-1 MV DC UHV Power Supply for ITER NBI

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Abstract. Japan Atomic Energy Agency as the JApan Domestic Agency (JADA) for ITER and the Domestic Agency of EU (EUDA) agreed the procurement sharing for the ITER NBI power supply system. The JADA contributes procurement of dc -1 MV ultra-high voltage (UHV) components such as a -1 MV dc generator, a transmission line and a -1 MV insulating transformer. The dc UHV insulation has been carefully analyzed since dc long pulse insulation is quite different from conventional ac insulation. Voltage sharing varies from capacitive distribution to resistive one during long pulse dc application. Electric field distribution for multi-layer (oil/paper composites) insulation structure of the transformer has been investigated for a long pulse dc up to 3600 s. The insulation structure has been designed and the overall dimensions of the dc UHV components have been finalized. A surge energy suppression system is also essential to protect the accelerator from electric breakdowns. The JADA contributes to provide an effective surge suppression system composed of core snubbers and resistors. Input energy into the accelerator from the power supply can be reduced to about 20 J which satisfies the design criteria of the total 50 J at -1 MV breakdown. From these studies, major technical issues were considered and the functional technical specifications of the UHV components have been developed for the procurement by the JADA.

1. Introduction

A dc -1 MV ultra high voltage (UHV) power supply system is required for the ITER neutral beam injector (NBI) to accelerate negative ion beams up to the energy of 1 MeV with the beam current of 40 A [1]. The required voltage of -1 MV is twice higher than that of the existing JT-60U N-NBI system [2]. A pulse length of 3600 s for the ITER NBI is two orders of magnitude longer than that of the JT-60U N-NBI. JAEA (Japan Atomic Energy Agency as the Japan Domestic Agency (JADA) for ITER) and the EUDA have basically agreed the procurement sharing for the ITER NBI power supply system. Contribution by the JADA is to supply UHV components of the power supply system, namely they are a dc -1 MV generator (DCG) which consists of step-up transformers with rectifier diodes, a dc filter capacitor, a transmission line and a -1 MV insulating transformer for the ion source power supply which is one of the components shared by the EUDA. A major concern of such UHV, high power and long pulse power supply components is in reliable insulation of the dc -1 MV. Especially the dc insulation in the transformers for the DCG and the insulating transformer is one of essential subjects to realize the system.

Even the electric breakdowns in the accelerator are unavoidable phenomena in the NBI system, continuous beam injection is strongly required for heating and current drive of the ITER plasma. Therefore a high speed switching function which can cutoff the short circuit current and reapply the high voltage to continue the beam acceleration is a key issue in the

NBI power supply. The inverter controlled power supply has been adopted for the beam acceleration power supply system to satisfy the high speed switching. A frequency of the inverter and major circuit constants of the DCG have been designed and adopted to meet the requirements. As well as the high speed switching, surge suppression is essential to obtain stable beam acceleration with protecting the accelerator from the electric energy dissipation due to breakdowns [3]. Distribution of the core snubbers and installation of an additional series resistor to suppress surge energy into the accelerator have been designed.

In the present paper, detailed design for the UHV components and the surge suppression system are reported as part of the JADA contribution.

2. Design of the dc UHV Components

2.1. Outline of the ITER NBI Power Supply

The required specification of the ITER NBI power supply is shown in TABLE I. Figure 1 shows a schematic diagram of the power supply system with indication of sharing by the JADA and the EUDA. The power supply system consists of the -1 MV power supply for the accelerator (AGPS: acceleration grid power supply) and power supplies for the ion source (ISEPS: ion source and extraction power supply). Based on the experience of the 500 kV power supply development for the JT-60U N-NBI [2], the similar concept using a high frequency inverter system at the low voltage ac primary side has been adopted for the AGPS [3,4]. This circuit configuration can eliminate a dc -1 MV switch which is difficult to realize. The dc UHV output voltage and switching are controlled by the inverter at low voltage side. The EUDA shares the low voltage part of the AGPS including the inverter system. The inverter system controls not only the switching the dc UHV, but also regulation of the output voltage of the DCG by feedback control. Ripple specification and voltage stability depend on the inverter, however, over voltage at the load off timing cannot be controlled by the inverter regulation. Such over voltage affects the total insulation design of the power supply, so the over voltage should be suppressed as low as possible by a compromise between the inverter cut-off speed and circuit constants of the UHV components such as the filter capacitor.

