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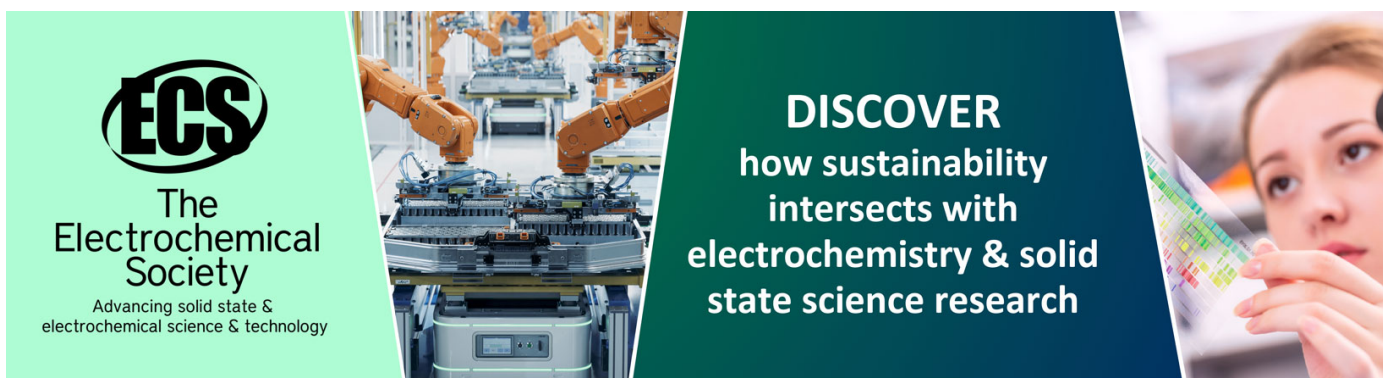
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Study on the operation mode of repetitive inductive pulsed power supply

Y Chen, H T Li*, Y Zh An, Y Ch Hu, C Jiao and X Y Liang

The School of Electrical and Electronic Engineering, Shandong University of Technology, Zibo, China

Email: lihaitao840812@163.com

Abstract. Inductive hybrid pulsed power supplies (PPS) have attracted widespread attention in the field of electromagnetic Launch (EML). In our previous studies, a repetitive inductive PPS circuit topology based on a bridge-type capacitor switching circuit and a high-temperature superconducting pulsed power transformer(HTSPPT) was proposed. By using superconducting inductors, this circuit reduces the power requirements of the primary power supply. However, to prevent the charging current from exceeding the critical current of the superconducting inductors, the circuit must enter the discharging phase immediately when the charging current reaches the designated value, even the discharge time is inappropriate. On the issue, this paper proposes a new operation mode, which is inspired by the trickle charging of accumulators. In this mode, the circuit can keep working in the introduced trickle charging phase until the discharge pulse is required. To study the feasibility of this mode, a preliminary experiment was carried out based on an HTSPPT. The results show that the discharge time can be controlled by instructions and the proposed operation mode is feasible. In addition, the critical parameters and error control methods of the proposed operation mode are also analysed and discussed.

1. Introduction

Inductors are potentially more energy dense than capacitors, making a battery-inductor hybrid pulsed-power supply (PPS) an attractive alternative to capacitor-based pulsed power supplies [1-3]. Inductive energy storage has a great prospect in the field of military equipment [4-6], especially on electromagnetic launch (EML) platforms. Until now, there are mainly three basic types of inductive PPS topologies, i.e., the meat grinder [7], the XRAM [8-9], and the pulsed power transformer topologies [10]. Based on these topologies or ideas, researchers have proposed many modified inductive PPS circuit topologies [11-14].

In our previous studies, a repetitive inductive PPS based on a bridge-type capacitor switching circuit and a high-temperature superconducting pulsed power transformer (HTSPPT) was proposed [15], as shown in figure 1. It was demonstrated that the circuit has the advantage of recovering the residual energy of the system at the end of the discharging phase and reducing the power requirements of the prime source by using superconducting inductors. However, when the charging current in the primary superconducting inductor reaches the designed value, the opening switch must be opened immediately even if the discharge time is not appropriate. This defect will seriously affect the flexibility and accuracy of EML. The previously proposed operation mode still has room for improvement.



