The energy recovery sub-circuit for multiple stages of the stretch meat grinder with ICCOS circuit

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Abstract. The STRETCH meat grinder and the ICCOS are two typical inductive pulsed power supply circuits for electromagnetic launch system. On the basis of combing both, a new topology-STRETCH meat grinder with ICCOS was put forward by Tsinghua University in 2013. After launching the railgun load, all of the remaining energy is stored in the energy transfer capacitor of the circuit. In this paper, the corresponding recovery circuit is designed for the circuit containing four STRETCH meat grinder with ICCOS circuits connected in a XRAM way in order to reuse the remaining energy. The prototype system has 4kA charging current, and thus 28.19kJ magnetic energy. More remaining energy can be recovered by triggering the related thyristors with more times. Simulation results show that the topology with the suggested energy recovery circuit can roughly recover 1/3 of the residual energy to the primary power and has potential prospects for high energy storage systems in the future.

1. Introduction
The previous studies on the inductive energy storage system have indicated that the energy density of inductive energy storage is one order of magnitude higher than that of the capacitive ones at the same power output level [1-5]. At present the key difficulties of inductive pulse power lie in three areas, such as the supply capacity of the primary source, the current turn-off technology, and the current magnification.

IAT (Institute of Advanced Technology) put forward an inductive pulse power topology called the STRETCH (Slow Transfer of Energy Through Capacitive Hybrid) meat grinder [6] which is on the basis of the improvement of the traditional meat grinder [7-8]. In this topology, an integrated gate-commutated thyristor (IGCT) is capable of breaking about 8kA charging currents [1], and it may encounter difficulties in extending to higher energy systems.

Based on the ICCOS (Inverse Current Commutation with Semiconductor) devices, ISL (German-French Institute of Saint Louis) proposed a topology called XRAM [9]. Until now 8 stages and 20 stages XRAM [10-11] are achieved and a prototype of XRAM with 3kA charging current, 60kA discharging current, and 4.7kJ pulse power supply has implemented by ISL. The comparison between the STRETCH meat grinder and the XRAM is explained in detail in literature [12].

The STRETCH meat grinder topology has a large current amplification factor and IGCT is selected as the main switch. IAT have done many experiments to get a better current turning-off technology and a higher level system, but the result is not ideal [13]. In the XRAM topology, the inductors are charged in series and discharged in parallel. And the main switches are thyristors. Compared with the STRETCH meat grinder, the XRAM is easy to be extended and its disadvantage is the low current...
amplification factor. Based on these two topologies, the STRETCH meat grinder with ICCOS with back commutation was proposed and the corresponding recovery circuit is given by Tsinghua University [14]. The thyristor is adopted as the main switch and ICCOS is applied to turn off the current. It overcomes the limitations of the original part and has potential prospects for high energy storage systems in the future while reducing a lot of the cost [14]. In this article, a recovery circuit is added in the 4-stage of the STRETCH Meat Grinder with ICCOS with front commutation. Simulation results show that the recovery circuit recovers 1/3 of the capacitive remaining energy back to the primary power supply.

2. 4-stage of the stretch meat grinder with iccos of front commutation added recovery circuit

2.1. STRETCH Meat Grinder with ICCOS of front commutation

The STRETCH Meat Grinder with ICCOS topology has the advantages of both the STRETCH Meat Grinder topology and the XRAM topology. Its magnification factor is the multiplier of magnification factor of STRETCH Meat Grinder and XRAM. Improving the current of the primary source or increasing the number of unit can make the load current larger. The structure has a double current waveform adjustment system. We can get almost any desired current waveform by the double adjustment system. One is each stage of the current waveform can be adjusted by controlling the trigger \( T_{1i} \). The other is the synthesized current waveform of the respective stages can be adjusted by controlling the trigger \( T_{2} \). The structure improves the efficiency of the system because of adding energy feedback mechanism. Figure 1 shows the topology of the STRETCH Meat Grinder with ICCOS with front commutation. And it is adopted as the unit circuit in this article. Literature [15] describes the difference between the back and front commutations of the STRETCH Meat Grinder with ICCOS topology, but their performances are basically the same. The STRETCH Meat Grinder with ICCOS topology improves the turning-off current capacity compared with the STRETCH Meat Grinder topology and has a higher single amplification factor to the XRAM topology. In this paper, a recovery circuit for the 4-stage STRETCH meat grinder with ICCOS with front commutation is chosen to illustrate the basic principle of the extension topology.

![Figure 1](image_url)  
**Figure 1.** Topology of STRETCH meat grinder with ICCOS of front commutation.

