Design and Testing of Quench Protection System for ITER Magnet Cold Test Bench

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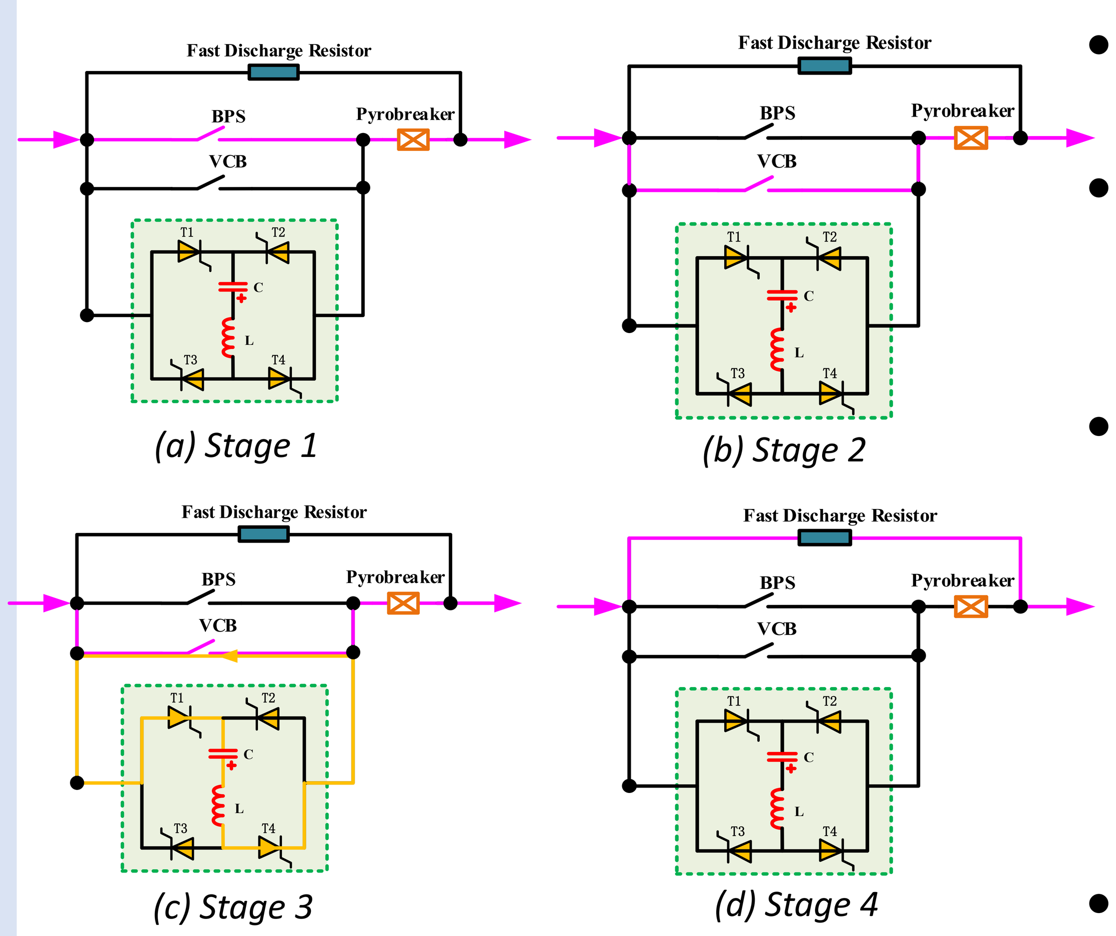
ABSTRACT

The paper focuses on the design and optimization of the QPS to meet the 70 kA/4.1 kV parameter requirements. Specifically, it proposes a permanent magnet bistable actuator to enhance the response performance of the mechanical bypass switch (BPS), designs an electromagnetic repulsion mechanism to improve the switching speed of the vacuum circuit breaker (VCB), optimizes parameters in the auxiliary oscillation zero-crossing loop, and introduces a spiral pulse reactor to improve conversion efficiency and stability. Additionally, a self-disturbing arc contact structure is introduced to enhance the heat dissipation and current-carrying capacity of the pyro-breaker (PB). Finally, 72 breaking tests were conducted at 70 kA, achieving an interruption response time of ≤240 ms.

