# A Novel Coupling Method of Power Supplies With High Power Density, Efficiency, and Fast Dynamic Response for Spacecraft Hollow Cathode Power Supply Applications

Ming Fu, *Student Member, IEEE*, Donglai Zhang, *Member, IEEE*, and Tiecai Li

***Abstract*—This paper presents a coupling method of power supplies to improve power density, efficiency, and dynamic response by taking the case of heater supply, ignitor supply, and keeper supply for hollow cathode of an all electric propulsion (AEP) Hall thruster. The working principle and timing characteristic of the coupled supply, as well as the three-loop control, current sampling and chopping switch control are also illustrated. With the proposed coupling method, the power density is improved since three supplies are coupled into one supply. Additionally, the test on the coupled supply prototype with 200 W maximum output power shows that the efficiency of the coupled supply could reach up to 89.7%, increasing by 3.9%–14.2% as being compared with that of traditional three supplies with heater current between 4 and 10 A, and the joint test of the coupled supply with an AEP hall thruster proves the achievement of fast dynamic response and the ability to extend useful life of hollow cathode. Hence, the coupling method proposed in this paper could achieve the power supply system with high power density, efficiency, and fast dynamic response.**

***Index Terms*—Coupling, hollow cathode, power density, three-loop control.**

## I. Introduction

With the limitation on bulk, cost and specific payload characteristic, high power density, high efficiency, and fast dynamic response are of the most important consideration during the design of power supplies for aerospace or specific industrial equipment [1]–[5]. For single supply, the achievement of aforementioned characteristics has been widely investigated by increasing switching frequency through employment of new switching devices (such as Silicon Carbide (SiC) and Gallium Nitride (GaN) transistors) or series-parallel connection of switching devices [2], [5]–[7], or investigated by employing novel topology of power converter [8], [9], ripple cancellation technology [10], [11], filtering inductance coupling technology [1], [12]–[14] or advanced control technique [4], [12], [15]. For multiple supplies, a common method in the industry to increase the power density is to use the multipleoutput isolated converter, for which, each output voltage is always constant, and the investigation mainly focuses on how to ensure low output voltage regulation and how to eliminate the interaction and cross-regulation between different outputs when there is change in payload power or input voltage, or there is mismatching between output payload power of each channel, etc [16]–[20]. However, the multipleoutput isolated converter is not applicable in the occasion when each output outputs changeable current/voltage for different functions and there is a certain timing between each output.

For power system of specific industrial equipment, which are often constituted of more than one supply with each supply powering the equipment in a certain sequence [2], [21]–[23], the optimal design in the aspect of power system should be considered to achieve high power density, high efficiency, and fast dynamic response. The coupling of power supplies could fit this need, and it can make one supply possess functions of one more supplies without the change of power supply functions, which is achieved through appropriate topology coupling and corresponding control design. In fact, this technique has been widely investigated to significantly improve power density, efficiency, and dynamic response of power system [14], [24], [25].

Based on the consideration that electric propulsion (EP) has increasingly become the main configuration of propulsion platform in spacecraft [26]–[28] with ion thruster and stationary plasma thruster of the most wide application [22], [23], [29], [30], as well as the importance of hollow cathode to the ionization of xenon in thruster [29], [31]–[33], a novel coupling method of power supplies was proposed by taking the case of power system for hollow cathode.

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M. Fu is with the Power Electronic and Motion Control Research Center, Harbin Institute of Technology Shenzhen Graduate School, Shenzhen 518055, China, and also with the Shenzhen Academy of Aerospace Technology, Shenzhen 518057, China (e-mail: fm701.student@sina.com).

D. Zhang is with the Power Electronic and Motion Control Research Center, Harbin Institute of Technology Shenzhen Graduate School, Shenzhen 518055, China (e-mail: zhangdl@hitsz.edu.cn).

T. Li is with the School of Electrical Engineering and Automation, Harbin Institute of Technology, Harbin 150001, China, and also with the Shenzhen Academy of Aerospace Technology, Shenzhen 518057, China (e-mail: litc611@public.hr.hl.cn).

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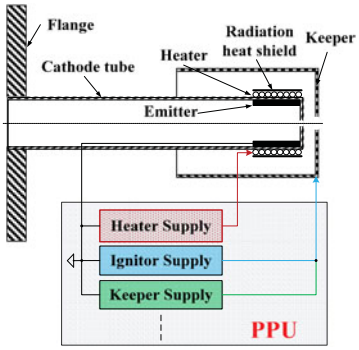


Fig. 1. Scheme of the hollow cathode and its power supplies in EP.

TABLE I
SPECIFICATIONS OF THE SUPPLY FOR HOLLOW CATHODE

| Parameter | Value | Comments |
|---|---|---|
| Input voltage $V_{\rm in}$ | $100 \pm 3$ V | Regulated power bus |
| Ignitor voltage $V_{\rm ik}$ | $300 \pm 20$ V | |
| Ignitor pulse width | 5 ms/100 ms | Settable |
| Keeper current limit $I_{\rm keeper}$ | 0.3 – 1.5 A | Step of 0.1 A, rated current of 0.5 A |
| Keeper Voltage limit $V_k$ | ≤60 V | Maximum output voltage |
| Heater current $I_h$ | 4 – 10 A | Step of 0.1 A, rated current of 8 A |
| Heater Voltage limit $V_{h\_\max}$ | ≤20 V | Maximum clamping output voltage |
| Output power $P_{\rm out}$ | ≤200 W | Total output power of three supplies |
| Efficiency $\eta$ | $>$ 80% | Rated condition |

Fig. 1 shows the hollow cathode applied in a stationary plasma thruster and its power supplies in power processing unit (PPU) of EP. Among which, hollow cathode consists of flange, cathode tube, heater, emitter, radiation heat shield, and cathode keeper; and traditionally, in most PPU, there are often three independent supplies for hollow cathode, that is, heater supply, ignitor supply, and keeper supply, with the latter two connecting to cathode keeper and all three outputting power based on the same basis ground. Since there would be a self-heating phenomenon in hollow cathode and long-delayed regulation on the heating power after successful ignition of thruster following the successful ignition of hollow cathode [34]–[36], the above traditional power supply system for hollow cathode, which are also shown in this literatures [29], [33], possesses the following disadvantages: decreased useful life of hollow cathode due to its long duration under excessive high temperature, and large bulk and weight resulted from presence of three supplies.

In this paper, the novel coupling method was proposed based on the working timing and electrical characteristic of the above power system for hollow cathode. It should be noted that this coupling method is not limited to the application in hollow cathode power supplies, that is, it can be also applicable in other power supplies with certain working timing and different settable output voltage/current, such as power supplies for arcjet propulsion system, travelling wave tube, or some plasma devices, etc [37], [38]. The following work has been illustrated for the novel coupling method: coupling design, working principle, timing characteristic, and control strategy. Besides, the coupled supply prototype with 200 W maximum output power has been designed and tested with results showing that there is increased efficiency and dynamic response of the coupled supply as being compared with the traditional three supplies, additionally, the power density is also improved since three supplies are coupled into one supply, thus resolving the aforementioned problems, in agreement with the expected coupling design purpose.

## II. COUPLING DESIGN

In this paper, the coupling is designed by taking the case of heater supply, ignitor supply, and keeper supply for the hollow cathode of an all electric propulsion (AEP) Hall thruster with specifications illustrated in Table I.

