变换器的工作过程分析

变换器 Q_1 ~Q_4 的控制信号、两桥臂中点电压 u_{AB}、变压器原边电流 i_p 的波形示意图如图 3所示, 变换器工作原理分析如下。

(1) 工作状态 1($0<t<t_0$), 如图 5所示。

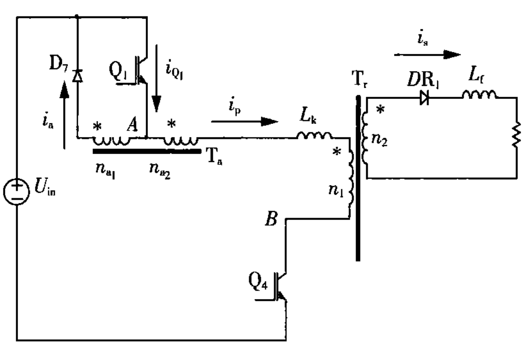

图 5　工作状态 1时变换器等效电路原理图

Fig. 5　Equal converter scheme in mode 1

Q_1和 Q_4 共同导通, 主变压器原边向副边传递能量, 流过 Q_1的电流为

$$i_{Q_1} = (1 + \frac{1}{n}) i_p。\qquad (6)$$

(2) 工作状态 2 ($t_0<t<t_1$), 如图 6所示。在 t_0时刻关断 Q_1, 原边电流从 Q_1 中转移到 C_1 和 C_2 支路中, C_1 充电, C_2 放电。 t_1时刻, C_2 电压下降到零, Q_2 反向并联二极管 D_2 自然导通, 从而结束工作状态 2。

(3) 工作状态 3 ($t_1<t<t_2$), 如图 7所示。 t_1时刻由于 D_2 导通, T_a 原边 n_{a_1}被接于 U_{in}两端, 即 T_a的原边有反向电压 U_{in}, 该电压由 T_a 反射到主变压器的原边, 直接加在变压器的漏感上, 使主变压器

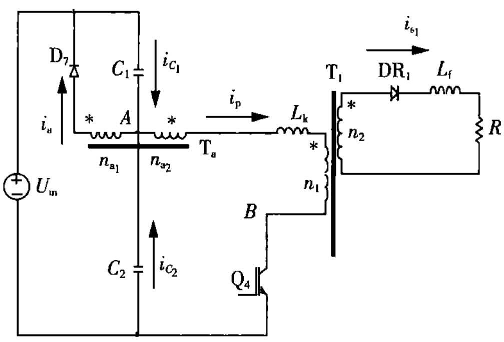

图 6　工作状态 2时变换器等效电路原理图

Fig. 6　Equal converter scheme in mode 2

原边电流很快衰减。设 I_p为 t_1时刻主变压器原边电流, 则在该工作状态中

$$i_p = I_p - \frac{U_{in}}{nL_k} (t - t_1)。\qquad (7)$$

在 t_2时刻 I_p减小到零。该状态持续时间 ΔT为

$$\Delta T = t_2 - t_1 = \frac{nI_pL_k}{U_{in}}。\qquad (8)$$

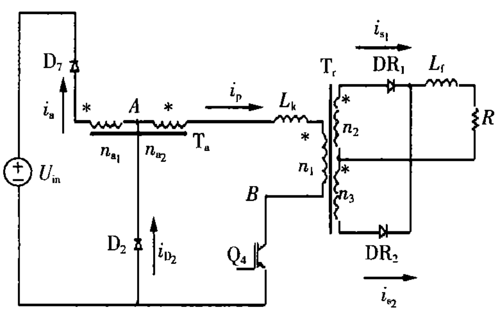

图 7　工作状态 3时变换器等效电路原理图

Fig. 7　Equal converter scheme in mode 3

(4) 工作状态 4 ($t_2<t<t_3$)。该工作状态原边电流为零, 为滞后臂零电流关断创造了条件。另半个周期滞后臂的工作过程相同。

2.3　仿真与试验结果

图 8、9为 200 A /28 V和 200 A 短路时变换器 u_{AB}与 i_p 的仿真波形, 图 10、11是对应的实测波形。分析波形可知, 原边峰值电流相同时, 原边环流电流衰减时间相同 ($\Delta T = \Delta X = 3.3\ \mu s$), 即 ΔT 不受占空比影响, 克服了输出电压低时滞后臂难以实现零电流关断的缺点, 从而使逆变弧焊电源在输出短路状态下也能实现软开关。