OVERVIEW OF QPS MECHANISM



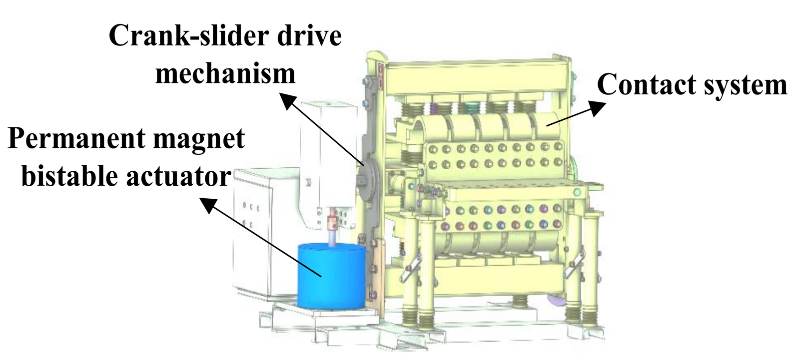
The current transfer diagram when the QPS operates

- *Stage 1: During normal operation, both the BPS and VCB are closed, the system load current primarily flows through the BPS branch.*
- *Stage 2: When a quench is detected, the BPS opens and generates an arc. Under the arc voltage, the current in the BPS branch rapidly decreases and is fully transferred to the VCB branch.*
- *Stage 3: Once the BPS has regained sufficient voltage-blocking capability, it begins to interrupt the VCB. At the same time, the thyristors are triggered into conduction. The pre-charged discharge capacitor releases energy through the inductor into the VCB branch, generating an artificial current zero, which forces the VCB current to decrease rapidly until it reaches zero, at which point the VCB is fully disconnected.*
- *Stage 4: The current is completely transferred to the FDR, which dissipates the magnet energy in the form of heat, thereby protecting the magnet.*

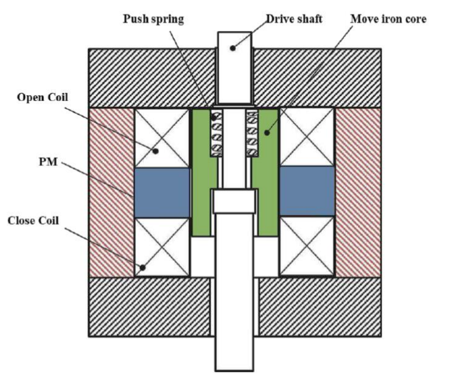
DESIGN AND SIMULATION OF QPS

- ***Design and analysis of key components of BPS***

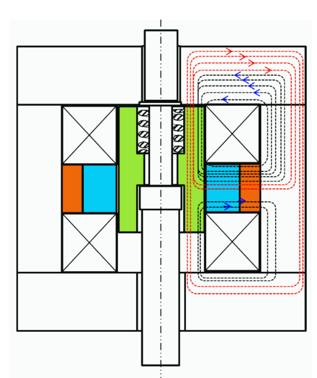
The BPS is mainly composed of the contact system, permanent magnet bistable actuator, and crank-slider drive mechanism. Through the collaborative action of these components, the BPS meets the high-speed breaking requirements while ensuring compact structure and operational reliability.