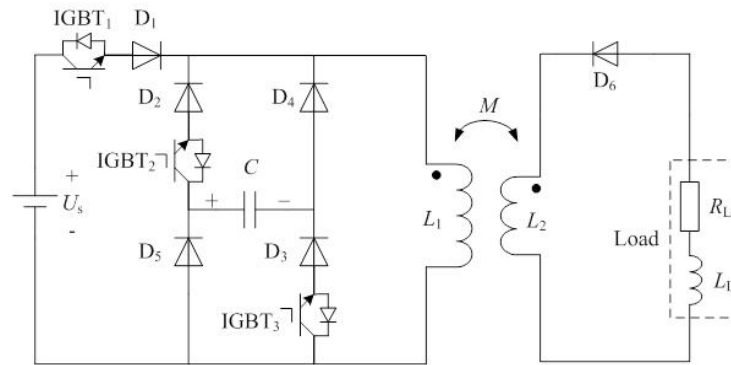


Figure 1. Circuit topology of the repetitive inductive PPS.

To accurately control the discharge time, a new flexible operation mode is proposed by applying the methodology of accumulators' trickle charging. A trickle charging phase is introduced between the charging phase and the discharging phase of the original operation mode. After the charging phase is completed, the circuit can enter the trickle charging phase that includes two alternating states, a freewheeling state, and a charging state. The circuit can keep working in the trickle charging phase until the discharge pulse is required, and the circuit can be switched flexibly to the discharging phase without considering which working state the circuit is in during the trickle charging phase. In this paper, the principle of the proposed operation mode was described in details and a preliminary experiment was carried out to illustrate the feasibility of the principle. Additionally, the critical parameters and error control methods were analyzed and discussed.

2. The proposed operation mode

The purpose of the proposed operation mode is to precisely control the start time of the discharging phase decided by discharge instructions. Therefore, after the charging phase is completed, the circuit should be in a standby state until a discharge instruction is received. Based on this idea, a new operation mode is proposed in this paper by introducing a trickle charging phase before the discharging phase of the operation mode of [15]. This novel mode has three phases, the charging phase, the trickle charging phase, and the discharging phase. The first and third phases are inherited from the original mode, while the second is unique. The detailed illustration of the proposed mode is presented as follows.

The first phase is the charging phase. The circuit is initiated by closing the opening switch IGBT₁, and the primary inductor L_1 of the HTSPPT is energized by the prime source. When the charging current reaches the designed value, the prime source is cut off by opening the switch IGBT₁.

The second phase is the trickle charging phase. In view of holding the energy while waiting for the discharge instruction, a freewheeling circuit is needed for the primary current. In this paper, the bridge-type capacitor switching circuit in figure 1 provides two freewheeling loops by closing the switches IGBT₂ and IGBT₃. However, the switches and wires in the freewheeling circuit have a certain resistance, which means that there will be energy loss during the primary current freewheeling process. To keep the current within a range to meet the minimum energy requirement of an EML firing, L_1 must be charged again when the current decays to a certain value. Therefore, the introduced trickle charging phase contains two alternate working states, the freewheeling state, and the charging state.

In order to switch between the two states, an upper limit current value I_a and a lower limit current value I_b are specified in the charging state and the freewheeling state, respectively. When the current in L_1 reaches the upper limit current value in the charging state, IGBT₂ and IGBT₃ are actively closed and IGBT₁ is opened. Then the circuit enters the freewheeling state, and the primary current is allowed to conduct through the two branches, "D₅→IGBT₂→D₂" and "IGBT₃→D₃→D₄". The equivalent circuit of the freewheeling state is shown in figure 2.

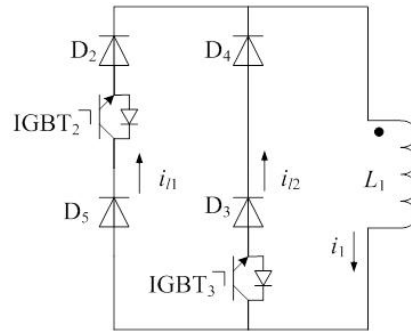


Figure 2. equivalent circuit of the freewheeling state.