For hollow cathode, its working characteristic is shown as follows. The heating filament in heater is first heated to about 1200 °C by heater supply to make emitter generate electrons. The electrons then excite xenon to transform to plasma under the high voltage pulse provided by ignitor supply, and the successful ignition is obtained. At the moment of successful ignition, the impedance between cathode keeper and basis ground (shown below as keeper impedance) decreases sharply, leading to the quick decrease of voltage between cathode keeper and basis ground (shown below as keeper voltage). By detecting the sharp decrease of keeper voltage, ignitor supply identifies successful ignition, and then stops outputting power so as to prevent ignitor supply and cathode keeper from being damaged. At the shutdown moment of ignitor supply, keeper supply provides low-voltage constant current to maintain plasma state of xenon in hollow cathode. After successful ignition of thruster following the successful ignition of hollow cathode, there would be a self-heating phenomenon and thus increased temperature in hollow cathode. When each function part of thruster starts up and works stably, the EP control system sends commands to shut down heater supply and ignitor supply.

The coupling method of the above heater supply, ignitor supply, and keeper supply is detailed below, which is based on dual-switch forward topology.

### A. *Coupling of Ignitor Supply and Keeper Supply Into Ignitor-keeper Supply*

Based on the timing characteristic of ignitor supply and keeper supply, which is illustrated below, as well as the same input and output for these two supplies, the coupling of these two supplies into ignitor-keeper supply is considered at first. Fig. 2(a) and (b) show the topology of ignitor supply and keeper supply before coupling and after coupling, respectively.

In Fig. 2(a), for ignitor supply, the dc voltage (output voltage at point $A1$, $V_{A1}$) is constant at 300 V through closed-loop control (also called voltage PID control loop), while the high voltage pulse is generated through switch $Q3$, which works at chopping control mode with pulse width/period of 5 ms/100 ms; for keeper supply, the current through filter inductor $L3$ (also the output current of keeper supply) is constant at set value through closed-loop control (also called current PID control loop), meanwhile, the maximum output voltage at point $B$ is limited to 60 V by setting the maximum duty cycle of pulse width modulation (PWM) for primary switches [see $Q6$, $Q7$ in Fig. 2(a)]. The Ignitor_Keeper_out, which connects to cathode

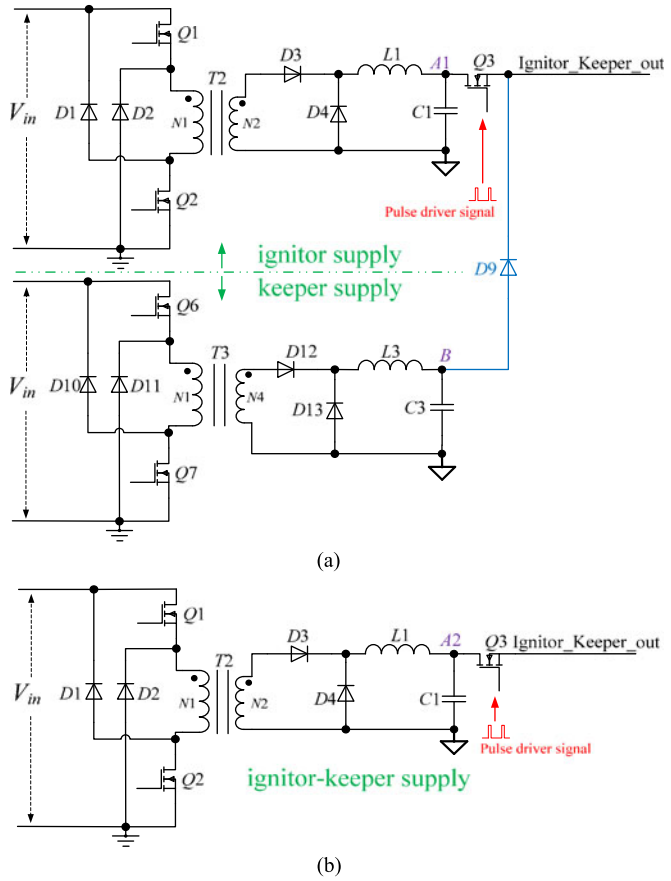


Fig. 2. Topology of ignitor supply and keeper supply: (a) before coupling; and (b) after coupling.

keeper, is formed by connecting the output of keeper supply and $Q3$ through a high voltage diode $D9$.

In Fig. 2(b), the topology possesses the function of igniting and keeping, and the output of ignitor supply and keeper supply is controlled through an appropriate control strategy. That is, the ignitor voltage PID control loop is formed by sampling voltage at point $A2$ ($V_{A2}$), and the keeper current PID control loop is formed by sampling the current through filter inductor $L1$, and the PWM duty cycle is regulated through choosing the smaller output of the above two PID control loops. Before successful ignition of hollow cathode, the keeper impedance is high, and the current through cathode keeper is 0, and the keeper current PID control loop is off work; at this time, the ignitor voltage PID control loop is on work to keep $V_{A2}$ constant at 300 V. After successful ignition, the keeper impedance decreases sharply, then $V_{A2}$ decreases and ignitor voltage PID control loop is off work with output error voltage at the maximum value. When $V_{A2}$ decreases to smaller than 60% peak voltage (180 V), which is detected by the control circuit of $Q3$, the successful ignition is identified. At this moment, different from the off state of $Q3$ in Fig. 2(a), $Q3$ is set at on state all the time and keeper impedance decreases further. When the keeper impedance decreases to that the current through cathode keeper increases to the set value of keeper supply, the keeper current PID control loop starts to work to keep current through $L1$ constant at the set value.

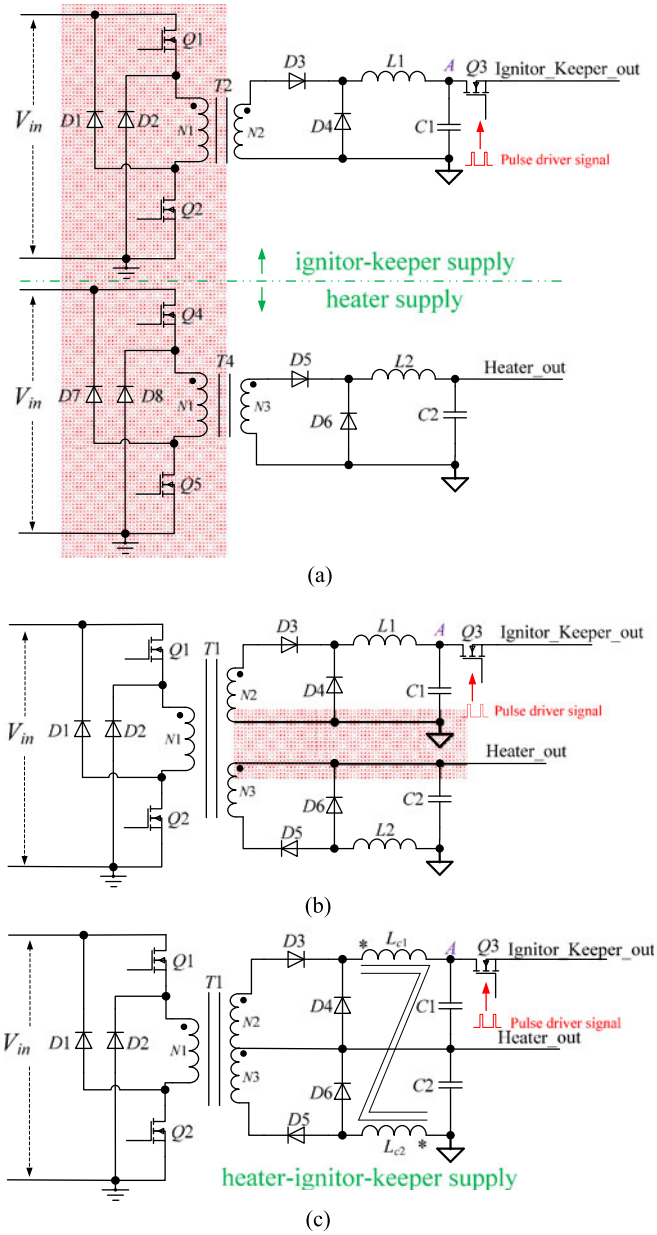


Fig. 3. Topology of: (a) ignitor-keeper supply and heater supply before coupling; (b) ignitor-keeper supply and heater supply with coupling of dc–ac conversion in primary side; and (c) the final coupled supply: heater-ignitor-keeper supply.