TABLE I: SEPCIFICATION OF THE ITER NBI POWER SUPPLY.

Out put voltage	-200 kV ~ -1 MV
Maximum accelerated beam current	40 A for D^- beam
Voltage Ripple	< 10 % pp
Cut off time	< 300 μs
Duty	25 %
Pulse Length	< 3600 s
Maximum energy into the accelerator at breakdown	< 50 J

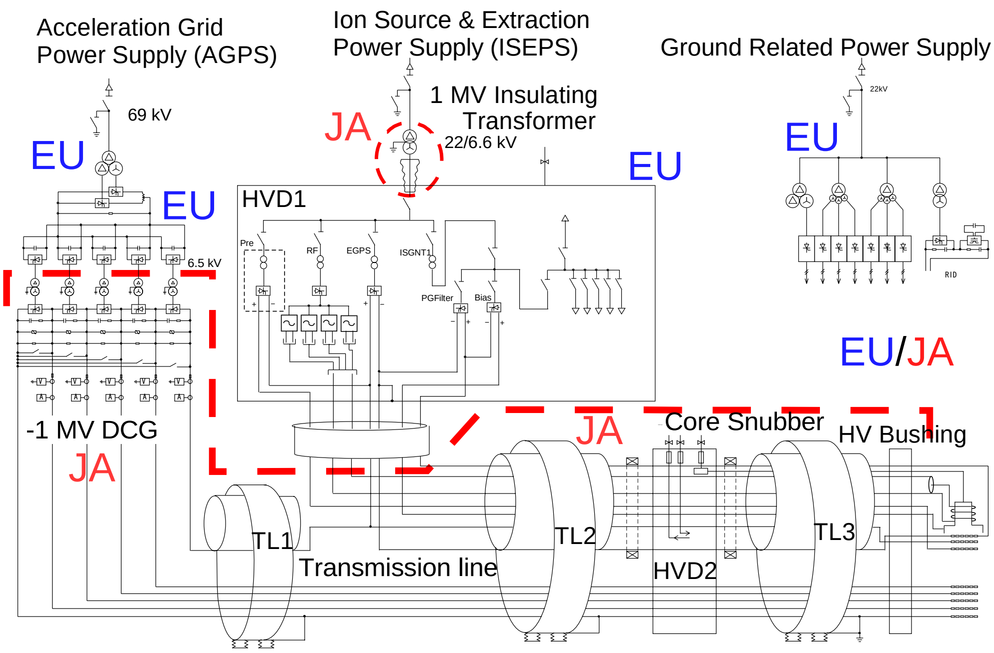


FIG. 1. ITER NBI Power supply system.

2.2. Design of Major Circuit Constants of the Acceleration Grid Power Supply

A conceptual circuit diagram of the -1 MV DCG with the converter and inverter system is shown in FIG. 2. The DCG consists of five sets of the step-up transformer and rectifier. Each 200 kV dc output is connected in series to generate the dc -1 MV for the accelerator. Each 200 kV DCG has the filter capacitor and a resistor (CR) to reduce the voltage ripple and over voltage at the load off timing when the negative ion production is stopped before the AGPS inverter cut-off the power. A capacitance value of the CR filter should be designed as small as possible, since such filter capacitors are sources of the surge energy at the breakdown. For this reason smaller capacitors are favorable for reduction of the energy input into the accelerator. However a ripple of the dc output increases by reducing the capacitor. Further the over voltage at the load off timing during the beam acceleration increases by reducing the capacitor. It is necessary to optimize the capacitors to satisfy these requirements with the inverter performance of frequency and the cut-off speed. In the design, an over voltage less than 110 % of the rated voltage was set as a design criteria with considering the system performance.

