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# A new three-structure repetitive pulse magnetic field power supply system


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## I Introduction

The Repetitive Flat-top Pulsed High Magnetic Field (**RFPHMF**) as a special field is concerned in some scientific researches such as neutron diffraction, NMR and so on.

In order to have an **RFPHMF** waveform, several characteristics are in need: can build-up the magnetic field rapidly; have a high stability flat-top; can demagnetize the field validly; and have a short intervals time between the repetitive magnetic field pulses.

Hence the required current waveform would have the corresponding 4 stages: the current rising stage, the flat-top stage, the current fall stage, and the cooling stage.

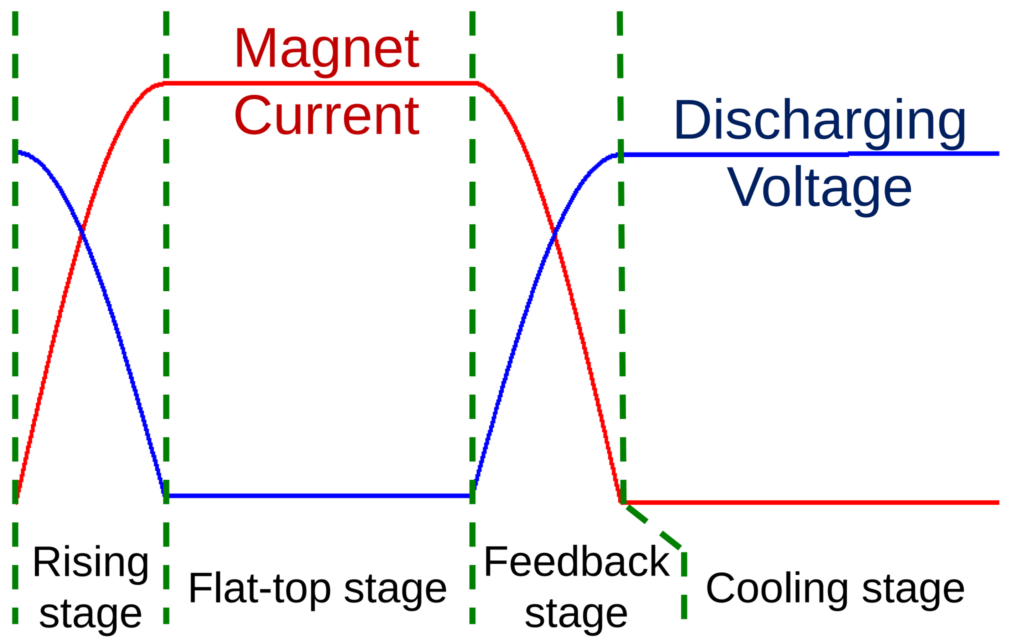


Fig. 1 Required Current Waveform

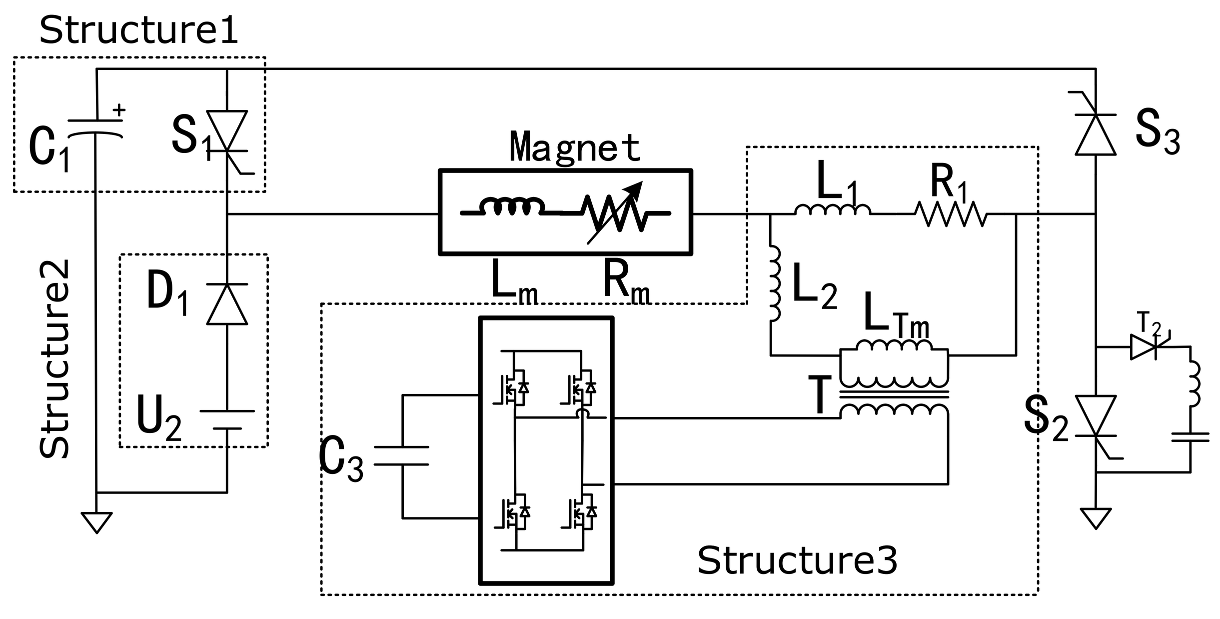


Fig. 2 Multi-structure Charging System

A new topology has been proposed to realize the required current waveform.

An energy feed-back full-bridge structure was designed to extract the residual magnet energy to recharge the capacitor instead of being dissipated as heat. Use the battery to approximately compensate the voltage-drop on the magnet resistance. A serial inductor $L_1$ and a high frequency voltage adjusting structure was added to achieve the flat-top current.