The structural diagram of the BPS

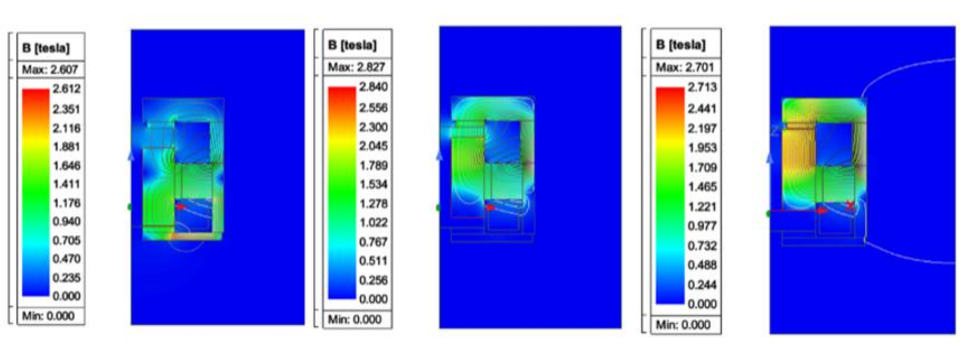


The structure of the permanent magnet bistable actuator

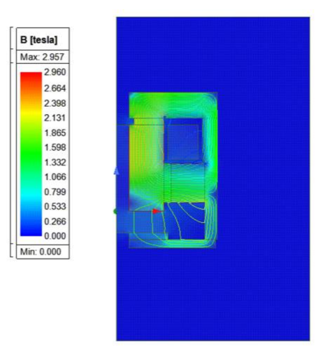


Magnetic flux distribution of the permanent magnet actuator

A 3D model of the permanent magnet bistable actuator is created using Ansys/Maxwell.

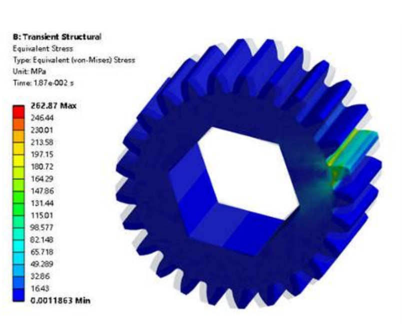


The closing operation of the permanent magnet actuator

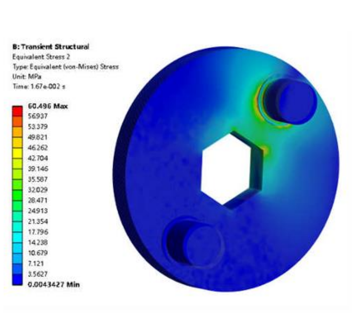


The opening operation of the permanent magnet actuator

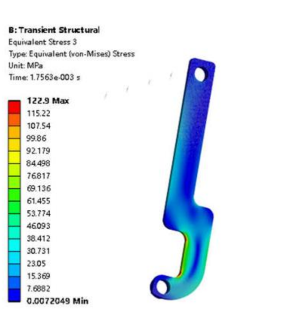
The analysis indicates that the strength of the key components meets the allowable stress requirements, and the safety factor is greater than or equal to 1.3, ensuring their reliability and safety under actual working conditions.