In the freewheeling state, the primary current can be expressed using eq.(1):

$$i_1 = I_a e^{-\frac{R_e}{L_1} t} \quad (1)$$

where R_e is the equivalent resistance of the freewheeling loop.

When the primary current decays to the lower limit value in the freewheeling state, IGBT₁ is actively closed while IGBT₂ and IGBT₃ are opened. Then the prime source charges L_1 again and the circuit enters the charging state. The primary current can be evaluated using eq.(2):

$$i_1 = I_b + \frac{U_s}{R_s} (1 - e^{-\frac{R_s}{L_1} t}) \quad (2)$$

where R_s is the total resistance of the charging loop including the internal resistance of the prime source and the line resistance of the primary loop.

In this trickle charging phase, due to the resistance of the freewheeling loop, the circuit works in the freewheeling state and the charging state repeatedly. Figure 3 shows the ideal primary current waveform of this working process.

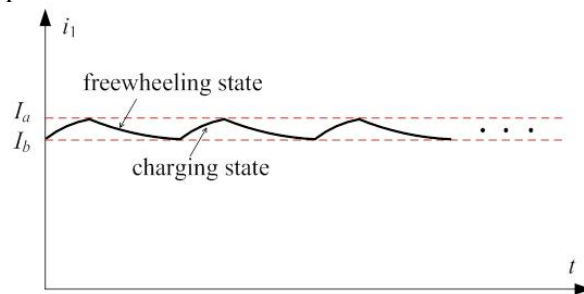


Figure 3. Current waveform in the trickle charging phase.

The third phase is the discharging phase. This phase consists of three stages, namely, the stage of L_1 discharging to capacitor, the stage of load current decaying, and the stage of residual energy recovering. When a discharge instruction is received, the circuit is quickly switched from the trickle charging phase to the discharging phase. Since the circuit has two different states during the trickle charging phase, the control methods are different when circuit enters the discharging phase. If the discharge instruction is received in the charging state—IGBT₂ and IGBT₃ are in an open state, the main opening switch IGBT₁ is opened. If the discharge instruction is received in the freewheeling state—the opening switch IGBT₁ is in an open state, IGBT₂ and IGBT₃ are simultaneously opened as opening switches. Although the discharge control methods are different, their subsequent discharge processes are the same. At the end of residual energy recovering stage, the voltage of capacitor drops to zero and the opening switch IGBT₁ is closed, and then the circuit enters the charging phase of the next cycle.

3. Preliminary experiment results

For the proposed operation mode, its feasibility is mainly determined by whether the circuit can switch smoothly from the two states of the trickle charging phase to the discharging phase. The switching from the charging state of the trickle charging phase to the discharging phase is the same as the circuit control method in switching from the charging phase to the discharging phase. This method has been demonstrated in the literature [15]. Therefore, to preliminarily verify the proposed operation mode, the switching process of the circuit from the freewheeling state of the trickle charging phase to the discharging phase is tested in this experiment.

3.1. Laboratory setup

In our previous studies, a small HTSPPT with a primary inductance of 6.15 mH and a secondary inductance of 20.94 μ H was fabricated to verify the repetitive inductive PPS topology. However, the coupling coefficient of the HTSPPT is only 0.93, which is lower than the value we expect to be greater than 0.95. To improve the coupling coefficient, the HTSPPT has been modified in this experiment. Specifically, the insulation layer thickness of the secondary winding is reduced and the total turns of the secondary winding are increased from 9 turns to 12 turns. Figure 4 shows the photo of the modified HTSPPT. The primary and secondary inductances of the modified HTSPPT measured by an LCR tester are 6.45 mH and 34.18 μ H, respectively, with a high coupling coefficient of 0.96. The total resistance of the primary charging loop is about 16 m Ω , including the wire resistance and the joint resistance. The total resistance of the secondary loop is about 5.3 m Ω , including the wire resistance and the load resistance. The detailed parameters of the modified HTSPPT are listed in table 1.



