A Novel 6.5kV Reverse Asymmetric Bypass Thyristor (RAByT) for VSC HVDC Systems

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Abstract

Modern MMC VSC HVDC systems increasingly employ 6.5 kV trench-gate IGBT modules. These systems incorporate a dedicated **bypass thyristor** connected across the antiparallel fast recovery diode (FRD) to provide **resettable protection against DC ground surge current faults**. At voltage ratings of 6.5 kV, standard thyristor designs use relatively thick silicon, leading to high on-state dynamic forward voltage, thus limiting their protection capability in this application. This poster presents a 6.5 kV reverse asymmetric bypass thyristor (RAByT), designed with an N-buffer diffusion located on the cathode side of the device enabling the use of significantly thinner silicon, **improving the dynamic forward voltage drop.** Furthermore, an optimised interdigitated gate-arm structure gives a **low anode pick-up voltage**, providing further enhanced protection. Finally, the high-resistivity N-base design **improves the device's reliability (cosmic ray FIT rating)**, making the RAByT an even more robust protection solution.

Application

- **6.5 kV MMC VSC HVDC systems:** operate at several hundred kV (e.g., offshore windfarms).
- **Half-bridge converter modules:** employ IGBT/FRD modules and a **bypass thyristor Figure 1**.
- **Bypass thyristor:** resettable protection against DC side faults, diverting away the DC side fault currents which is far beyond FRD capacity **Figure 2**.
- **Elevated fault current levels:** bypass thyristors with higher surge current ratings.

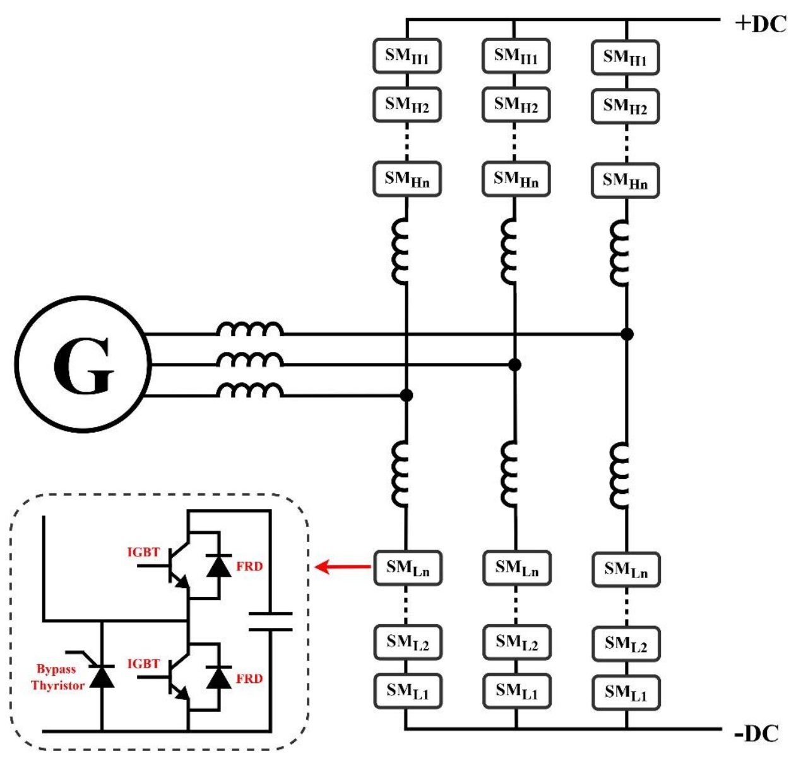


Figure 1. Schematic of a VSC-based MMC with half-bridge submodule.

Figure 2. Press Pack Reverse Asymmetric Bypass Thyristor (RAByT).

Reverse Asymmetric Bypass Thyristor Design

A. Challenge to overcome

When designing a high-power thyristors, often the optimisation for a specific rating is to the detriment of others. To achieve 6.5kV blocking capability required in the application relatively thick Si have to be used which results in an increase of the on-state dynamic forward voltage drop and hence puts more stress on the FRD diode during ground fault events.

B. Reverse asymmetric configuration

By incorporating an asymmetric PN junction configuration with a novel N+ buffer on the cathode side of the thyristor as seen in **Figure 3**. the overall thickness of the device can be reduced and consequently **reducing the dynamic forward voltage drop** as seen in **Figure 2.** compared to standard thyristor junction configuration.

