SWITCHING NETWORK UNITS FOR HIGH CURRENTS AND VOLTAGES FOR PLASMA APPLICATIONS

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Abstract

OCEM and ENEA gained a wide experience in the design and experimental characterization of fast and accurate switching systems for high DC currents, as required to control magnets and superconductors. The exploited idea consists in inserting an electronic switch in parallel to a fast electromechanical switch in air, to combine the benefits of both devices. The electronic switch is turned on and off to support the electromechanical commutations, reducing the jitter to tens microseconds and limiting the arcs that would reduce the system lifetime. During the performed tests, DC currents up to 20 kA were diverted in less than 100 µs with good repeatability. In case of emergency, the current can be interrupted in few tens of milliseconds. If necessary, a resistor can be inserted in parallel to the switch to dissipate the energy trapped in inductive loads or to produce desired overvoltages (a voltage up to 5 kV was reached in this configuration). Specific circuits were designed to preserve the components from transient voltage overshoots. This switching system is expected to work for 10000 operations without major maintenance. The developed solutions may be extended to many relevant applications as particle accelerators and HVDC networks.

INTRODUCTION

The poloidal field (PF) coils, as the central solenoid (CS), of a new Tokamak generally consist of a number of superconducting coils, each connected to a dedicated power supply (PS) circuit. To initiate the plasma breakdown, an abrupt current derivative shall be produced almost simultaneously in all the PF coils, to produce an adequate voltage transient across them [1], [2]. As the power and voltage ratings of the PSs are limited, to about 20÷30 MVA and ±1 kV dc, a Switching Network Unit (SNU) is put in series to each of the poloidal circuits. An interruption nominal voltage up to 5 kV, a DC current up to 20 kA and an opening/closing time lower than 1 ms are required. The simultaneous opening of the SNUs shall be synchronized within 0.5 ms. The coil inductance is normally very high (up to tens of mH), so the current must be diverted into resistor banks R1 (the R1 resistance value can be pre-adjusted by selectors, in order to match the maximum current to be interrupted). After plasma breakdown and current ramp-up, the SNU hybrid switch shall be reclosed and from this time on the PSs will control the current in the circuit. The basic circuit diagram of Hybrid Switching Unit is reported in Fig. 1.

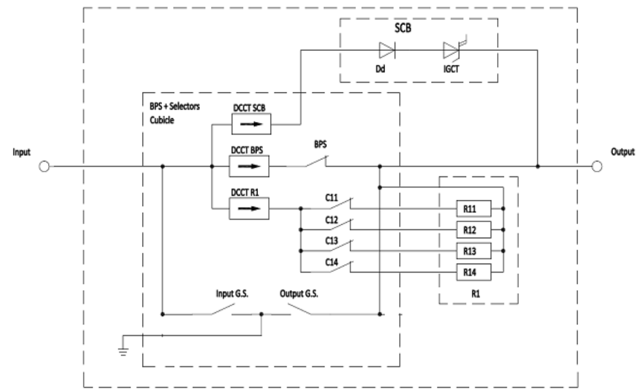

Figure 1: Functional Scheme of the hybrid SNU.

CHARACTERISTICS AND OPERATION OF THE HYBRID SWITCHING CIRCUIT

Operation and Ratings of the Switching Network Unit

Table 1 reports the main SNU parameters, whose detailed power circuit diagram is reported in Fig. 2. The opening and re-closing of the hybrid switch (hereafter referred to as SS) can be repeated every thirty minutes, generally for about ten hours per day; the SS structure improves and adapts the use of a solid state Static Circuit Breaker (SCB), in parallel with the main electromechanical By-Pass Switch (BPS). The use of a hybrid circuit breaker for DC applications is in principle not new and has been proposed and developed in the past for some Tokamak and Naval applications [3], [4].

When applied to Tokamaks, the reasons of the hybrid configuration come from the specific working cycle: the central solenoid current is ramped up for a maximum of 60 s and then, at a predefined time, the voltage across them is abruptly reversed. So, while the mechanical BPS carries the current for most of the operational time, the SCB “masks” the inadequate velocity and repeatability of the BPS in commutation, giving the hybrid switch the precision timing and velocity of solid state devices; moreover, the power dissipated in the arcing across the BPS contacts is greatly reduced and the operational life of mechanical contacts is correspondingly increased.