### *B. Coupling of Heater Supply and Ignitor-Keeper Supply Into Heater-Ignitor-keeper Supply*

The further coupling of ignitor-keeper supply with heater supply is shown in Fig 3. Fig. 3(a) shows the topology of ignitor-keeper supply and heater supply before coupling, from which it can be seen that the ignitor-keeper supply and heater supply both adopt dual-switch forward topology and work at the same time, thus, the function parts of dc–ac conversion in primary side are coupled at first, which is shown in Fig. 3(b). In Fig. 3(b), except for the coupling of primary sides, there are also some changes on secondary rectifier circuit, that is, rectifier diode $D5$ and output filter inductor $L2$ in heater supply are

moved to the earth ground. Following this change, the rectifier circuit of ignitor-keeper supply is overlaid onto that of heater supply with the same ground return, and then the output filter inductor of ignitor-keeper supply ($L1$) and that of heater supply ($L2$) are coupled into one coupling inductor $L_c$ by winding on one magnetic core, finally, the heater-ignitor-keeper supply obtained from the proposed coupling method possesses the topology shown in Fig. 3(c). With the above overlay operation, the voltage at Heater_out is added onto the voltage at point $A$ ($V_A$), that is, the ratio of $V_A$ to input voltage $V_{\rm in}$ changes to ($N2 + N3$):$N1$ from $N2$:$N1$, thus, the turn number $N2$ decreases and the design of main transformer ($T1$) is simplified. Additionally, the above coupling of two inductors $L1$ and $L2$ can bring the following advantages: increase in the power density of supply, decrease in the output current ripple of ignitor-keeper supply, and decrease on the cross regulation of $V_A$ during the regulation of heater supply.

Through the above coupling, three independent supplies are integrated into a heater-ignitor-keeper supply, which brings the following three advantages as being compared with the traditional three supplies [29], [33]:

1) The power density is significantly increased since traditional three supplies become one supply.
2) The dynamic response of $I_h$ is significantly enhanced, that is, at the moment of successful ignition, the output power of heater supply decreases sharply and the current through cathode keeper is limited and constant at the set value soon. Thus, with enough protection, the hollow cathode has longer useful life.
3) The total efficiency increases since the power loss from auxiliary power supply, primary side switching transistors, main transformer, etc, decreased to about 1/3 power loss of traditional three supplies.

## III. Principle and Timing

### A. Principle

In the coupled supply, the secondary side of $T1$ possesses two outputs, namely, Heater_out and Ignitor_Keeper_out, among which, Heater_out is the output of heater supply, while Ignitor_Keeper_out outputs high voltage pulse for igniting, or low voltage and constant set current for keeping. As shown in Fig. 3(c), there are three windings in $T1$, with turns ratio as $N1$:$N2$:$N3$. Besides, the two windings at secondary side undergo rectification-filter independently, and the rectifying circuit of Ignitor_Keeper_out is overlaid onto that of Heater_out, with these two outputs based on the same basis ground. Additionally, two switches $Q1$ and $Q2$, are ON or OFF simultaneously. When $Q1$ and $Q2$ are ON, as shown in Fig. 4(a), the power from primary side is transferred through $T1$ to secondary side to charge coupling inductor $L_{c1}$ and $L_{c2}$ and store energy; when $Q1$ and $Q2$ are OFF, as shown in Fig. 4(b), there is freewheeling in $L_{c1}$ and $L_{c2}$ through $D4$ and $D6$, and the magnetic exciting current in primary side of $T1$ flows back into the power input through $D1$ and $D2$.

The theoretical operating waveforms of the coupled supply is shown in Fig. 5, with $T$ is the switching period. Before successful

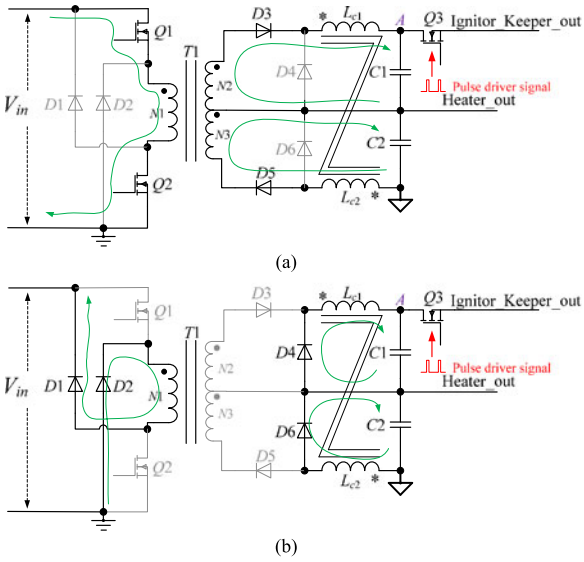


Fig. 4. Equivalent circuit diagram of heater-ignitor-keeper supply when $Q1$ and $Q2$ are (a) on or (b) off.

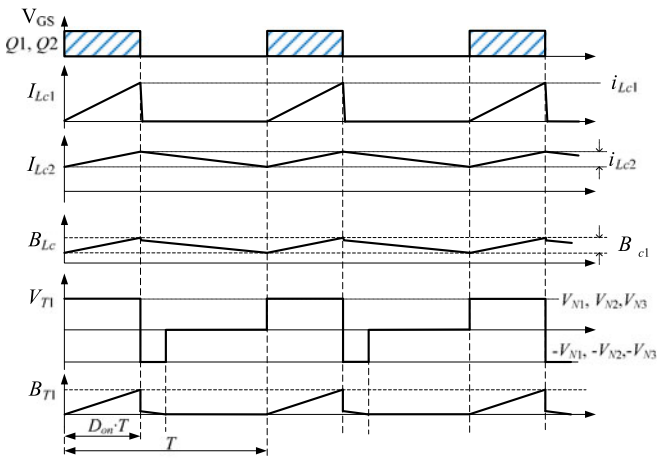


Fig. 5. Theoretical operating waveforms of the coupled supply.

ignition of hollow cathode, Heater_out outputs constant current at the set value in a settable range and provides energy to heating filament, and PWM is closed-loop controlled and regulated by heater current ($I_h$), and $L_{c2}$ works at continuous current mode with peak-to-peak value of current ($i_{\rm Lc2}$) determined through (1), where $V_{\rm in}$ is input voltage, $V_{F\_D5}$ is forward voltage of $D5$, $D_{\rm on}$ is duty cycle of PWM, and $V_h$ is output voltage of Heater_out

$$i_{\rm Lc2} = \frac{V_{\rm in} \cdot \frac{N_3}{N_1} - V_{F\_D5} - V_h}{L_{c2}} \cdot D_{\rm on} \cdot T. \tag{1}$$