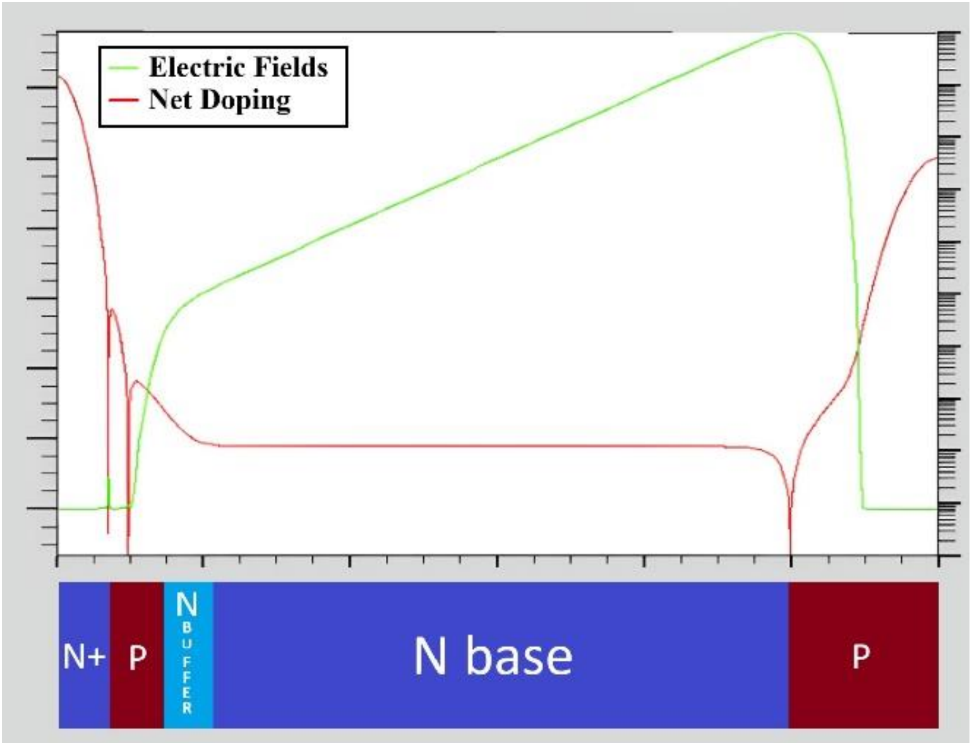


Figure 3. SRP and electric fields of RAByT device when reverse biased at full rating voltage.

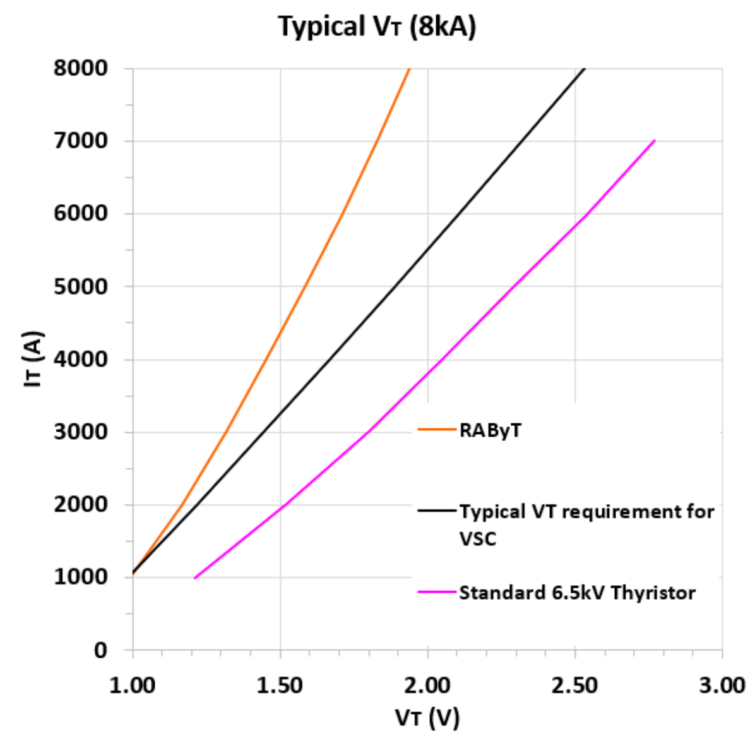


Figure 4. On-state voltage (VT) versus current.