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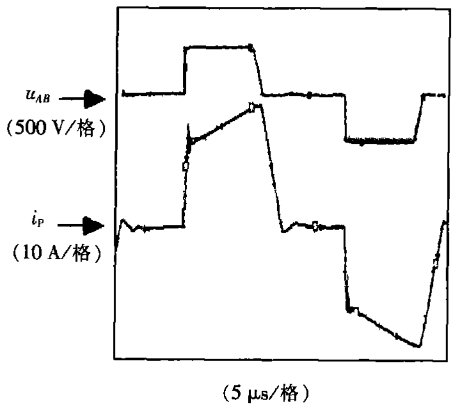

图 8 200 A /28 V输出时变换器仿真波形

Fig. 8 Converter simulation waveforms with output 200 A /28 V

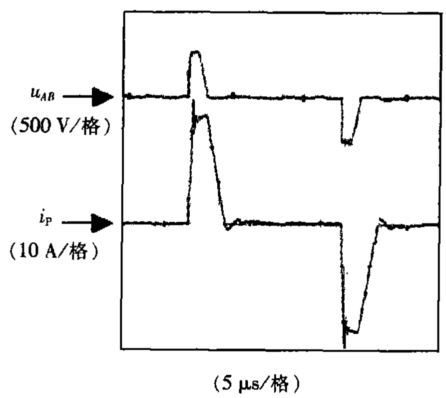

图 9 短路电流为 200 A时变换器仿真波形

Fig. 9 Converter simulation waveforms with 200 A current in short circuit

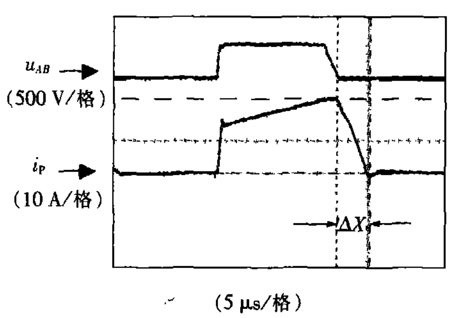

图 10 200 A /28 V输出时变换器实测波形

Fig. 10 Converter measuring waveforms with output 200 A /28 V

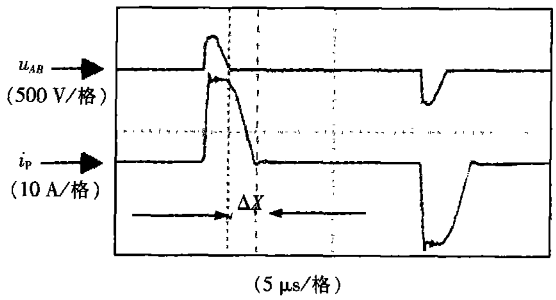

图 11 短路电流为 200 A时变换器实测波形

Fig. 11 Converter measuring waveforms with 200 A current in short circuit

4 结 论

(1) 采用电容衰减原边环流电流的 FB – ZVZCS – PWM 变换器,原边电流衰减到零所需的时间 ΔT与占空比D成反比,当占空比很小(输出电压很低)时,ΔT很大,滞后臂难以实现零电流开关。

(2) 采用原边辅助变压器衰减原边环流电流的 FB – ZVZCS – PWM 变换器,原边电流衰减到零所需的时间不受占空比影响,而与原边峰值电流成正比。根据最大峰值电流值设计适当的辅助变压器变比,可以实现所有负载范围的软开关。

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MAIN TOPICS, ABSTRACTS & KEY WORDS