In Fig. 2, the $C_1$ is used to quickly charge the magnet. The magnet, illustrated as inductor $L_m$ and resistor $R_m$ connected in series, has an increasing resistance because of the quickly rising temperature. The battery in Structure 2 along with the structure 3 is used to provide a flat-top duration, which is a high frequency current injecting structure with an isolated transformer.

The topology has several merits as follow:

1. Feed back the magnet energy, decrease the recharging power and reduce the heat of the magnet;
2. Maintaining the magnetic field with lower voltage and reducing the flat-top magnet field ripple by high frequency smaller current;
3. Simple and reliable electric isolation between different voltage grades of main circuit and flat-top tuning structure;

## II Topology Analyzing

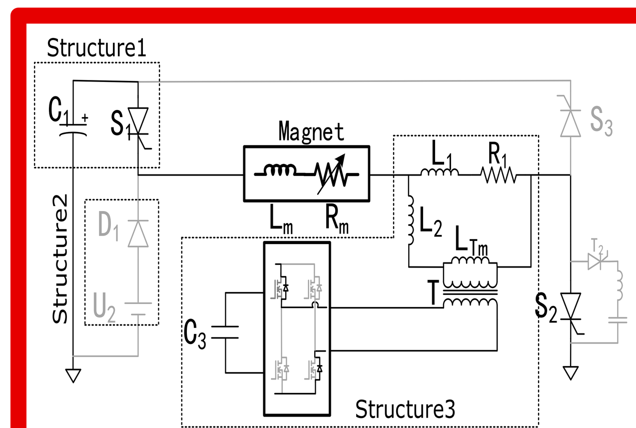

Fig. 3 Rising stage equivalent circuit

1. Rising stage

Turn on the thyristor $S_1$ and $S_2$. The structure 1 is activated. The topology starts to operate in charging mode. The magnet is charged by $C_1$ and the magnetic field is built quickly.

The battery $U_2$ is disconnected because the voltage of $C_1$ is higher than that of the battery, so the diode $D_1$ is forced to turn off. There might be an inrush current that flows through the transformer T and the H-bridge. To prevent inrush current, the subdivision part of the capacitor voltage on $L_{Tm}$ should be smaller than the equivalent voltage on original side of the transformer.