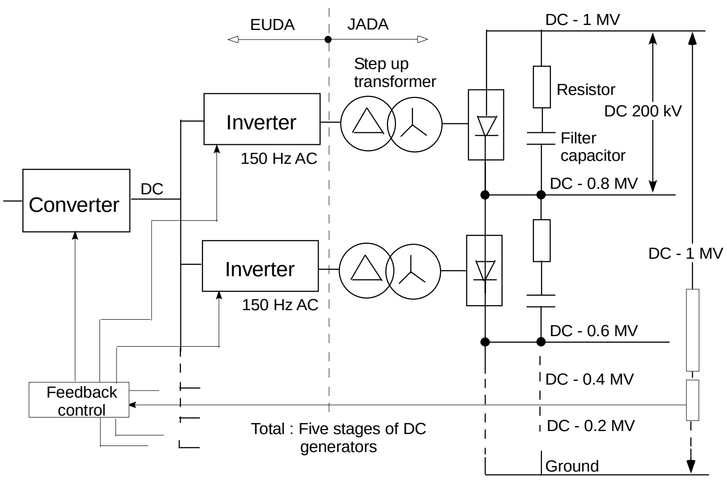


FIG. 2. -1 MV AGPS system and its control system.

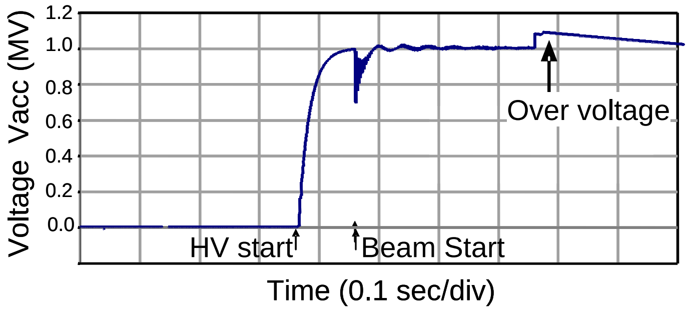


FIG. 3. Simulated waveform the AGPS output.

The circuit analysis has been conducted with using EMTDC code [5] to determine these elements constants. Figure 3 shows a typical waveform of the AGPS by the simulation. A capacitor of 0.3 μF has been selected to suppress the over voltage less than ~110 %. The voltage ripple is smaller than 1.5 %pp, so the capacitor value is high enough. It was confirmed that the frequency of the inverter does not affect the over voltage with this capacitor. This shows that an inverter frequency of 150 Hz is high enough to satisfy the specification. The JADA proposed this frequency and it was adopted into the inverter system.

2.3. -1 MV Insulation Design in the Transformers

The dc high voltage insulation is one of the most essential issues for the AGPS and an insulating transformer of the ISEPS, because dc long pulse insulation is quite different from conventional ac insulation. Voltage sharing varies from capacitive distribution to resistive one by dc long pulse application. Electric field distribution in multi-layer (oil/paper composites) insulation structure of the transformer has been studied by simulating the long pulse operation up to 3600 s. Figure 4 shows a simulation result of the time variation of relative electric field strength at the insulator in the DCG transformer. It was confirmed that the electric field varies from ac distribution to dc, and saturated after 3000 s. The insulating structure and the overall dimensions of the DCG transformer and the insulating transformer for the ISEPS have been finalized to sustain such electric field variation.

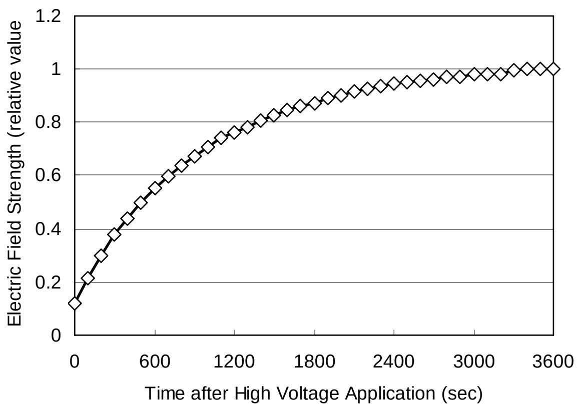


FIG. 4. Time variation of electric field strength in the insulation of transformers.