Table 1. Parameters of the modified HTSPPT

Designation	Value
Primary inductance L_1	6.45 mH
Secondary inductance L_2	34.18 μ H
Coupling coefficient	0.96
Critical current of the primary	110 A (77K)
Total primary resistance	16 m Ω
Total secondary resistance	5.3 m Ω

Figure 4. Photo of the modified HTSPPT.

According to the experimental results in [15], a 5 V constant voltage source capable of outputting current 100A is used as the prime source, and a 110-A fuse is connected in series with the prime source to prevent the prime source from short-circuit fault and the charging current from exceeding the critical value of the superconducting inductor. In this experiment, IGTB₂ and IGBT₃ in figure 1 were actually used as opening switches. In terms of controllability and turning off speed, IGBT₁, IGTB₂ and IGBT₃ are all selected the INFINEON FZ400R17KE3 IGBT, which has microsecond-level turn-on and turn-off speeds. The capacitor selected in the bridge-type switching circuit is a 100 μ F, 4 kV pulse capacitor.

3.2. Experimental results

To verify the feasibility of the circuit switching from the freewheeling state of the trickle charging phase to the discharging phase, we assume that the circuit receives a discharge instruction when it enters the freewheeling state for 10 milliseconds. The actual experimental circuit is shown in figure 5, which is connected according to the repetitive inductive PPS circuit topology shown in figure 1. The experimental results are shown in figure 6.

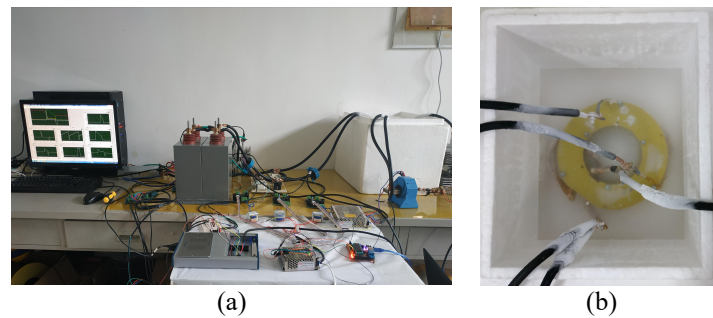


Figure 5. Photograph of the experimental circuit: (a) experimental circuit. (b) HTSPT dipped in liquid nitrogen.