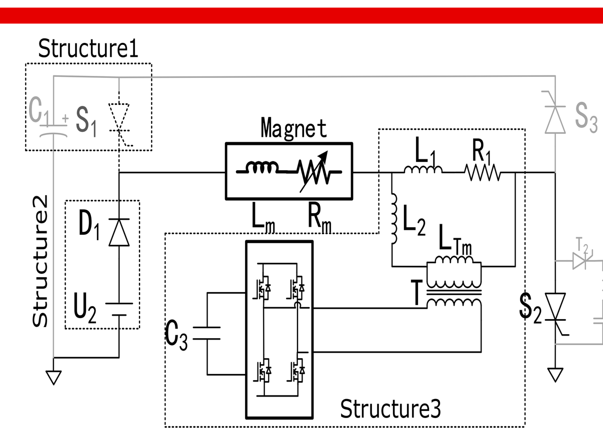

Fig. 4(a) Flat-top stage equivalent circuit

2. Flat-top stage

When $U_1 \leq U_2$, $S_1$ is shut down. The battery is connected to the circuit. At the same time, activate structure 3. The topology starts to operate in flat-top mode.

At the flat-top stage the structure 2 and 3 work together to provide the magnet voltage. If the magnet current actually is 'flat-top', the magnet voltage would drop on the magnet resistance which is much less than the voltage of the magnet needs in rising time.

On this stage, the magnet resistance will increase continuously due to the heat of the magnet built-up, so the required magnet voltage will increase as well. The average non-changed part will be provided by battery while the remaining changing part will be compensated by structure 3. Fig 4(b) is the equivalent circuit on this stage.

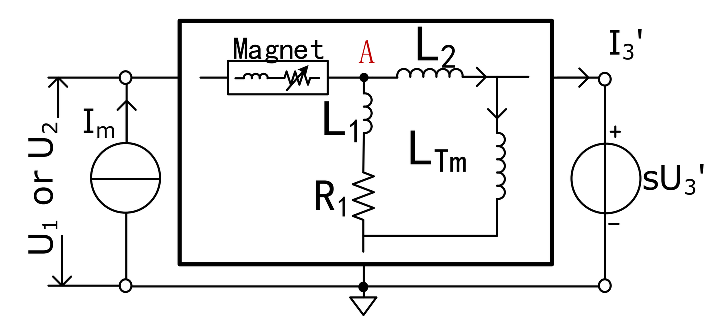

Fig. 4(b) Flat-top stage equivalent circuit

By changing the way $U_3'$ connected to the circuit, one can change the equivalent voltage of point A, hence adjusting the magnet current.

Most of the main discharging current flow through the inductor $L_1$, make the injecting current of the structure 3 much smaller.

The injecting current which flow through the H-bridge of the structure 3 should be concerned because of the limit of the maximum switch current.

The H-bridge current equals to the difference value between $i_2$ and $i_{Tm}$, so the envelope value of the $i'_3$ is:

$$i_{3env}(t) = U'_3\left(\frac{1}{L_2+\frac{L_1 L_m}{L_1+L_m}}+\frac{1}{L_{Tm}}\right)\int_0^t s\,d\tau$$

s means the way $C_3$ is connected to the circuit, s=1 or -1. The **one-way** change of the resistance make it extra difficult for structure 3 to trimming the current.

The more dramatic the resistance changes the more voltage structure 3 should provide, meaning $\int_0^t s\,d\tau$ would keep increasing with the flat-top time.