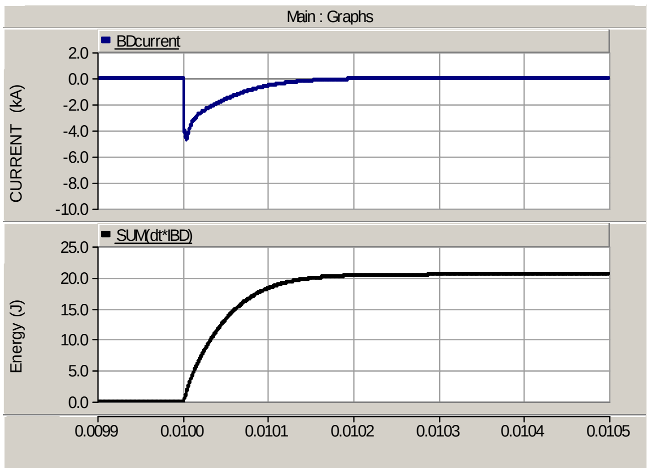
For the SF_6 gas insulated components such as the transmission line has been designed based on the data base obtained with the prototype test performed in the Engineering Design Activity phase [3]. These UHV components have been arranged in the layout of the ITER NBI system.

2.4. Protection System for the Accelerator

As well as the high speed switching, surge suppression is also essential issue to obtain stable beam acceleration. Stored energies in the stray capacitances between the high voltage parts and the ground potential of the power supply flow into the accelerator grids at the breakdown. The stored energy gives electrical damages at the breakdown in spite of the inverter system turns off the high voltage main power immediately. Because the inverter system cannot cut-off surge current from the stored energy. If the electrical damage due to the breakdown is heavy, the accelerator would not be operated due to degradation of voltage holding, i.e. continuous breakdowns. The stored energy increases proportional to the stray capacitance, and to the square of voltage. The high voltage and high power NBI power supply has a large stored energy in the system. The total stored energy was estimated to be about 43 kJ between the -1MV parts and the ground potential part including the filter capacitor.

To suppress energy input the core snubber and an additional resistor have been designed with precise circuit simulations. The simulation has been done by using equivalent circuit of the power supply including possible circuit constants for the components. The core snubbers have been arranged to absorb the stored energy in the high voltage parts in the power supply. Due to the limited space available inside the tokamak building, some of the core snubbers are arranged within the transmission line inside the tokamak building, and the other to be installed outside of the building. The magnetic flux of each core snubber is designed to be 0.3 Wb in the tokamak building and 0.7 Wb outside the building, respectively.

In addition, a resistor element of 50 Ω is directly connected to the return line at the DCG of the AGPS for fast dump of circulating current in the DCG diode after the breakdown. Figure 5 shows the results of simulation analysis for surge current and input energy into the accelerator using EMTDC code. A peak value of the breakdown surge current is 4 kA and the current is decayed within about 100 μs. An input energy was estimated to be 20 J from this current waveform with assuming an arc discharge voltage during the breakdown is constant to be 100 V. It has been confirmed by the simulation that these elements can



Time (100 μs/div)

FIG. 5. Simulated waveforms of breakdown current and input energy into the accelerator.

reduce the input energy into the accelerator less than 20 J which is lower than the design criteria of 50 J [6].

3. Summary

The major UHV components of the DCG, the insulating transformer, the transmission line and the surge suppression system which are the components shared by the JADA have been designed. The design includes the dc -1 MV insulation for the long pulse, major circuit parameters for the UHV components, and the surge suppression against the electric breakdown in the accelerator to protect the system. From these studies, functional technical specifications are ready for procurement arrangement of the UHV components in the ITER NBI power supply.

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