For Ignitor_Keeper_out, the high voltage pulse is generated through chopping on $V_A$ by $Q3$. Since cathode keeper is at totally off before successful ignition, namely, the keeper impedance is high, and the output at point $A$ is designed to provide only the power loss of dummy payload $R_D$ (shown in Fig. 9), the output current of Ignitor_Keeper_out could not reach the limited

value of keeper current, that is, the current closed-loop of Ignitor_Keeper_out is off work. In this case, $V_A$ depends on turns ratio of *N*2:*N*1 and $R_D$, and $L_{c1}$ works at discontinuous current mode with peak-to-peak value of current ($i_{\mathrm{Lc1}}$) determined through

$$i_{\mathrm{Lc1}} = \frac{V_{\mathrm{in}} \cdot \frac{N_2}{N_1} + V_h - V_A}{L_{c1}} \cdot D_{\mathrm{on}} \cdot T. \tag{2}$$

When $Q1$ and $Q2$ are OFF, and the current through $L_{c1}$ decreases to 0 within the time of $D'_{\mathrm{off}} \cdot T$, the following expression (3) can be obtained:

$$\begin{cases} i_{\mathrm{Lc1}} = \dfrac{V_A - V_h}{L_{c1}} \cdot \mathrm{D}'_{\mathrm{off}} \cdot T \\ \mathrm{D}'_{\mathrm{off}} < 1 - D_{\mathrm{on}} \end{cases}. \tag{3}$$

Since $L_{c1}$ and $L_{c2}$ belong to the same coupling inductor $L_c$, the magnetic flux density of $L_c$ ($B_{\mathrm{Lc}}$) is influenced by current through $L_{c1}$ and $L_{c2}$. For three windings in *T*1, each working voltage ($V_{N1}$, $V_{N2}$, $V_{N3}$) has three levels. When $Q1$ and $Q2$ are ON, $V_{N1}$, $V_{N2}$, and $V_{N3}$ equal to $V_{\mathrm{in}}$, *N*2/*N*1·$V_{\mathrm{in}}$, and *N*3/*N*1·$V_{\mathrm{in}}$, respectively; when $Q1$ and $Q2$ are OFF, and there is freewheeling of primary winding magnetic exciting current through *D*1 and *D*2, $V_{N1}$, $V_{N2}$, and $V_{N3}$ equal to –$V_{\mathrm{in}}$, –*N*2/*N*1·$V_{\mathrm{in}}$, and $-N3/N1 \cdot V_{\mathrm{in}}$, respectively; when $Q1$ and $Q2$ are OFF, and the freewheeling is finished, $V_{N1}$, $V_{N2}$, and $V_{N3}$ all equal to 0. Thus, the magnetic core of *T*1 is in one-way magnetization, with peak value of magnetic flux density $B_{T1}$ determined by $V_{\mathrm{in}}$ and on-time of $Q1$ and $Q2$ ($D_{\mathrm{on}} \cdot T$). Since the output of Ignitor_Keeper_out at point *A* only provides the power loss of $R_D$, $V_A$ is close to the sum of peak voltage at *N*2 and output voltage from Heater_out. In this case, $L_{c2}$ in Heater_out still works at continuous current mode, and the output voltage of Ignitor_Keeper_out and Heater_out can be given by

$$\begin{cases} V_{\mathrm{Ignitor\_Keeper\_}A} = \dfrac{V_{in} \cdot N_2}{N_1} + V_{\mathrm{Heater\_out}} \\ V_{\mathrm{Heater\_out}} = \left( \dfrac{V_{\mathrm{in}} \cdot N_3}{N_1} - V_{F\_D5} \right) \cdot D_{\mathrm{on}} \end{cases}. \tag{4}$$

After successful ignition, the control mode of supply is changed from current closed-loop control of Heater_out to that of Ignitor_Keeper_out, and Ignitor_Keeper_out outputs constant set current $I_{\mathrm{ik}}$ to keep plasma state of xenon. At this time, the keeper voltage is determined by keeper impedance ($R_K$), which is dependent on the structure of hollow cathode, flow rate of xenon, and working state of thruster, that is, the keeper voltage changes along with the change in working condition of thruster. $L_{c2}$ in the output of Heater_out works at continuous current mode, and the output voltage of Ignitor_Keeper_out and Heater_out can be shown in (5), where $V_{Q3}$ is the drop voltage of $Q3$

$$\begin{cases} V_{\mathrm{Ignitor\_Keeper\_}A} = I_{\mathrm{ik}} \cdot R_K + V_{\mathrm{Q3}} \\ V_{\mathrm{Heater\_out}} = \left( \dfrac{V_{\mathrm{in}} \cdot N_3}{N_1} - V_{F\_D5} \right) \cdot D_{\mathrm{on}} \end{cases}. \tag{5}$$

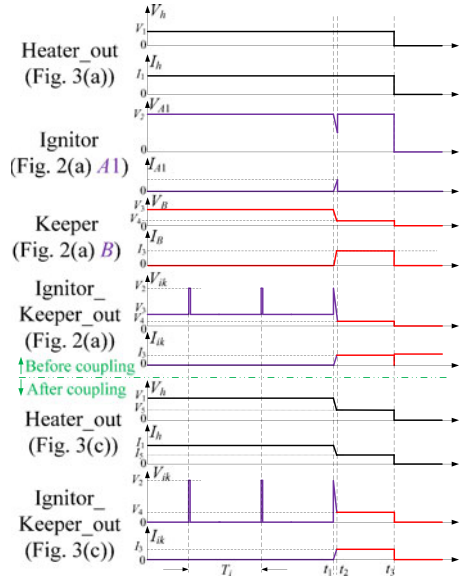


Fig. 6. Voltage/current timing waveform of each supply before coupling and after coupling during igniting process of hollow cathode in hall thruster.

## B. Timing

After the coupling of traditional three supplies into heater-ignitor-keeper supply, the voltage/current waveforms of each supply before coupling and after coupling during igniting process of hollow cathode would change, as can be seen in Fig. 6.

**0 ~ $t_1$:** the successful ignition has not been achieved.

During this time, there is no difference between output current/voltage of Heater_out ($I_h/V_h$) in traditional three supplies and coupled supply, $I_h$ is set at the value of $I_1$, and $V_h$ is $V_1$, which changes with the change of heating filament resistance ($R_h$). For output current/voltage of Ignitor_Keeper_out ($I_{\mathrm{ik}}/V_{\mathrm{ik}}$), $I_{\mathrm{ik}}$ is 0 and $V_{\mathrm{ik}}$ is the pulse voltage with peak/valley value of $V_2/0$ in coupled supply, while $I_{\mathrm{ik}}$ is 0 and $V_{\mathrm{ik}}$ is the pulse voltage with peak/valley value of $V_2/V_3$ (drop voltage of *D*9 is ignored, same below) in traditional three supplies, where $V_2$ is the output voltage of ignitor supply (voltage at point *A*1 in Fig. 2(a), $V_{A1}$) and $V_3$ is the output voltage of keeper supply (voltage at point *B* in Fig. 2(a), $V_B$).