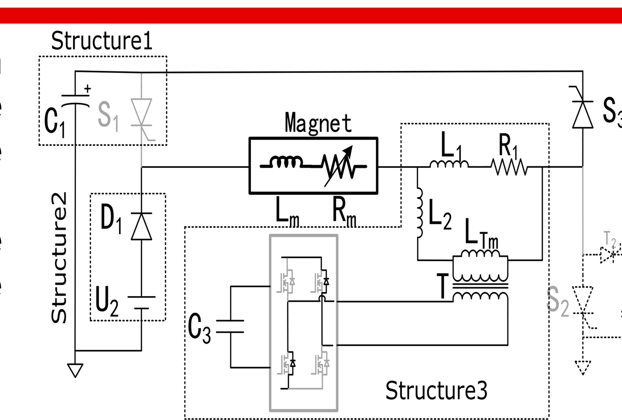

Fig. 5 Feedback stage equivalent circuit

3.Feedback stage

Turn ON the $S_3$. Turn OFF the $S_2$ (by Turn ON $T_2$ first to force $S_2$ to Shut down by reverse voltage). Shut down the structure 3. The topology start to work in feedback mode.

If there is no inrush current, the feedback structure is supposed to extract the current from the magnet and recharging the capacitor. The capacitor voltage after the feedback can be proximately estimate by calculating the energy changes. The feedback voltage in shortage will be:

$$\Delta U_1 = \sqrt{(\pi-2)(R_1+R_m)(L_1+L_m)}I_{ref}$$

4. Cooling stage

In this stage, no current flows through the magnet. The magnet's temperature decreases and so does the magnet resistance. The outer circuit charges the $C_1$, $C_2$ to the setting voltage before next pulse.

## III Designing Procedure

With the given magnet (already known $L_m$ and the changing $R_m$ ), and the limited discharging voltage (withstand voltage level of the thyristor) and rising time(request by the magnetic field), a step by step designing procedure of electrical parameters is given down below:

**Step1:** Determine the battery voltage $U_2$ and the resistance $R_1$ of the serial inductor;
Choose $U_2$ that can provide the average non-changed part of the voltage the magnet needs.
Choose $R_1$ to help the actual battery voltage $U_2$ match the flat-top current.

**Step2:** Determine the transformer ($L_{Tm}$ and ratio);
Use the possibly biggest $L_{Tm}$ to decrease the H-bridge operating current.
Choose the ratio slightly bigger than the *discharging voltage : structure 3 Withstand Voltage*

**Step3:** Determine the inductor $L_1$;
Choose the proper $L_1$ that can satisfy the limits of the Discharging Voltage, the Rising Time, and the range of the duty ratio.

**Step4:** Determine the DC bus voltage of structure 3;
Choose the voltage slightly bigger than the subdivision voltage of $U_1$ to prevent inrush current.

**Step5:** Determine the $L_2$;
Choose the proper $L_2$ with the limit of H-bridge operating current (with certain duty ratio).

**Step6:** Determine the $C_1$ and $U_1$;
Determine the $C_1$ to satisfied the limits of max discharging voltage and the max rising time.
Determine the $U_1$ to ensure the flat-top current was the setting value.

## IV Experiment & Conclusion

According to the designing procedure, a 20T RFPHMF charger has been designed. The parameters are as follow:

TABLE I Simulation Design

| Parameters | Symbol | Value |
|---|---|---|
| Magnet inductance | $L_m$ | 1.117mH |
| Magnet resistance | $R_m$ | 10 ~15 mΩ |
| Flat-top current | $I_{ref}$ | 7kA |
| Charging frequency | $f_c$ | 10Hz |
| Rising time | $t_r$ | 4.95ms |
| Flat-top duration | $t_{flattop}$ | 10ms |
| Charging capacitance | $C_1$ | 3.8mF |
| Disdischarging voltage | $U_1$ | 5809V |
| Battery voltage | $U_2$ | 96V |
| Trimming voltage | $U_3$ | 500V |
| Serial inductance | $L_1$ | 1.5mH |
| Current choke inductor | $L_2$ | 10.481mH |
| Magnetizing inductor | $L_{Tm}$ | 50mH |
| Transformer Ratio | k | 8:1 |

The simulation result of a 20T **RFPHMF** is shown in below:

Fig. 5(a) Simulation result

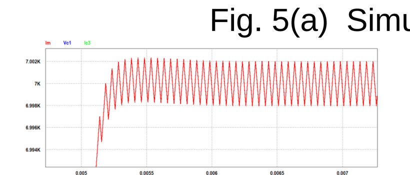

Fig. 5(b) Magnet current

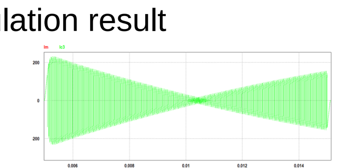

Fig. 5(c) trimming current

The blue curve is the discharging voltage. The red curve is the magnet current. The green curve is the H-bridge operating current. The results shows that the topology can generate repetitive flat-top high magnetic filed. The flat-top precision is under 300ppm. The H-bridge operating current is under 200A.

A low charging energy experiment has been done to prove the feasibility of the topology. The parameter is as follow:

TABLE II Experiment Design

| Parameters | Symbol | Value |
|---|---|---|
| Magnet inductance | $L_m$ | 1.27mH |
| Magnet resistance | $R_m$ | 107mΩ |
| Flat-top current | $I_{ref}$ | 300A |
| Charging frequency | $f_c$ | 50Hz |
| Rising time | $t_r$ | 1.5ms |
| Flat-top duration | $t_{flattop}$ | 4ms |
| Charging capacitance | $C_1$ | 600uF |
| Disdischarging voltage | $U_1$ | 470V |
| Battery voltage | $U_2$ | 36V |
| Trimming voltage | $U_3$ | 50V |
| Serial inductance | $L_1$ | 204.86uH |
| Current choke inductor | $L_2$ | 10.48mH |
| Magnetizing inductor | $L_{Tm}$ | 25mH |
| Transformer Ratio | k | 4:1 |

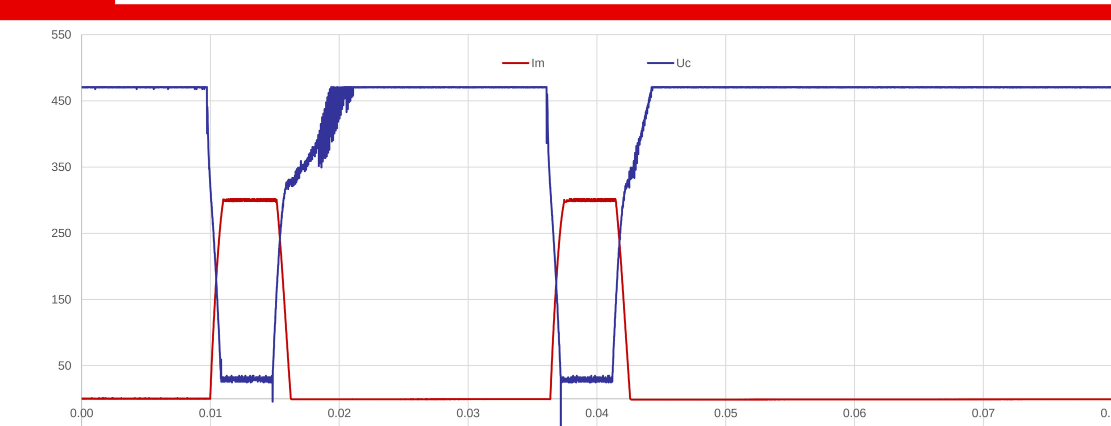

Fig. 5(a) Experiment result

In rising stage, the $C_1$ of the structure 1 discharge the magnet, providing a steep rising edge. The magnet current boost to 300A in 1.5ms. In flat-top stage, the battery of the structure 2 provide a 36V voltage to provide a steady current for 4ms and the structure 3 operate to provide magnet the shortage of the voltage. In feedback stage the current falls rapidly and feeds back to the capacitor. In cooling stage the outer circuit charges the capacitor back to the setting voltage.

**Conclusion** In this paper, a new three-structure topology has been proposed to generate RFPHMF. All of the three structure can work properly at their stage to generate high discharging current, to stabilize the flat-top, and to realize the energy feedback. The experiment result shows this topology is feasible.

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