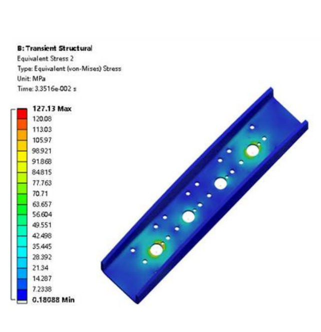
Von Mises stress of the gear



Von Mises stress of the turntable



Von mises stress of the connecting rods

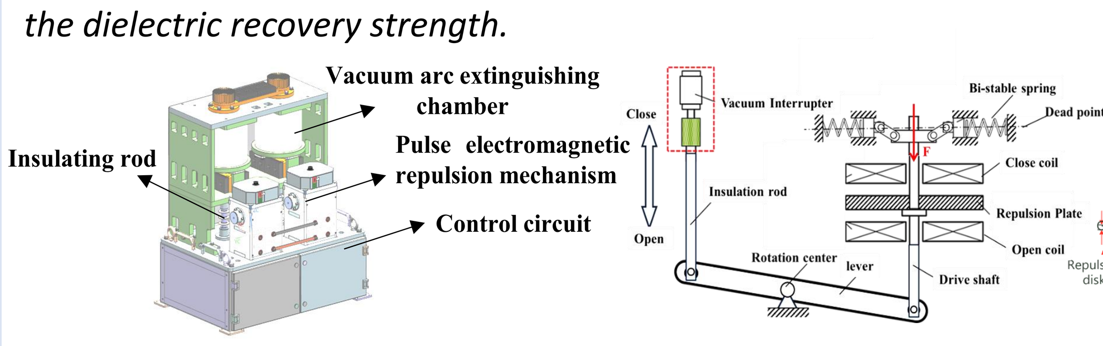


The mises stress of the beam

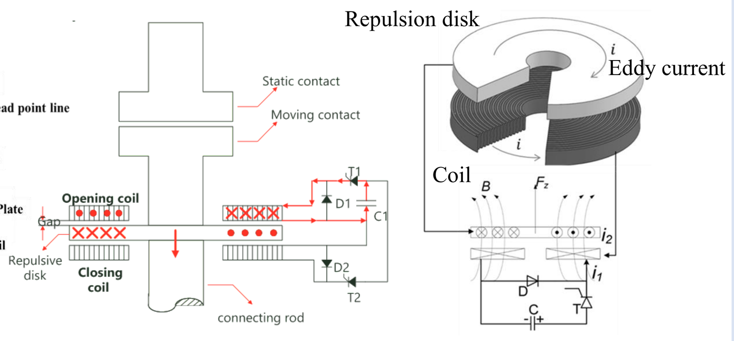
DESIGN AND SIMULATION OF QPS

- ***Design and analysis of key components of VCB***

The VCB structure design mainly consists of the vacuum arc extinguishing chamber, pulse electromagnetic repulsion mechanism, insulating rod, and control circuit. The VCB adopts a double-break structure to enhance the dielectric recovery strength.

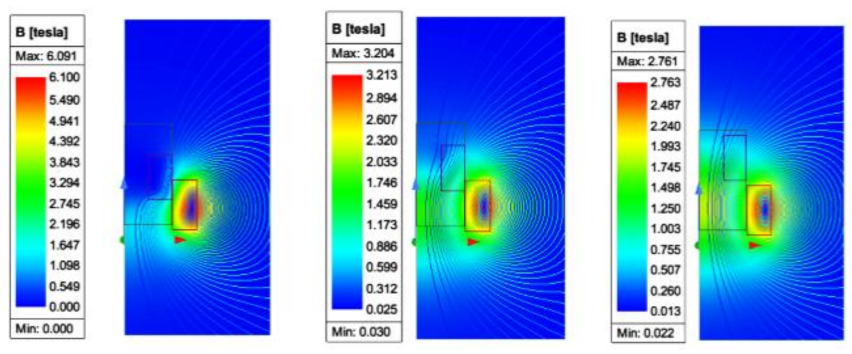


The structure diagram of VCB



Schematic diagram of electromagnetic repulsion mechanism

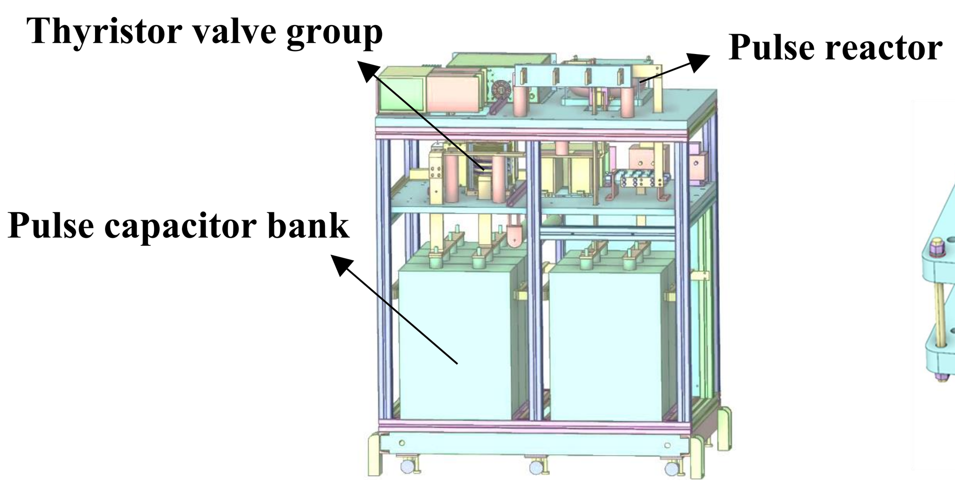
A simulation of the closing operation of the repulsion mechanism has been conducted.