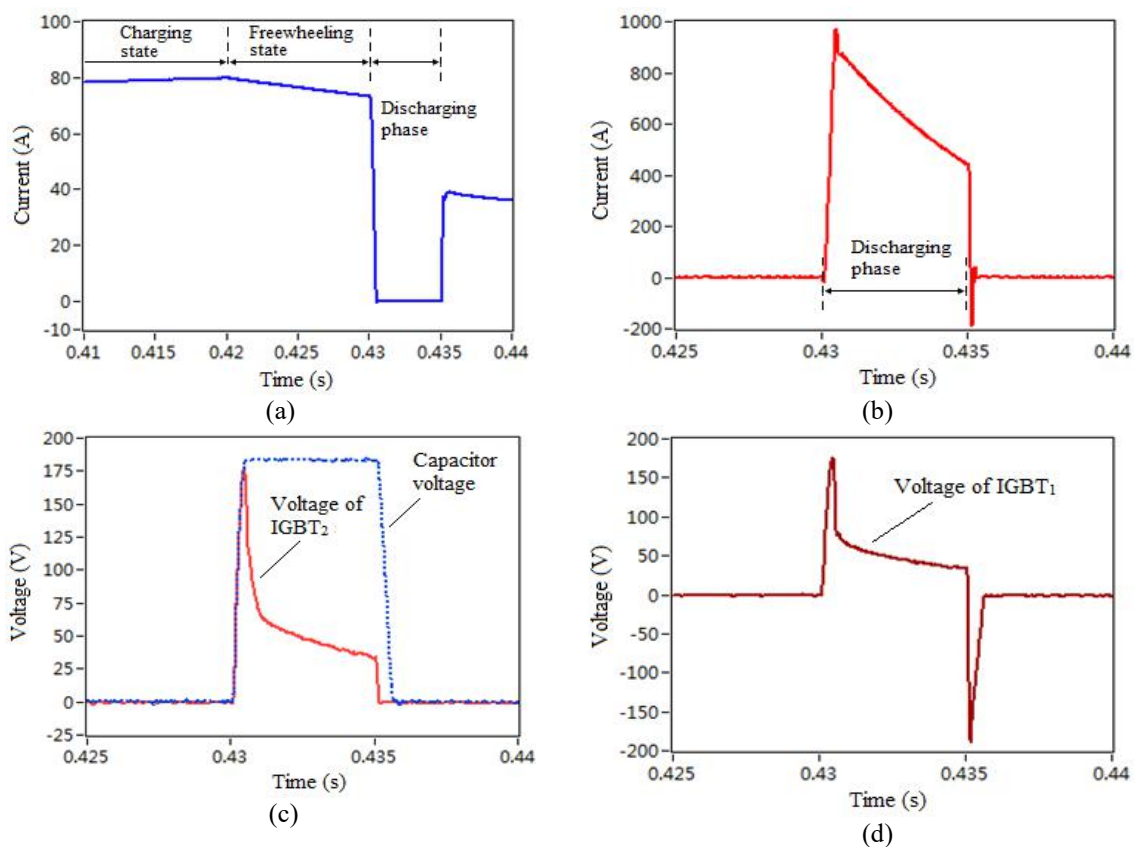


Figure 6. Experimental waveform: (a) primary current. (b) output current pulse. (c) the voltage of the capacitor and IGBT₂. (d) the voltage of IGBT₁.

From figure 6(a), when the primary current reaches 80 A, the circuit enters the freewheeling state of the trickle charging phase. After 10 milliseconds of freewheeling, the circuit is smoothly switched to the discharging phase. It is indicated that the switches IGBT₂ and IGBT₃ in the bridge-type capacitor switching circuit can be used as opening switches. However, due to the relatively high line resistance of the freewheeling circuit in this experiment, the primary current in the freewheeling state of the trickle charging phase decays rapidly. As a result, a high switching frequency between the two states of the trickle charging phase is required.

From figure 6(b) – (d), it can be seen that the discharging process is the same as that in which the circuit is switched from the charging phase. In figure 6(b), the primary current is 73 A at the beginning of the discharging phase, and the output current increases to 970 A by after using the modified

HTSPPT. The current amplification factor of the modified HTSPPT is 13. It is higher than 12 of the HTSPPT in [15]. From figure 6(c) – (d), it can be seen that the capacitor still has the ability to limit the voltage of the opening switches and recover the energy remained in the system.

In general, the experimental waveforms are in line with theoretical trends and the performance of the modified HTSPPT has been improved. Experimental results show that it is feasible to insert a trickle charging phase between the charging phase and the discharging phase. It is advantageous for the repetitive inductive PPS circuit to determine the discharge time according to discharge instructions.

4. Simulation and preliminary discussion

It can be seen from the experimental results that the resistance of the freewheeling loop has certain influences on the circuit performance. So, in this section, we mainly study the effect of freewheeling resistance on the critical parameters including the switching frequency between the two states of the trickle charging phase. And simulations are carried out by Simplorer software.

4.1. Simulation with a single unit system

The simulation model is built according to the topology of figure 1. In detail, the circuit parameters are the same as those in section 3. The inductance of the load is 1 μH , and the voltage of primary dc source is 13 V. Assuming the HTSPPT operates at 20 K, the critical current can be estimated to be greater than 550 A. In simulations, we supposed that the upper limit and the lower limit current value are 510 A and 500 A, respectively. And the discharge instruction is received just when the primary current decreases from 510 A to 500 A. And the other common parameters are held constant except for the freewheeling resistance. $U_{C\max}$ is the maximum voltage of capacitor. $U_{K\max}$ and $I_{2\max}$ are the maximum voltage of the switch IGBT₂ and the maximum load current, respectively. The simulation results are shown in table 2 and figure 7.