C. Off-state junction termination optimization and gate design optimisation

A double positive bevel, as shown in **Figure 5(b),** was used which significantly reduce surface electric fields with maximum field equal to bulk allowing to use the full potential of the silicon and not having localised centres of maximum electric fields. This optimises the reduction in silicon thickness and forward voltage drop. Furthermore, T-CAD simulations were used (**Figure 9(a)**) to optimize the gate pattern as shown in **Figure 5(c).** The shortened gate arms showed **significant reduction in pick-up voltage (Vpu).**

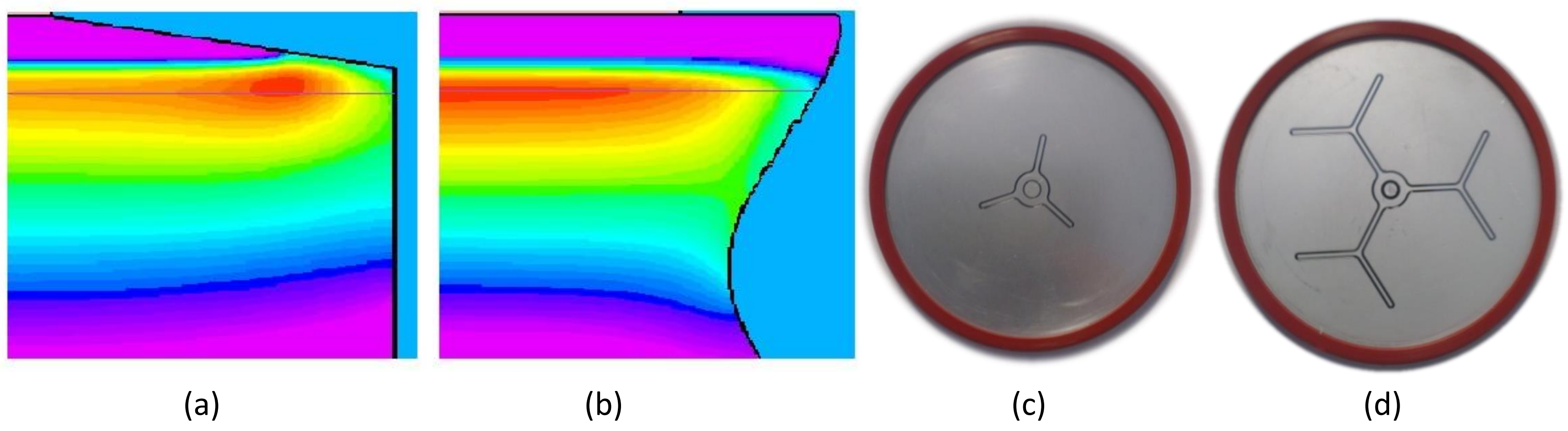

(a) (b) (c) (d)

Figure 5. (a) TCAD visualisation of the electric field characteristics during blocking for negative bevel junction termination (b) Positive bevel junction termination (c) Gate patter RAByT (d) Gate pattern standard thyristor.

D. Increased N-base resistivity to reduce Cosmic ray-induced failures (FIT)

In the VSC HVDC systems, the bypass thyristor will be subject to DC operating conditions for its entire service life making it vulnerable to cosmic ray-induced failures. A well-known approach to mitigate this issue is to increase the resistivity of the N-base silicon. The RAByT's buffer diffusion profile enables the use of higher-resistivity and thinner silicon without the associated penalty in forward voltage drop, thereby **significantly improving cosmic ray 'Failure in Time' (FIT) ratings** while maintaining efficient conduction performance.

Manufacturing Challenges

From a manufacturing perspective, achieving the desired buffer dopant profile is limited to a narrow phosphorous implant dose window (**Figure 7)** followed by a long diffusion drive to achieve the required depth. This limited process window requires the use of implantation equipment (**Figure 6**) instead of traditional tube liquid/gaseous deposition techniques.