2.2. The principle of 4-stage STRETCH Meat Grinder with ICCOS of front commutation added the recovery circuit

The topology of the 4-stage STRETCH meat grinder with ICCOS with front commutation and recovery circuit is drawn in figure 2. And the working procedure of this circuit can be divided into five steps.
Figure 2. Topology of N-stage STRETCH Meat Grinder with ICCOS (front commutation) with the recovery circuit (N=4).

Step 1, the groups of inductors $L_{i1}$ and $L_{i2}$ ($i=1\sim4$), connected in series, are charged by the primary source $u_s$. After the main switch $T_i$ is triggered, the constant voltage $u_s$ which is usually a low voltage source like batteries about 100V, begins to charge the series connected inductors $L_{i1}$ and $L_{i2}$ so that the current increases straight climb. When the charging current achieves the specified value, $T_{i2}$ is triggered to switch off the main switch. Capacitor $C_{i2}$ is pre-charged with an initial voltage about 1000V to turn off the main switch $T_i$. 

(a) The first sub-step
Step 2, thyristor $T_i$ is turned off by using the commutation circuit which is composed of $T_{i2}$ and $C_{i2}$.

The process of commutation can be divided into two sub-steps so as to elaborate the principle more clearly. The first sub-step begins from the moment $T_{i2}$ triggered, ends at the moment when the current through the main switch $T_i$ ($1 \leq i \leq 4$) crosses zero. figure3(a) shows this working step. After $T_{i2}$ is triggered, the current $i_{12i}$ increases quickly until it equals to the current of the inductors. When the current through the main switch $T_i$ crosses zero, the second step starts. The period of the first step is so short that the current in the inductors is almost unchanged. figure3(b) shows the second sub-step. In the second sub-step, the voltage of $C_{i2}$ is still higher than $u_i$ so that it exerts an inverse voltage on the main switch $T_i$ ($1 \leq i \leq 4$). During this period, $i_{12i}$, $i_{11i}$ and $i_{i2i}$ continues to increase to a certain value because of the residual voltage across $C_{i2}$ ($\sum (C_{i2}-T_{i2}, L_{i1}, L_{i2})-T_{i} u_{i}$ ($1 \leq i \leq 4$)). The second step ends at the moment the diodes $D_{i1}$ and $D_{i2}$ are turned on. As shown in figure4 the diodes $D_{i1}$ and $D_{i2}$ conduct almost simultaneously. The voltage across the load can be omitted because of its low impedance value.
(1.5mΩ, 1μH). On account of the voltage across $C_1$ remained unchanged (i.e. zero) before $D_1$ and $D_2$ conducts. The voltage across $D_2$ equalizes the voltage on $L_1$ and the voltage across $D_1$ equalizes the total voltages across $L_1$ and $L_2$. The diodes $D_1$ ($L_1$-$D_2$-$T_{n+1}$-Load-$D_3$-$C_{11}$-$D_1$) and $D_2$ ($L_2$-$D_3$-Load-$T_{n+1}$-$D_2$) are turned on when the currents of inductors begin to reduce. And the second sub-step ends.

Step 3, the commutation process ends after the diodes $D_1$ and $D_2$ are turned on.

The third step is beginning at the end of the second step. Figure 4 shows the equivalent circuit of step 3 after the thyristor $T_2$ is turned off. $C_{11}$ is charged by $L_1$ through the loop ($L_1$-$D_2$-$T_{n+1}$-Load-$D_3$-$C_{11}$-$D_1$). The voltage across $C_{12}$ decreases from zero and the voltage across $C_{11}$ is negative [10]. To the first stage, if the voltages of $D_{11}$, $D_{13}$, $D_{43}$ and $T_0$ are omitted, the voltage across $T_{12}$ holds that: $U_{T12}=U_{C12}-U_{C11}+u_s$. To the other three stages, if the voltages of $D_{11}$, $D_{13}$ and $D_{43}$ ($2≤i≤4$) are omitted, the voltage across $T_{12}$ holds that: $U_{T12}=U_{C12}-U_{C11}$. Because capacitance $C_{11}$ is ten times larger than $C_{12}$, the voltage of $C_{12}(U_{C2})$ varies faster than the voltage of $C_{11}(U_{C1})$. The value of $u_s$ is very smaller than $U_{C11}$ and $U_{C2}$. So $T_2$ withstands the inverse voltage, which makes the reliable shutdown of $T_{2}$. After $T_2$ is safely turned off, the commutation process ends and the following working steps are same as the STRETCH meat grinder with main switch IGCT.

Step 4, four stages discharge in parallel.

![Figure 5](image_url)

**Figure 5.** The equivalent circuit of step 5 after the armature has been launched.

Step 5, the remaining energy feedback.