The Hybrid SNU detailed circuit diagram is reported in Fig. 2. It is worth pointing out that even though the Base Power Supplies are normally able of four-quadrant operation, the SCB are unidirectional devices, since they operate at the beginning of the tokamak current pulse; but

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the BPS mechanical switch is obviously bidirectional, so the SNU as a whole is also bidirectional. As said before, during the current ramp-up, the BPS is closed and the current flows through it only. When the plasma breakdown is required, the hybrid switch is opened. The sequence is reported in Fig. 3.

Table 1. SNU Main Operational Parameters

Description	Value
Nominal Current	± 20 kA
SS Maximum conducting Current	± 23 kA
SS Maximum Interrupting Current	20 kA
Maximum Pulse Length	250 s
Minimum repetition time	1800 s
Current Interruption	Unidirectional
Rated Voltage	5 kV
Reference highest voltage for equipment (IEC 60071)	7.2 kV
SS maximum switch-on/off time	≤ 1.0 ms
SS operation accuracy/repeatability	≤ 1.0 ms
Accuracy of each breakdown resistor (at 20 °C)	±2%
Maximum variation of resistors with temperature	±10%
Number of operations without maintenance (excluding sacrificial contacts)	10000

The SCB is activated, but the current still flows in the BPS, until the mechanical contacts begin to open. Across the opening contacts, an electrical arc develops and this voltage forces the current into the activated SCB; correspondingly, the conduction voltage across the SCB (a few volts) limits the arcing voltage to some tens of volts and greatly reduces the corresponding dissipated power in the contacts.

After a time margin ensuring the completion of the current transfer and the de-ionization of the air across the BPS contacts, the SCB can be opened, producing across the resistors R1 the high voltage necessary to ignite the plasma breakdown (from a minimum of 4.4 kV to a max of 5.5 kV).

The energy ratings of resistor R1 have been designed in order to match the insertion time of about 300 ms. When the SS hybrid switch must be closed again: first the SCB is turned on and most current returns to flow through it; then the BPS contacts close, while the voltage across its closing contacts has come down to a few volts and the arc, if any, sets in when the contacts are so close that duration and energy are negligible.

IMPLEMENTATION AND TESTS RESULTS

In order to test the SCB design in the most critical conditions, concerning specifically the steady state current balance and the behavior of the devices at turn-off, two SCB modules (S/N 001 and S/N 002) were first assembled. The IGCTs and the associated decoupling diodes Dd were selected in order to obtain the worst possible situation concerning voltage drop in conduction and turn-on /turn-off delay times.

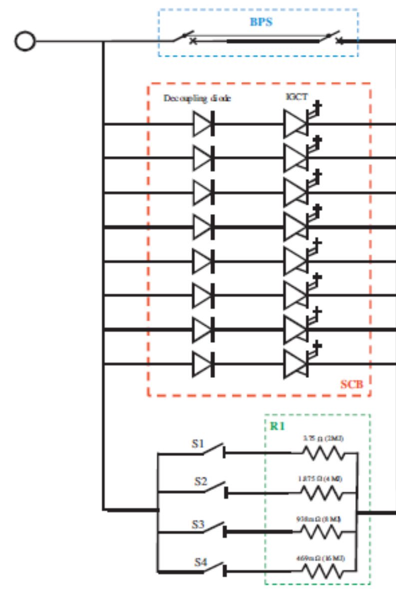

Figure 2: Functional Scheme of the hybrid SNU with emphasis on the main semiconductor components [5].

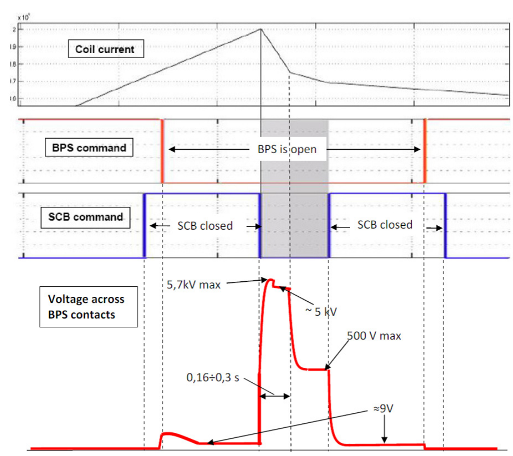

Figure 3: Operational sequence of the SS hybrid Switch, with the expected current and voltage across it.

The test circuit used a capacitor bank of 1.2 mF, which is discharged through a 70 µH inductor into the two SCB modules in parallel; the starting voltage of the capacitor bank was adjusted to achieve the desired peak current at turn-off of 4200 A. The test was first simulated using a PSIM model, which took all the circuit elements into account, including the stray inductances (Fig. 4); the waveforms resulting from the test are in very good agreement with them (Fig. 5).