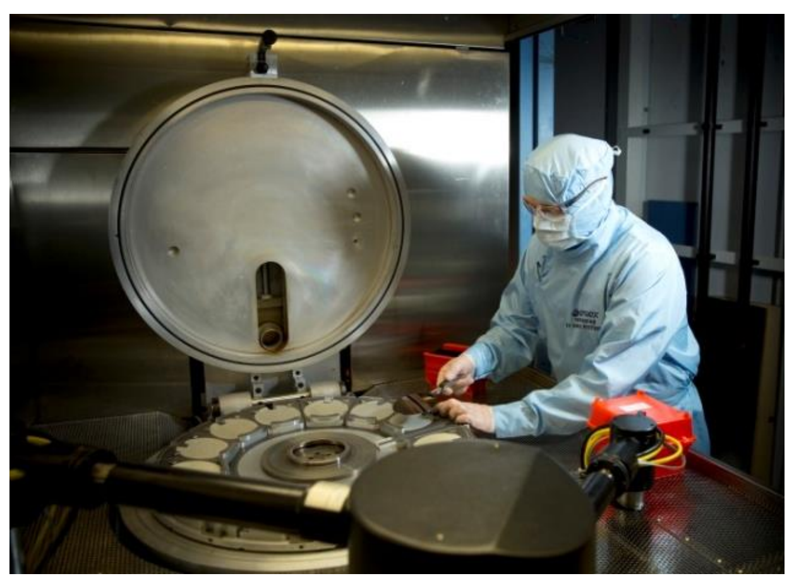


Figure 6. Phosphorus implanter.

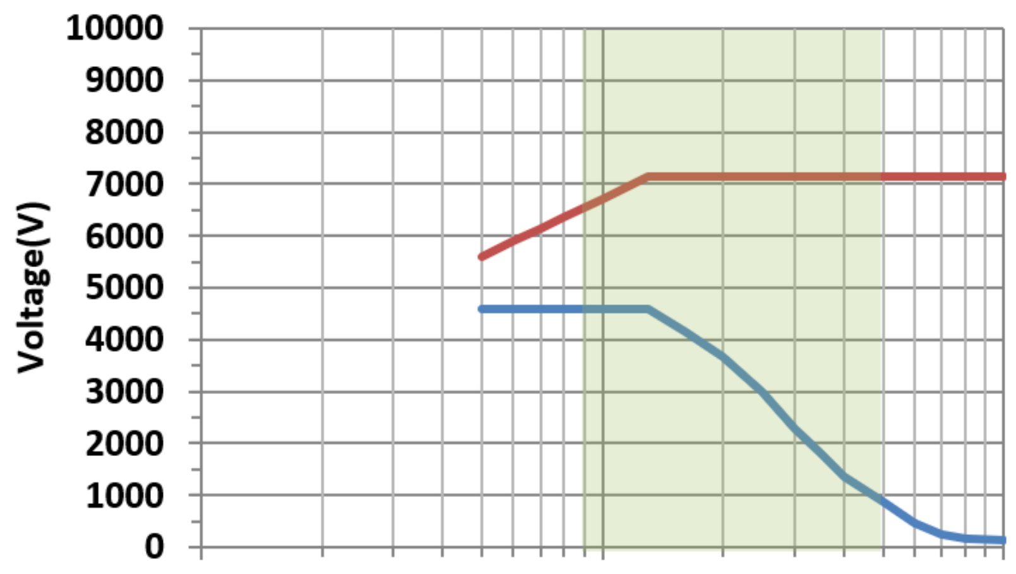


Figure 7. Reverse(red) and forward(blue) avalanche blocking voltage for a of N+ buffer concentrations.

Electrical Characterisation

Prototypes have been manufactured and electrically tested. Avalanche blocking voltages are shown in **Table 1**. The results align well with TCAD simulation within the phosphorus implant window **(Figure 7)**. All measurements were conducted at room temperature.

Table 1. RAByT Avalanche Blocking Voltage

Device	Forward blocking voltage (Vd)	Reverse blocking voltage (Vr)
RAByT	2.1 kV	7.2kV

The device was clamped using the recommended clamping force of 50 kN and tested using the laboratory set-up shown in **Figure 8.** The results are presented in **Table 2.** Compared to a standard 6.5 kV thyristor of similar diameter, the RAByT samples exhibit a significantly lower pick-up voltage. The results matched the T-CAD simulations shown in **Figure 9(a).**