**$t_1$ ~ $t_2$:** the igniting is under progress.

During this time, the igniting process begins when the peak value of pulse voltage is coming, then $V_{\mathrm{ik}}$ decreases to $V_4$, and $I_{\mathrm{ik}}$ increases to $I_3$ from 0 for both traditional supplies and coupled supply. Following that, for coupled supply, the control mode changes from current closed-loop control of Heater_out to current limitation closed-loop control of Ignitor_Keeper_out, $Q3$ is on all the time after identifying successful ignition, and Heater_out is under open-loop control. Since PWM duty cycle corresponding to current limitation closed-loop control of Ignitor_Keeper_out is smaller than that corresponding to current closed-loop control of Heater_out, $V_h$ decreases to $V_5$ from $V_1$ and $I_h$ decreases to $I_5$ from $I_1$. For traditional three supplies, $I_h$ keeps constant, $V_{A1}$ decreases from $V_2$ ,and $I_{A1}$ increases from 0 at first, and then $V_{A1}$ and $I_{A1}$ (output current of ignitor supply) return to $V_2$ and 0, respectively, when $Q3$ is OFF after

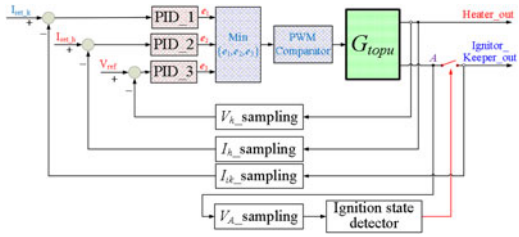


Fig. 7. Scheme of three-loop control and chopping switch logic control in the coupled supply.

identifying successful ignition; for keeper supply, $V_B$ decreases to $V_4$ from $V_3$, while $I_B$ (output current of keeper supply) increases to $I_3$ from 0.

**$t_2 \sim t_3$:** the successful ignition of thruster followed the successful ignition of hollow cathode has been identified by EP control system.

During this time, for traditional three supplies, $I_h$ still keeps constant, and there is self-heating in hollow cathode, thus, there would be great increase in the temperature of hollow cathode. The longer this process is, the shorter the useful life of hollow cathode would be. The period from $t_2$ to $t_3$ is also the response time of $I_h$ after successful ignition, which is determined according to the identification time of EP control system on the successful ignition of hollow cathode and anode in EP thruster, the command sent time and the command execution time. This response time for the traditional three supplies is about at least 500 ms according to the engineering experience. For coupled supply, $I_h$ is much smaller than that in traditional three supplies, thus the useful life of hollow cathode could be extended.

**$t_3 \sim\rightarrow$:** supplies have been shut down under the command from EP control system.

At this time, for hall thruster, both the coupled supply and all the traditional three supplies have been shut down, and the anode supply in PPU could keep plasma state of xenon. For ion thruster, in coupled supply, Heater_out stops outputting power for heating filament by closing switch between Heater_out and heater, and Ignitor_Keeper_out still outputs power to maintain plasma state of xenon; while in traditional three supplies, heater supply, and ignitor supply have been shut down, and keeper supply should be on all the time to keep plasma state of xenon.

It should be noted that the required timing of Heater_out and Ignitor_Keeper_out in the coupled supply depends completely on the design of control strategy, which is shown below.

## IV. Control Strategy

In this part, the design of three-loop control, current sampling, and chopping switch control is illustrated with details shown below.

### A. Three-Loop Control

In the coupled supply, there are two outputs (Heater_out and Ignitor_Keeper_out) with three electric characteristics (heating, igniting, and keeping), which is achieved through regulation on PWM duty cycle of $Q1$ and $Q2$, and logic control on $Q3$. Fig. 7 shows the scheme of three-loop control and chopping switch logic control in the coupled supply, which also includes the sampling of voltage and current, minimizing operation on three PID outputs, etc.

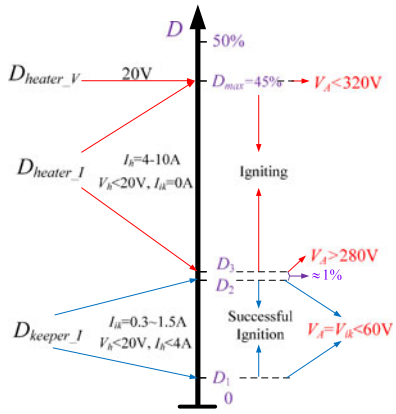


Fig. 8. Distribution of PWM duty cycle for three closed-loops.

As can be seen in Fig. 7, three-loop control consists of closed-loop control of $I_h$, clamping loop control of $V_h$, and limiting loop control of $I_{\rm ik}$, and each output is controlled through regulation on the output error voltage signal of corresponding PID ($e_1$, $e_2$, $e_3$). With minimizing operation on $e_1$, $e_2$, and $e_3$, the three closed-loop control provides decreasing control on the coupled supply. The minimum error voltage signal is transformed into duty cycle through PWM comparator, with duty cycle used to regulate the output of coupled supply. The three levels of duty cycle, that is the level of duty cycle when clamping loop control of $V_h$ at work ($D_{\rm heater\_V}$), the level of duty cycle when closed-loop control of $I_h$ at work ($D_{\rm heater\_I}$), and the level of duty cycle when limiting loop control of $I_{\rm ik}$ at work ($D_{\rm keeper\_I}$), should conform to following (6), with distribution of PWM duty cycle for three loops shown in Fig. 8

$$\begin{cases} D_{\rm keeper\_I} < D_{\rm heater\_I} < D_{\rm heater\_V} \\ D_{\rm heater\_V} = D_{\rm max} < 45\% \\ D_3 < D_{\rm heater\_I} < D_{\rm max} \\ D_1 < D_{\rm keeper\_I} < D_2 \\ D_3 - D_2 \approx 1\% \end{cases} . \tag{6}$$

In (6) and Fig. 8, the maximum duty cycle of PWM is limited to 45% so as to ensure the effective magnetic reset of $T1$ in dual-switch forward topology. For clamping control loop of $V_h$, it is used to limit $V_h$ to 20 V, which corresponds to the maximum duty cycle ($D_{\rm max}$) of the supply in steady operation. In closed-loop control of $I_h$, the minimum $D_{\rm heater\_I}$ ($D3$) corresponds to the minimum $V_h$. When the duty cycle is between [$D3$, $D_{\rm max}$], $V_A$ is under open-loop control, with the value designed as $V_A <$ 320 V at $D_{\rm max}$ and designed as $V_A >$ 280 V at $D3$. In limiting loop control of $I_{\rm ik}$, the duty cycle $D_{\rm keeper\_I}$ is between $D1$ and $D2$, which completely depends on the set value of $I_{\rm ik}$ and keeper impedance. Additionally, there should be an interval of about 1% between $D3$ and $D2$.

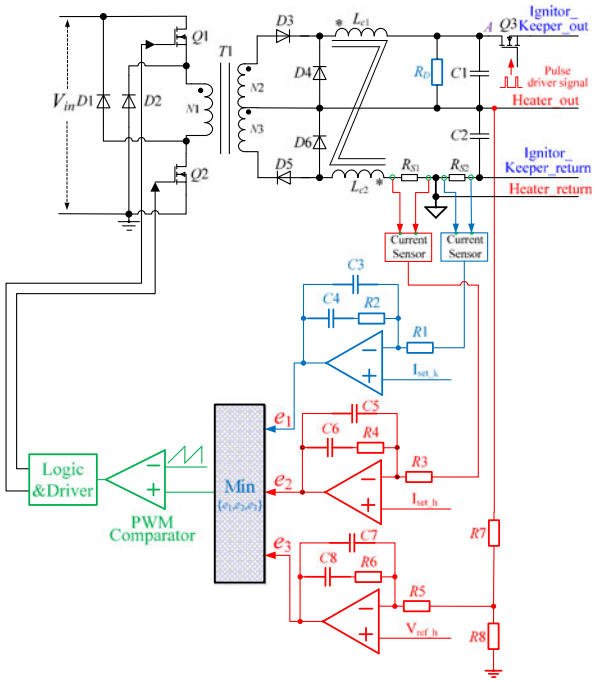


Fig. 9. Three-loop control circuit sketch of the coupled supply.