After the armature has been launched, the residual energy is stored in the capacitors $C_{11}$ ($1≤i≤4$). Figure 5 is the equivalent circuit after the armature has been launched. In the circuit $L_i$ ($i=1$–$4$) is the total inductance of $L_1$ and $L_2$. The current-limiting resistor $R_{fi}$ can be placed alongside $T_i$ in order to limit the recovering currents through $u_s$. Triggering the thyristors $T_{2.4}$, $T_{2.4}$ and $T_{2.4}$ simultaneously, one part of the residual energy is recovered to the primary power supply, and another part is consumed in the resistors of the circuit. After the energy conversion between the inductors and the capacitors as well as among the capacitors, the remaining energy is stored in the capacitors at last. And it can be recovered again by triggering the corresponding thyristors. More remaining energy can be recovered by triggering the recovery circuit more times.
3. Simulation results

Compared to the STRETCH meat grinder topology and the XRAM topology, the STRETCH meat grinder with ICCOS topology has many better performances [14]. In order to verify the performances of the recovery circuit with 4-stage STRETCH meat grinder with ICCOS, simulations are done by Simplorer 8.0. The simulation parameters are as follows. In the STRETCH meat grinder section, the inductances of $L_{i1}$ and $L_{i2}$ are 632$\mu$H and 23.56$\mu$H respectively and the coupling factor is 0.8. The capacitance of $C_{i1}$ is 800$\mu$F and the load is the small 1.5m$\Omega$ resistor and 1$\mu$H inductor. The primary voltage source $(u_0)$ is 210V. For the properly working of the STRETCH meat grinder with ICCOS, $T_{i1}$ is exerted at 72.25ms. And during the recovery process, $T_{2-4}$, $T_{i1}$ and $T_{fi0-4}$ are exerted at 80ms. In order to recover more energy, we do another two example recovery by triggering $T_{2-4}$, $T_{i1}$ and $T_{fi0-4}$ at 87ms and 95ms respectively. In the ICCOS section, the capacitance of $C_{i2}$ is 80$\mu$F with the initial voltage 1200V. In order to avoid the too large recovery current, $R_{Tfi}$ ($R_{Tfi}=1$ $\Omega$) is connected to the circuit and series with $T_{fi}$.

Figure 6 shows the recovery currents by triggering the recovery circuit three times. And the total recovery current of the whole recovery system is 6.33kA. The maximum total recovery currents of four stages are 0.51kA, 1.22kA, 1.94kA and 2.66kA respectively by triggering the recovery circuit three times.

Figure 7 shows that the total recovered energy is 282J with recovering three times. Figure 7 and Table. I show that the three recovered energy to the primary power ($W_{us}$) for the above three examples are 236J, 274J and 282J respectively.

![Figure 6. The recovery current waves with recovering three times.](image)

| Current (A) | Max value |
|------------|-----------|
| $T_{i1}$   | 0.208kA   |
| $T_{i2}$   | 0.194kA   |
| $T_{i3}$   | 1.222kA   |
| $T_{i4}$   | 1.937kA   |
| $T_{i5}$   | 2.667kA   |

![Figure 7. The recovered energy of the primary power with recovering three times.](image)

| Name | X    | Y    |
|------|------|------|
| m1   | 84.9946 | 236.3952 |
| m2   | 91.6901 | 237.6501 |
| m3   | 97.6671 | 282.2546 |
Figure 8 shows that the maximum reverse voltages across $C_{11-41}$ are 0.7293kV, 0.7268kV, 0.7268kV and 0.7269kV after lunching the railgun. And the total residual energy ($W$) stored in $C_{11}$ is 847J. The percentage of the recovered energy compared the total residual energy ($W/n/W$) are 27.9%, 32.3% and 33.3% respectively. Other energy is consumed on the limiting resistors ($R_{7b}$). From figure6, figure7, figure8 and Table. I, we can know that triggering the recovery circuit once can produce one peak current and recover part of the rest energy. The rear stages recovery current and the recovered energy become less than those of the former ones. And more residual energy can be recovered by triggering the recovery circuit more times.

### Table. I
The recovered energy compared
| Triggering times | Triggering once | Triggering twice | Triggering three times |
|------------------|-----------------|------------------|------------------------|
| $W_{us}$         | 236J            | 274J             | 282J                   |
| $W$              | 847J            |                  |                        |
| $W_{us}/W$       | 27.9%           | 32.3%            | 33.3%                  |

4. Conclusion
The energy recovery sub-circuit for 4-stage STRETCH meat grinder with ICCOS with front commutation is discussed in details in this paper. Improving the charging current or increasing the number of the unit can make the load current higher. From the simulation results, the recovery circuit can recover 1/3 of the residual energy which is stored in the capacitors to the primary power after the armature has been launched.

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