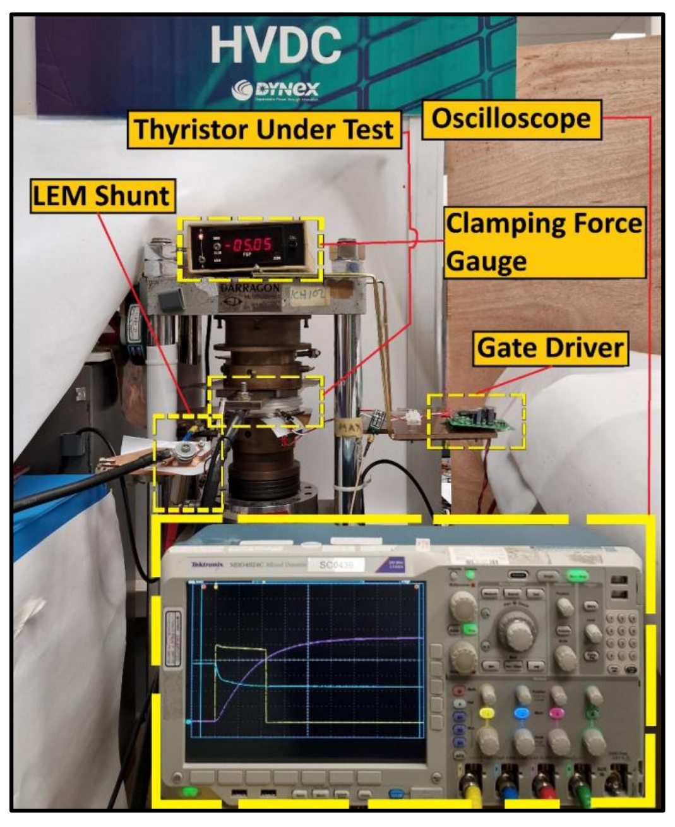


Figure 8. Pick-up voltage test set-up.

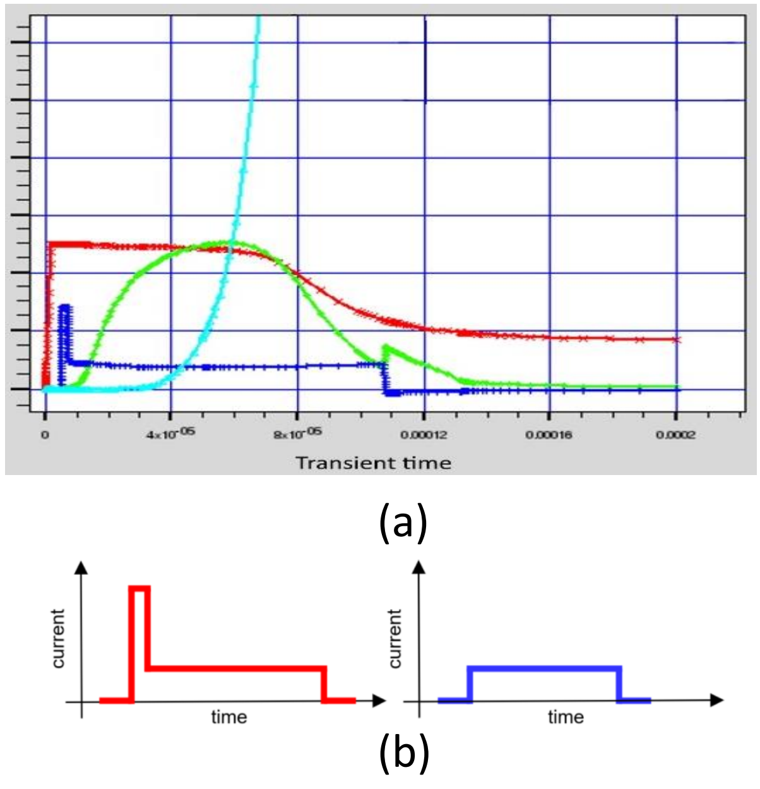


Figure 9. (a) TCAD simulation of RAByT triggering (b) Gate pulses.

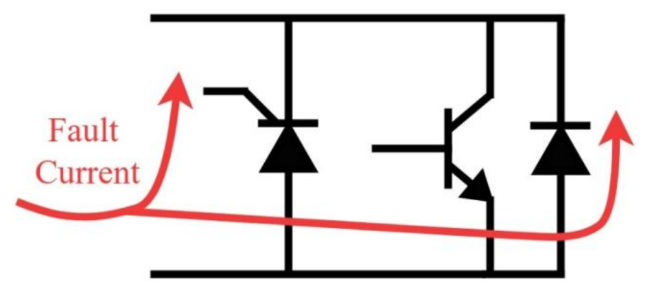
Table 2. Pick up voltage results

Device	Pick-up voltage for gate pulse in Fig. 9(b) RED	Pick-up voltage for gate pulse in Fig. 9(b) BLUE
Standard Thyristor	4.6V	9.6V
RAByT	1.5V	2.3V

RAByT Performance In The Application

Simulation Setup & Devices

- Simplified MMC sub-cell model simulated in PLECS (**Figure 10**).
- Fault current response shown in **Figure 11**.
- Bypass thyristors paired with IGBT module diode (FRDs).
- When the fault current is diagnosed, the bypass thyristor turns on.
- IGBT module: DIM750ASM65-TL000 (750 A, 6.5 kV).
- Standard thyristor: DCR2950W65.
- RAByT thyristor: ACR4000WR65 (similar footprint to DCR2950W65) **Figure 10.**
- Junction temperature: Tj = 125 °C.