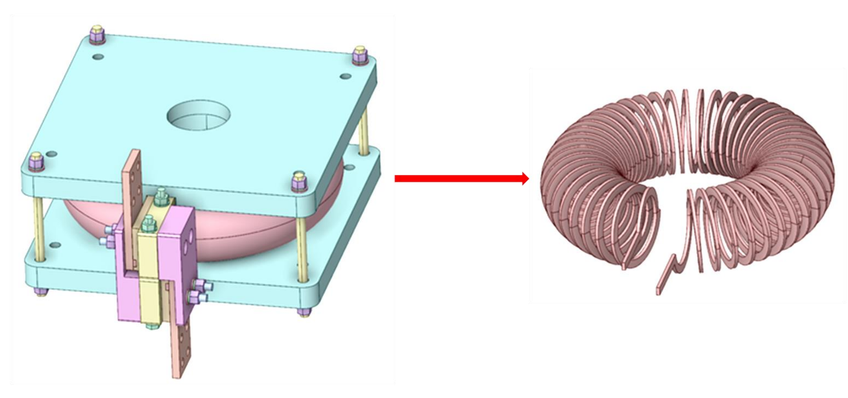
Repulsive mechanism opening simulation

- ***Design and analysis of key components of auxiliary oscillation zero-crossing***

The auxiliary oscillation zero-crossing cabinet structure design is shown in FIG.16. It mainly consists of the pulse capacitor bank, pulse reactor, and thyristor valve group. This circuit utilizes oscillation in the loop to generate a pulse current, which forces the VCB current to decrease, providing an artificial zero-crossing point for the VCB.

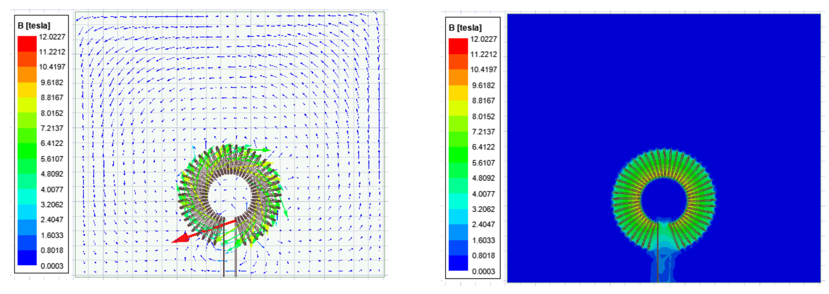


The structure diagram of auxiliary oscillation zero-crossing cabinet

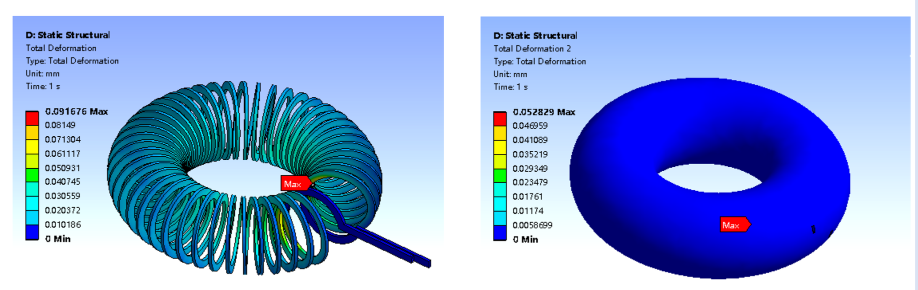


The structure diagram of helical pulse reactor pulse reactor

The maximum magnetic flux density reaching 12.0227 T, meeting the operational requirements under high current pulses. The maximum deformation of the coil is 0.092 mm, and the maximum deformation of the epoxy support components is 0.053 mm,



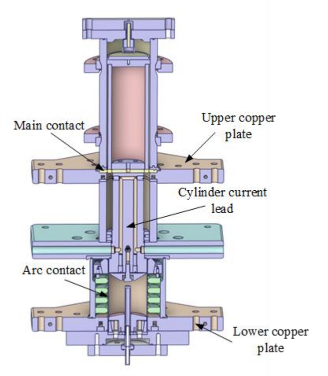
The magnetic flux density distribution of the pulse reactor