Fig. 9 shows the three-loop control circuit sketch of the coupled supply, which achieves the following functions:

*1) Closed-loop control of $I_h$:* During heating process, $R_h$ changes slowly with the change of heating filament temperature, and there is high requirement for precise and stable control on $I_h$ and low requirement for dynamic response of $I_h$, thus, $I_h$ is sampled and under closed-loop control with basis reference $I_{\text{set\_h}}$ set through commands. Before successful ignition, $I_h$ could be set between 4 and 10 A, and PWM duty cycle of the coupled supply changes in the range of $[D3, D_{\max}]$. At this time, there is no closed-loop control on $V_A$, and $V_A$ changes within a specified range by designing appropriate turn ratio ($N2$: $N1$) of $T1$ and resistance value of $R_D$.

*2) Clamping Loop Control of $V_h$:* Since $R_h$ increases with the increase of heating filament temperature, so does $V_h$ when $I_h$ is set to be constant, there should be a limitation on $V_h$ to avoid the damage of hollow cathode and the coupled supply. In this paper, $V_h$ is limited at 20 V through closed-loop control of $V_h$ by setting basis reference Vset_h at 20 V.

*3) Limiting Loop Control of $I_{\text{ik}}$:* At the moment of successful ignition, there is a severe dynamic regulation of $V_{\text{ik}}$ and $I_{\text{ik}}$ until to the achievement of stable plasma in hollow cathode. After the stable plasma is obtained, there is low level of keeper impedance, and $I_{\text{ik}}$ is closed-loop controlled quickly to the set limited value (that is basis reference $I_{\text{set\_k}}$ set through commands), so as to avoid the damage of coupled supply and cathode keeper.

In addition, the above three loops work independently under different periods with only one loop working each time, that is, there is switch over among different loops under different working conditions, but no interaction between loops at the same time. The PID parameters of three independent loops are designed according to the model of main-power topology, corresponding output current/voltage, and working condition of payloads. The PID parameters should ensure the stability of corresponding closed loop during the whole working process. Additionally, three loops correspond to different distribution of PWM duty cycle (D), and the duty cycle for limiting loop control of $I_{\text{ik}}$ is smaller than that for clamping loop control of $V_h$ and that for closed-loop control of $I_h$. The duty cycle is controlled through the minimum operation on outputs of three loops. At the moment of successful ignition, the coupled supply changes from working under closed-loop control of $I_h$ (or clamping loop control of $V_h$) to working under limiting loop control of $I_{\text{ik}}$, and $I_h$ automatically decreases instantaneously. This transient response is achieved through the quick close on loop control of $I_{\text{ik}}$ after successful ignition, which is realized by adopting two measures: the chopping switch is set at on state after identification of successful ignition by ignitor supply through the detection of $V_{\text{ik}} <$ set value and $I_{\text{ik}}$ is sampled through fast dynamic response and high-precision sampling circuit. The PID parameter for loop control of $I_{\text{ik}}$ is designed to possess high bandwidth so as to ensure the fast response of $I_{\text{ik}}$ and the quick closed loop to make $I_{\text{ik}}$ at the set value.

## B. Current Sampling

In the coupled supply, $I_h$ is under closed-loop control before successful ignition while $I_{\text{ik}}$ is under closed-loop control after successful ignition. For these two closed-loop control, $I_h$ and $I_{\text{ik}}$ should be sampled accurately, besides, the high-precise control on $I_h$ and fast dynamic response of $I_{\text{ik}}$ should also be ensured. Since the output filter inductor of Heater_out and that of Ignitor_Keeper_out are coupled together in the coupled supply, $I_h$ and $I_{\text{ik}}$ go through the same ground return. Thus, $I_h$ and $I_{\text{ik}}$ should be separated before being sampled, which could be obtained through specific layout of sampling resistance $R_{S1}$ and $R_{S2}$, as can be seen in Fig. 9.

In Fig. 9, $R_{S1}$ and $R_{S2}$ are laid before filter capacitor $C_2$, and are in series with $L_{c2}$. The Heater_return is connected between $R_{S1}$ and $R_{S2}$ and set as the control basis ground, while the Ignitor_Keeper_return is connected between $R_{S2}$ and $C_2$. Before successful ignition, the current through $R_{S1}$ is just $I_h$, that is $I_1$ in Fig. 6; and $R_{S2}$ can be considered as the equivalent ESR resistance of $C_2$, then the current through $R_{S2}$ is just the ac current ripple of $C_2$ ($\Delta I_{C2}$) with its average value of 0. Thus, the control of $I_h$ could be achieved through accurate sampling and closed-loop control of current through $R_{S1}$. After successful ignition, $I_h$ and $I_{\text{ik}}$ all flow through $R_{S1}$, and $I_{\text{ik}}$ and $\Delta I_{C2}$ all flow through $R_{S2}$, that is, the current through $R_{S1}$ and $R_{S2}$ equal to $(I_5 + I_3)$ (shown in Fig. 6) and $(I_3 + \Delta I_{C2})$, respectively. Hence, the settable limitation of $I_{\text{ik}}$ could be achieved through accurate sampling and closed-loop control of the current through $R_{S2}$, and filter on $\Delta I_{C2}$. Since $I_h$ is relatively high, the value of $R_{S1}$ could be small, and the value of $R_{S2}$ should be higher since $I_{\text{ik}}$ is smaller than $I_h$.

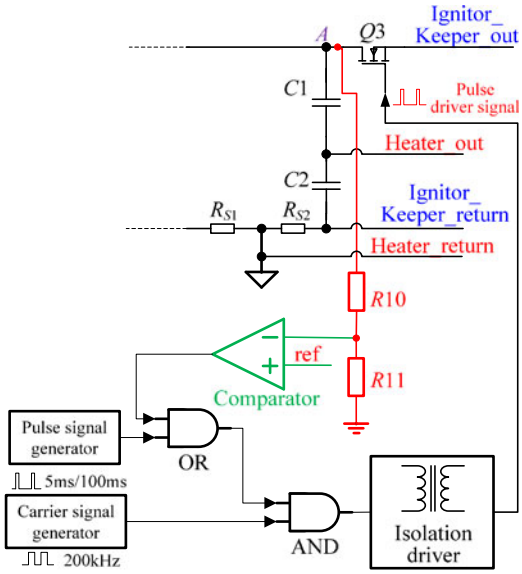


Fig. 10. Control circuit sketch of the chopping switch $Q3$.

### C. Chopping Switch Control

Fig. 10 shows the control circuit sketch of $Q3$, from which it can be seen that the identification of ignition state is through sampling $V_A$ and comparison between $V_A$ and reference voltage by comparator. Before successful ignition, $V_A$ is larger than designed value, and the output of comparator is "0" logic level. When $V_A$ is identified to be lower than designed value, which is resulted from the successful ignition, the output of comparator becomes "1" logic level, and the successful ignition is identified. Then the output of comparator is under OR operation with pulse signal, which is generated in pulse signal generator and used to set the period and width of chopping switch pulse (period/width of 100 ms/5 ms are set in Fig. 10). Next, the output of OR operation is then under AND operation with carrier signal, which is generated from carrier signal generator. Thus, through control on the availability of carrier signal, the pulse carrier signal is generated, which transforms to secondary side through isolated driver transformer, and is rectified to pulse driver signal to drive $Q3$ to chop $V_A$, finally high voltage pulse is generated. After successful ignition, the output of OR operation is constant at "1" logic level and $Q3$ is ON all the time through continuous carrier signal.