Table 2 shows that the influence of freewheeling resistance on the critical circuit parameters. With the freewheeling resistance increasing, the maximum voltage of capacitor and the maximum voltage of switch IGBT₂ both decrease slightly. Because a small amount of energy is consumed during the discharge of L_1 and C , the voltage of C decreases slightly. Similarly, the maximum load current $I_{2\max}$ decreases slightly because of the energy loss in the primary.

Table 2. Circuit parameters with different freewheeling resistance R_e

R_e (m Ω)	1	2	4	6	8	10
$U_{C\max}$ (V)	1419	1419	1418	1416	1415	1412
$U_{K\max}$ (V)	1434	1434	1433	1431	1430	1428
$I_{2\max}$ (A)	6181	6180	6179	6174	6173	6169

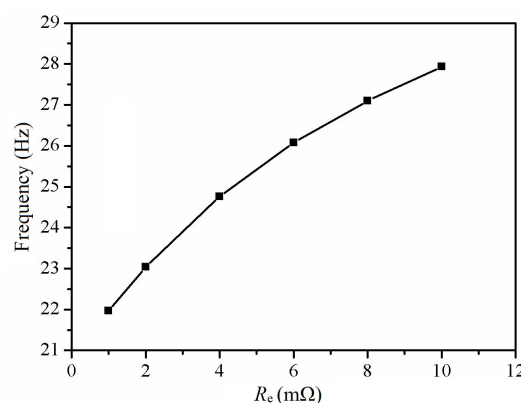


Figure 7. Simulation results of switching frequency with different freewheeling resistance.

Figure 7 shows the influence of freewheeling resistance on the switching frequency. With the freewheeling resistance increasing, the switching frequency between the charging state and the freewheeling state increases obviously. When the freewheeling resistance is 10 mΩ, the switching frequency nearly increases to 28 Hz. In the freewheeling state of the trickle charging phase, the attenuation rate of the primary current increases with the increasing of freewheeling resistance, which means that the duration of the freewheeling state is shortened and the switching frequency is increased.

4.2. Preliminary discussion

A practical railgun system usually needs tens or hundreds of kiloampere current. The configured parameters of the repetitive PPS circuit topology in this paper can act as one unit, and the whole system should be composed of more units. When multiple modules share the prime source, the charging time will increase, even up to hundreds of milliseconds. As a result, the long charging time will lead to the long working cycle, which will do great damage to the flexibility of the repetitive PPS, especially in practical railgun system. The introduced trickle charging phase gives the PPS a possible way to improve its flexibility. It provides the railgun system with the ability to wait for discharge instructions and a relatively short discharging response time during the trickle charging phase.

In a real system, the moment when the discharge instruction is received is uncertain. Since the primary current varies between an upper limit current value and a lower limit current value in the trickle charging phase, the output current pulse of the repetitive inductive PPS has a certain error based on the proposed operation mode. In order to reduce this error, the difference between the upper and lower limit current values should be reduced. Obviously, the difference can be reduced in two ways. One way is to increase the switching frequency between the charging state and the freewheeling state. However, the increase in switching frequency increases the requirements for IGBT switches. Another way is to reduce the line resistance of the freewheeling circuit. Moreover, from the perspective of reducing energy loss, the line resistance of the freewheeling circuit should also be reduced as much as possible. And the use of superconducting wires is a possible resolution to reduce the energy loss in the bridge-type capacitor switching circuit.

5. Conclusion

This paper presents a new flexible operation mode for the repetitive inductive PPS by introducing a trickle charging phase before the discharging phase. With this proposed operation mode, the discharge time can be determined by a discharge instruction. To demonstrate this operation mode, a preliminary experiment was carried out with a modified HTSPPT. The experimental results show that the proposed operation mode is feasible. The repetitive inductive PPS circuit can be smoothly switched from the trickle charging phase to the discharging phase. In addition, the method of reducing the output error was analyzed in this paper. To reduce the output error, the line resistance of the freewheeling circuit should first be reduced as much as possible, and then the switching frequency between the charging state and the freewheeling state should be increased.

Acknowledgments

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