Comparative Results

- **Figures 12(a)–(c)**: Both devices divert fault current, but the RAByT reduces FRD peak current significantly.
- **Figure 13**: Average I²t through the FRD is much lower with RAByT. This demonstrates substantial reduction in current stress on the IGBT FRD.

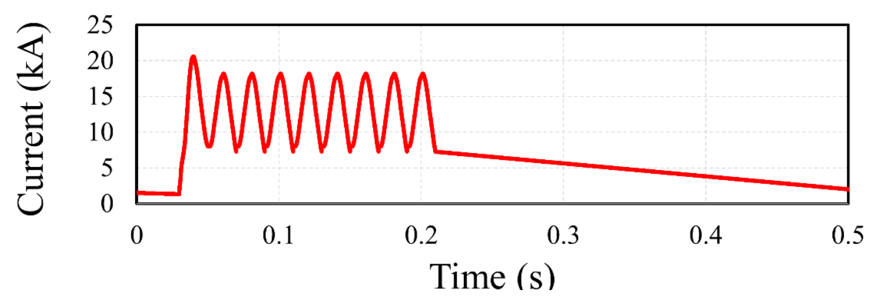
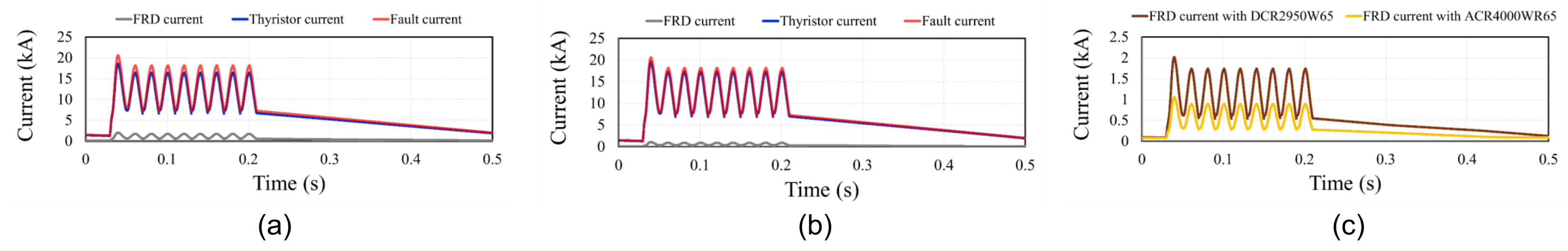


Figure 11.



(a) (b) (c)

Figure 12. (a) a standard thyristor and (b) a RAByT thyristor, and (c) FRD current comparison using either a standard or RAByT thyristor.

Key Advantages

- RAByT thyristor provides superior fault current bypassing capability, reducing stress on FRD in VSC HVDC applications.

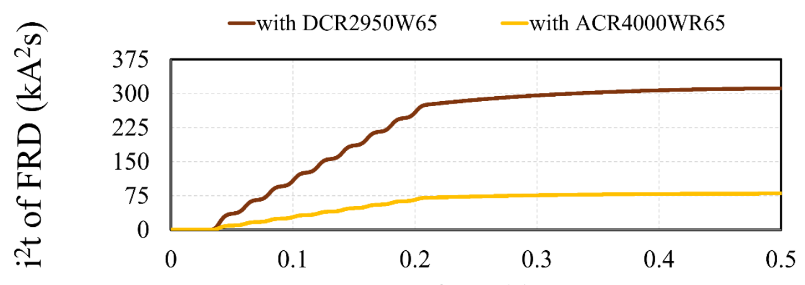


Figure 13.

Conclusion

The novel thyristor configuration explicitly designed as a protective, non-sacrificial bypass solution for MMC VSC HVDC applications. The proposed configuration incorporates an N+ buffer and optimised gate design, delivering significant performance advantages, including high surge current capability, low pick-up voltage, low cosmic ray FIT rating, and reduced on-state voltage. Extensive electrical testing conducted on the built samples has confirmed the effective performance of the proposed RAByT thyristor.

References
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