For the novel coupling method proposed in this paper, the key idea is coupling rectification and output filter of isolated secondary side, three-loop control, sampling, and chopping switch control. It should be noted that these ideas are not limited to the application in dual-switch forward topology, that is, the coupled supply could also be obtained through the application of aforementioned key ideas in the topology of flyback, push-pull, half bridge, full-bridge, etc. The employment of dual-switch forward topology in this paper is just based on the consideration of its simple main topology, drive and control, and low voltage stress on the primary switches and secondary rectifier diodes, needless of magnetic reset. Additionally, considering the high requirement of reliability in spacecraft and the oscillation characteristic of EP thruster under the working condition, as well as the comparison with traditional three supplies, the coupled supply prototype in this paper is built through normal dual-switch forward topology without application of secondary synchronous rectification and soft switching in converter, which are two commonly used strategies to increase efficiency in industry. It should be noted that, due to the complication in designing control, transformer, and coupling inductor, the coupling of three supplies into one supply also brings disadvantage of decreased reliability, that is, any malfunction would lead to all function loss for the coupled supply. However, similar with the adoption of redundancy configuration for three traditional supplies to ensure the reliability, the reliability of coupled supply can also be ensured to adopt the redundancy configuration.


Fig. 11. (a) Heater-ignitor-keeper supply prototype and (b) photo of AEP hall thruster employed in joint test.

## V. Experimental Results

A heater-ignitor-keeper supply prototype, as shown in Fig. 11(a), has been built and tested, and the joint test of the coupled supply with an AEP hall thruster, which is shown in Fig. 11(b), has also been conducted. Based on the consideration that the traditional three supplies are used for powering hollow cathode of EP thruster applied in aerospace, the electronic components with the parameters corresponding to the parameters of spacecraft-grade electronic components, rather than the optimal electronic components applied in industry, are selected to build the prototype. The prototype parameters are listed in Table II. In the coupled supply, Heater_out could output current of 4–10 A and maximum voltage at 20 V, while Ignitor_Keeper_out could output pulse voltage with peak value between 280 and 320 V and pulse width/period of 5 ms/100 ms during igniting process, and output current limited at a set value between 0.3 and 1.5 A after successful ignition.

### A. Electrical Characteristic Test

Before successful ignition, $I_h$ is under closed-loop control and Ignitor_Keeper_out is at open-loop control with high voltage pulse output. By employing electronic load set at 0.68 Ω as $R_h$, and a resistance of 1 MΩ as keeper impedance of hollow cathode before successful ignition, the coupled supply is tested with voltage/current waveforms of Heater_out and Ignitor_Keeper_out shown in Fig. 12. As can be seen in Fig. 12, Heater_out outputs current ($I_h$) of 9 A and voltage ($V_h$) of

TABLE II
PROTOTYPE PARAMETERS

| Parameter | Comment | value |
|---|---|---|
| Switching frequency | $f_s$ | 200 kHz |
| Power Mosfet | $Q_1$, $Q_2$ | IRFB42N20D |
| Pulse Chopper Mosfet | $Q_3$ | STF20N65M5 |
| Power Diode | $D_1$, $D_2$ | STTH4R02UY |
| | $D_3$, $D_4$ | STTH1210D |
| | $D_5$, $D_6$ | STPS60150CT |
| Main Transformer | $T_1$ | Ferroxcube TN32/19/13-3C95 |
| | | $N_1 : N_2 : N_3 = 18 : 41 : 12$ |
| Coupling Inductor | $L_{c1}$, $L_{c2}$ | Magnetics, 58324 |
| | | High Flux-125 |
| | | $L_{c1} = 240\,\mu$H |
| | | $L_{c2} = 90\,\mu$H |
| Filter capacitor | $C_1$ | 5.6 uF/600 V |
| | $C_2$ | 20 $u$F/100 V |
| Dummy Resistance | $R_D$ | 50 kΩ |
| Sample Resistance | $R_{S1}$ | 5 mΩ |
| | $R_{S2}$ | 20 mΩ |

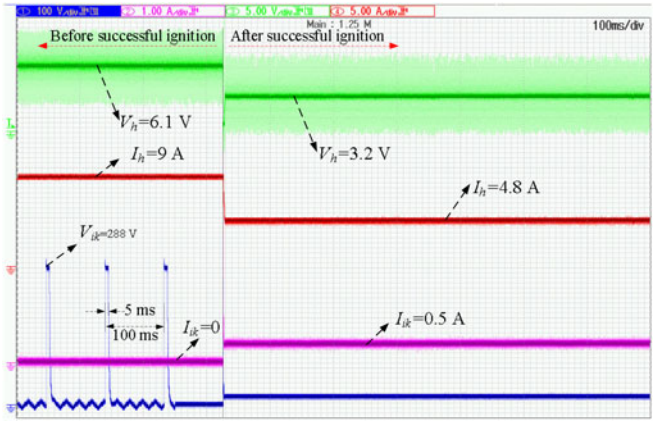


Fig. 12. Voltage/current waveforms of Heater_out and Ignitor_Keeper_out during the electrical characteristic test.

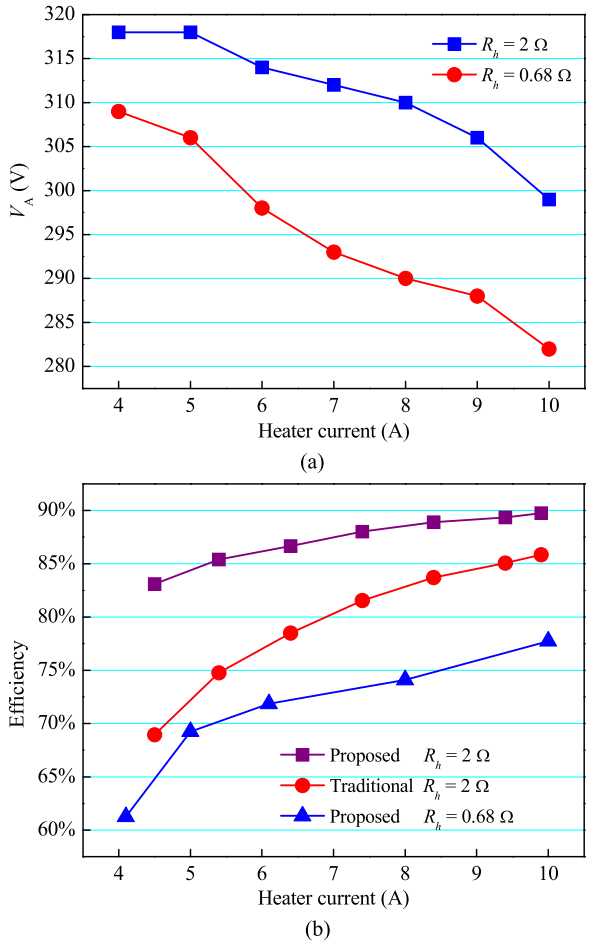


Fig. 13. (a) Plot of $V_A$ under $I_h$ in the range of 4–10 A and $R_h$ at 0.68 or 2 Ω; and (b) plot of the coupled supply efficiency under $I_h$ in the range of 4–10 A and $R_h$ at 0.68 or 2 Ω, and traditional three supplies efficiency under $I_h$ in the range of 4–10 A and $R_h$ at 2 Ω.

6.12 V, while Ignitor_Keeper_out outputs pulse voltage with pulse width/period of 5 ms/100 ms, and peak/valley value of 288 V/0. The peak voltage at Ignitor_Keeper_out equals to $V_A$.

At the moment of successful ignition, keeper impedance decreases sharply and the coupled supply is tested by adopting air switch to make Ignitor_Keeper_out short-circuit with voltage/current waveforms of Heater_out and Ignitor_Keeper_out also illustrated in Fig. 12. As can be seen in Fig. 12, at the moment of short-circuit, $I_h$ decreases to 4.8 from 9 A, $V_h$ decreases to 3.2 from 6.1 V, while $V_{\rm ik}$ decreases and $I_{\rm ik}$ increases to 0.5 A, achieving the purpose of quick decrease on the heating power.