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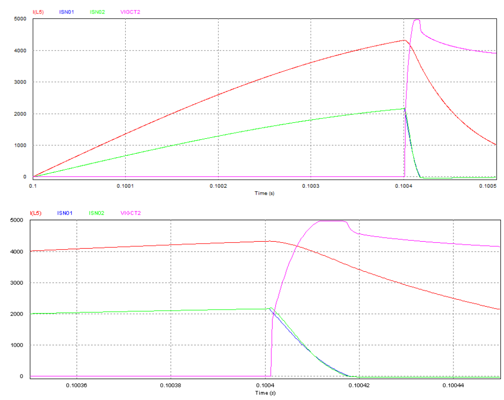

Figure 4: Simulation results of the parallel testing of the two SCB modules. Time scales: 0.1 ms /div (upper) and 20 µs/div (lower).

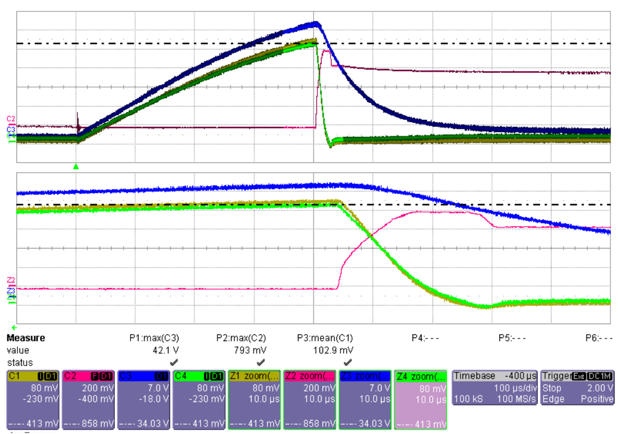

Figure 5: Test results of module 001 and 002 in par.: blue trace=total current: 700 A/div; yellow trace (S/N002), green trace (S/N001) = module current, 400 A/div; red trace = IGCT Voltage 1.25 kV/div.Time scale:0.1 ms/div and 10 µs/div [6].

The complete hybrid SNU was then built and tested. The most relevant tests were performed by inserting a complete single SNU in a PS circuit of the ENEA Frascati Tokamak Upgrade (FTU). The total inductance of this circuit is about 80 mH, and the test scenarios were adapted to perform the BPS closure at significant currents.

Fig. 6 summarizes the experimental characterizations of the BPS opening, showing the SNU voltage curves when the whole current is diverted to R1 for the two extreme cases producing 5 kV at the breakdown: the maximum nominal current 20 kA (for R1=250 mΩ) and 1333 A (for R1=3.75 Ω). At 20 kA, the measured SNU opening time was about 80 µs. Since the specific snubbers were introduced to shape the voltage derivative and the transient overshoots. Due to these snubbers, the opening is slower at lower currents. Then, the maximum possible opening time is slightly higher than that observed at 1333 A (≈700 µs), since the snubber effect is negligible at lower currents and voltages.

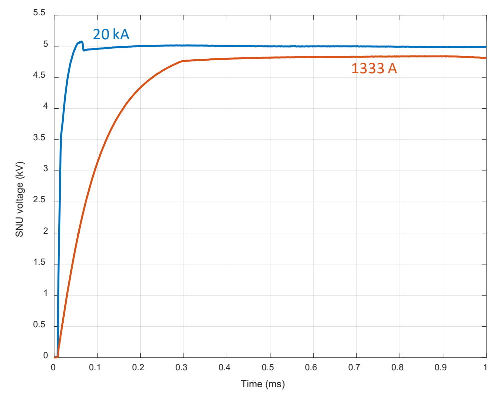

Figure 6: Voltage measured at the SCB opening during two full voltage tests (20 kA with R1=250 mΩ and 1333 A for R1≈3.75, respectively).

CONCLUSIONS AND PERSPECTIVES

A high power DC hybrid circuit breaker, capable of 20 kA for 5 minutes and able to commutate in less than 1 ms with extremely precise repeatability and low maintenance (in spite of the required 20 cycles per day) has been designed, built and tested. The overall footprint is 7.3 m x 4.2 m (excluding the local control cubicle). Four identical SNUs were then built and are now being installed.

Although designed and produced for a tokamak, possible applications include medium voltage DC networks (either naval or land based). The possibility to put several solid-state devices in series or even several static circuit breakers in series make the extension to higher DC voltages viable.

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