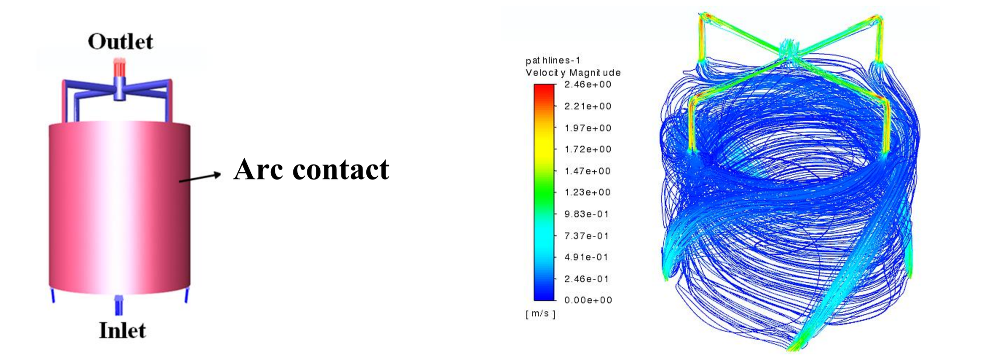
The deformation distribution of the pulse reactor

- ***Design and analysis of key components of PB***

The conductor parts consist of main contact, arc contact, upper copper plate, lower copper plate and cylinder current lead. Weaknesses exist in the main contact and arc contact. The PB is connected in series in the main loop of QPS.



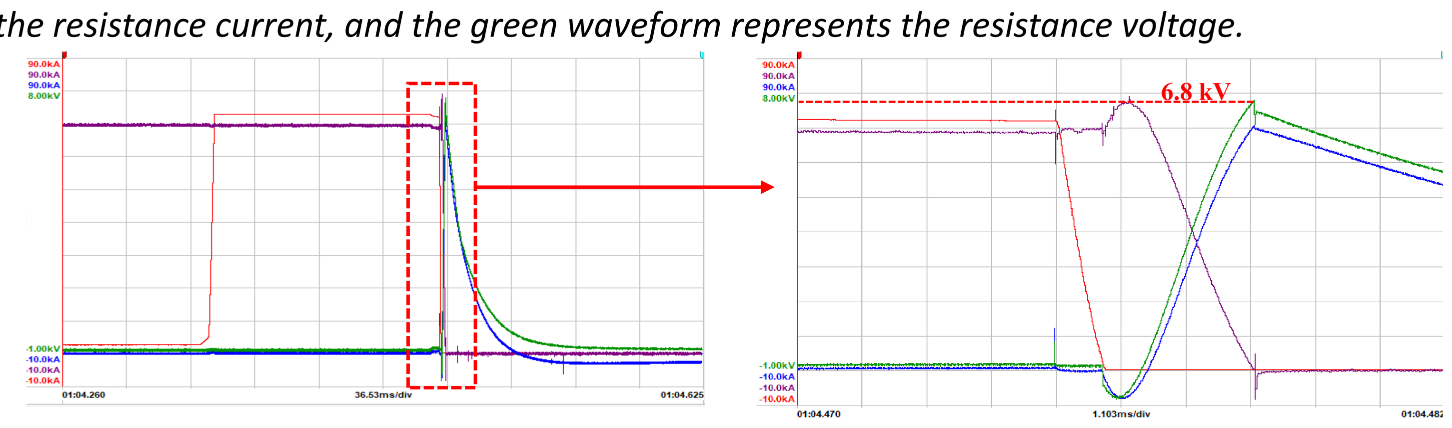
The structure diagram of PB



Schematic diagram of arc contact self-disturbing current

RELIABILITY TEST OF QPS

The QPS was tested through 72 circuit breaker interruption experiments under a 70kA. In the experiments, the red waveform represents the VCB current, the purple waveform represents the total current, the blue waveform represents the resistance current, and the green waveform represents the resistance voltage.



Interruption test waveform

CONCLUSION

Under 70 kA DC conditions, the system is able to achieve a fast interruption of ≤240 ms, validating the high efficiency and stability of the designed scheme under high current conditions, fully meeting requirements of MCTB for fast protection and safe operation.