Fig. 13(a) shows the change of $V_A$ along with the change of $I_h$ in the range of 4–10 A with $R_h$ at 0.68 or 2 Ω, from which it can be seen that, $V_A$ increases when $I_h$ decreases or $R_h$ increases (that is, $V_h$ increases), and $V_A$ changes between 280 and 320 V, in agreement with the design expectation. For the power loss of traditional three supplies, it is mainly from auxiliary power supply, primary side switching transistor, power transmission of isolated transformer, secondary-side rectification diode, filter capacitor, etc. The experiments show that, the power of auxiliary power supply is similar for three traditional supplies with value at 90 mA/12 V, and other power loss changes along with the change of working conditions. Fig. 13(b) shows the efficiency variation of coupled supply when $I_h$ changes in the range of 4–10 A and $R_h$ is 0.68 or 2 Ω, from which it can be seen that, the efficiency increases with the increase of $V_h$ (corresponds to the increase of $R_h$) and $I_h$, and the auxiliary power supply of coupled supply increases to 120 mA, smaller than the total auxiliary power supply of traditional three supplies (270 mA). Besides, the maximum efficiency could reach to 89.7% at the $V_h$ of 20 V (corresponds to the $R_h$ of 2 Ω) and $I_h$ of 10 A. Additionally, with $R_h$ of 2 Ω and $I_h$ in the range of 4–10 A, the efficiency of traditional three supplies has also been shown in Fig. 13(b) for comparison with coupled supply, with results demonstrating that the efficiency of coupled supply increases by 3.9–14.2% as being compared with that of traditional three supplies, and the smaller $I_h$ is, the more the efficiency increases.

### *B. Joint Test of the Coupled Supply With AEP Hall Thruster*

Fig. 14 shows the voltage/current waveforms of Heater_out and Ignitor_Keeper_out at the successful ignition moment of hollow cathode during the joint test of the coupled supply with

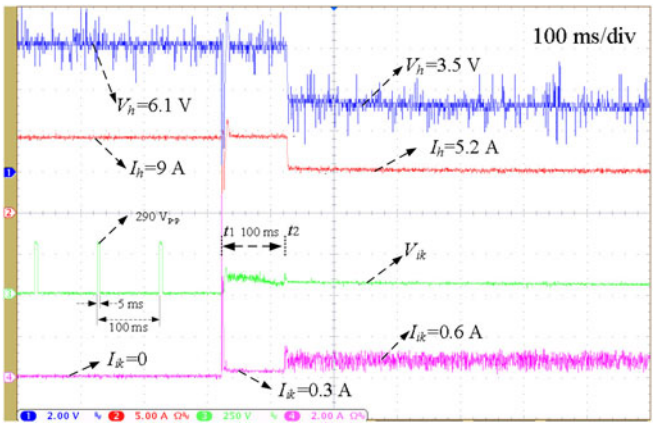


Fig. 14. Voltage/current waveforms of Heater_out and Ignitor_Keeper_out at the successful ignition moment of hollow cathode during the joint test.

AEP hall thruster. By setting $I_h$ at 9 A, $V_h$ is 5.2 V at first and then increases with the heating time during igniting process. At close to successful ignition, Ignitor_Keeper_out outputs current of 0 and pulse voltage with peak value of 290 V; when $V_h$ increases to 6.1 V, the successful ignition is obtained at one pulse rise of pulse voltage (that is, at the time of $t_1$), and followed by successful ignition of thruster. During the time from $t_1$ to $t_2$, the plasma at anode and hollow cathode is under severe dynamic regulation with regulation time of 100 ms in our test, and $V_{\rm ik}$ is clamped at 115 V at first and then decreases oscillatorily to 70 V, and $I_{\rm ik}$ shows a current peak at 8.9 A at $t_1$ and is then limited at 0.3 A. After $t_2$, $I_{\rm ik}$ is limited at 0.6 A under closed-loop control, $V_h$ decreases to 3.5 V sharply, $I_h$ is under open loop control and decreases to 5.2 A within the period $<$0.5 ms, which is much smaller than the response time of $I_h$ for traditional three supplies ($>$500 ms), achieving the purpose of sharp decrease of $I_h$ at the moment of successful ignition, that is, the purpose of fast dynamic response.

It should be noted that, for the above employed hollow cathode, $I_h$ is set at 9 A, and due to small $R_h$, $V_h$ only increases to 6.1 V during igniting process, which is smaller than 20 V, thus clamping loop control of $V_h$ is out of work all the time.

## VI. Conclusion

This paper presents a coupling method of power supplies to improve power density, efficiency, and dynamic response for future application in aerospace or specific industrial equipment. By taking the case of heater supply, ignitor supply, and keeper supply for hollow cathode of an AEP Hall thruster, the design, working principle, timing characteristic, and control strategy for the coupled supply obtained with the proposed coupling method were described in detail. Additionally, a coupled supply prototype was developed and tested with results showcasing the functionality of the proposed novel coupling method. That is, the power density is improved since three supplies are coupled into one supply; the coupled supply prototype shows the maximum efficiency of 89.7%, increasing by 3.9–14.2% as being compared with that of traditional three supplies with heater current between 4 and 10 A; and the joint test of the coupled supply prototype with an AEP hall thruster shows the sharp decrease of heater current at the moment of successful ignition, thus achieving the fast dynamic response and extending useful life of hollow cathode. These results clearly demonstrate that the improvements in power density, efficiency, and dynamic response of power supply can be achieved through the application of the proposed novel coupling method.

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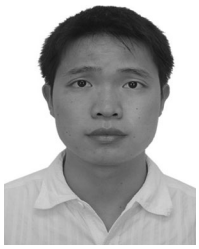

**Ming Fu (S'12)** was born in Hubei, China, in 1984. He received the B.S. degree from Harbin Institute of Technology, Harbin, China, in 2007, and the M.S. degree from Harbin Institute of Technology Shenzhen Graduate School, Shenzhen, China, in 2009, where he is currently working toward the Ph.D. degree in power electronics and power drives.

He is also a Power Electronics Engineer in Shenzhen Academy of Aerospace Technology, Shenzhen, China.

His research interests include space power conditioning unit, electric propulsion power processing unit, and fuel battery energy system.

**Donglai Zhang (M'03)**was born in Jilin, China, in 1973. He received the B.S., M.S., and Ph.D. degrees from Harbin Institute of Technology, Harbin, China, in 1994, 1996, 1999, respectively.

Since 2005, he has been a Professor at Harbin Institute of Technology Shenzhen Graduate School. His research interests include analysis, modeling and control of power converters, digital control techniques for power electronic circuits, and grid-connected converters for renewable energy systems. In these research fields, he was leading several industrial and government projects.

Prof. Zhang is a Member of the China Power Electronics Society.

**Tiecai Li** was born in Shanghai, China, in 1950. He received the B.S. and M.S. degrees in electrical engineering from the Harbin Institute of Technology, Harbin, China, in 1977 and 1990, respectively.

Since 1985, he has been a Member of the Faculty at the Harbin Institute of Technology. He was a Lecturer, Associated Professor, and Professor with the Department of Electrical Engineering, in 1985, 1990, and 1996, respectively. His research interests include the design and control of permanent-magnet motor and drives, design of control IC, and integrated motor research. He was the Outstanding Contribution Expert of China Aerospace Industrial Department in 1997. Now, he is also the Chief Technical Engineer of the Shenzhen Academy of Aerospace Technology, Shenzhen, China.