Prediction of grain size in the HAZ of the ultrafine grain steel joint

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Abstract: The welding temperature field of the ultrafine grain steel was computer simulated in this paper, and the thermal cycle curve was obtained. The grain size in HAZ was predicted based on the thermal cycle curve. The outcome of the prediction was in accordance with the outcome of the experiment. The heat affected zone (HAZ) is one of the main areas which affect the properties of welds. It is essential meaningful to complete the prediction of grain size by computer using proper methods and that can provide a new and important foundation for optimizing welding parameters and improving the quality of welds. The result showed that: (1) The width of the HAZ was about 6.5 mm; (2) The grain size in HAZ increased obviously and the largest was 180 μm; (3) The higher the cooling speed was, the more refined the grain was, but the refined extent was relatively limited, not obvious.

Key words: ultrafine grain steel; thermal cycle curve; HAZ; grain size

Research on friction stir welding technology of T2-H62

LIU Xiao-wen, MU Yao-zhao, YANG Ning-ning, YAN Jun-hui (Material Institute, Northwestern Polytechnical University, Xi'án 710072, China). p5 – 8

Abstract: Friction stir welding of T2-H62 was investigated in this paper. Many experiments were carried on the welding machine modified by ourselves. The material, shape and dimension of the nib had been optimized. The significance sequence of processing parameters of friction stir welding had been calculated by signal-noise (SN) ratio experiments. The mechanical performance of T2-H62 welded joints was tested through tensile experiments, hardness tests and bending tests.

Keywords: T2-H62; friction stir welding; SN ratio experiment

Auxiliary transformer FB-ZVZCS PWM inverter arc welding power supply

FANG Chen-fu[1,2], YIN Shu-yan[1], HOU Run-shi[2], WEN Yong-ping[2], YU Ming[2], LI Jun[3] (1. College of Mechanical Engineering & Applied Electronics Technology, Beijing Polytechnic University, Beijing 100022, China; 2. School of Material Science and Engineering, Jiangsu University of Science and Technology, Jiangsu Zhenjiang 212003, China; 3. Kaierda Electric Welding Machine Co. Ltd., Hangzhou 310018, China). p9 – 12

Abstract: The decreasing time of free-wheeling current is relative to duty cycle in the exiting FB-ZVZCS-PWM soft switching inverter arc welding power supply with the block capacitor, and it is hard to achieve zero current switching (ZCS) for lagging leg with low duty cycle. By adopting auxiliary transformer in the primary side of main transformer, the decreasing time of free-wheeling current is independent of duty cycle, which is proportion to the peak current in the primary side of main transformer. A new FB-ZVZCS-PWM soft switching inverter arc welding power supply was introduced, which adopted the auxiliary transformer and limited bipolar control mode. The principles of realizing zero voltage switching (ZVS) for leading leg by capacitor and ZCS for lagging leg by auxiliary transformer were explained. Simulation and experimental results showed that the soft switching could be realized under all loads as long as the auxiliary transformer was designed by the maximum peak current in the primary side of main transformer.

Key words: soft switching; inverter; arc welding; power supply

Finite element analysis of friction stir welding process

ZHANG Hong-wu, ZHANG Zhao, CHEN Jin-tao (State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Liaoning Dalian 116024, China). p13 – 18

Abstract: Friction stir welding (FSW) is a new solid-state joining process which was invented by The Welding Institute in 1991. FSW has been found to be effective for joining hard-to-weld metals and for joining plates with different thickness or different materials. 2D numerical model was constituted in this paper and then the friction stir welding process was simulated. The parameters of FSW process, the flow of the material and the stress and strain in the FSW process were studied. Compared with the data of the experiments, numerical results were shown to demonstrate the efficiency and the validity of the model developed.

Key words: friction stir welding; residual stress; finite element simulation; welding process

Analysis of weldability of X80 pipeline steel

ZHANG Min[1], YAO Cheng-wu[1], NIE Bin-ying[2] (1. School of Material Science and Engineer

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