Snubber Circuit Optimization of the Central Solenoid Power System for Versatile Experiment Spherical Torus

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1. Introduction

For the fusion experiment, tokamak devices such as KSTAR typically use a central solenoid (CS) for ohmic discharge. Since 2012, Versatile Experiment Spherical Torus (VEST) has successfully operated the double swing circuit as the power system of the CS [1]. However, the double swing circuit is complex to operate, and there is a waste of magnetic flux in the early stages of ohmic discharge in VEST. To resolve the problems, VEST is now preparing a new power system based on a modified H-bridge circuit using an insulated gate bipolar transistors (IGBTs) [2]. The IGBTs are able to switch off with high voltage conditions, so they will be used as the switches for the proposed target circuit. The most important point about using the IGBTs is to ensure that the IGBTs are turned off safely in high current conditions, because of the high cost of the IGBTs. When the IGBTs are switched off, a transient voltage across the IGBTs induced by the parasitic inductance in the circuit can cause the IGBTs broken. Therefore, the transient voltage should be suppressed as much as possible [3].

To reduce the transient voltage, it is one method to reduce the parasitic inductance of a circuit, though the most effective way is using a snubber [4]. Among the various types of the snubber, a RC snubber is the most suitable circuit for our system, because only one switching in high current condition is necessary [5]. Since stability of the IGBTs depends greatly on the values of the RC snubber elements, the selection criteria for the snubber values is required before using the IGBTs.

In this paper, the values of the snubber elements for the target circuit are determined. In section 2, the differences between the current system and the target system are discussed. Optimization of a circuit simulation through matching the simulation results to the experiment results is given in section 3. Section 4 discusses the optimized snubber for stable operations in the target circuit using the validated simulation code.

2. Target power system

The double swing circuit in Fig. 1. (a) uses three capacitor banks and fast current ramp down is made from C1. The new target circuit is shown in Fig. 1. (b). C1 induce positive current using the IGBTs 1 and 4. When the current reaches its maximum value, these switches are switched off to make fast current ramp down. Again, a negative current is created from C2 using the IGBTs 2 and 3.

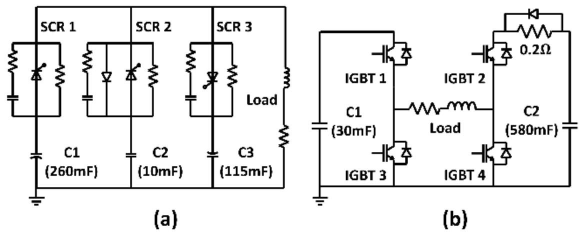

Fig. 1. Circuits of (a) the current power system and (b) the target power system.

In the Fig. 2. (a), the current of the target system rapidly declines after T_1. For this reason, the loop voltage of the target system rises very quickly to negative value. For the plasma discharge in VEST device, the loop voltage needs to be less than $-3\ \mathrm{V}\cdot\mathrm{s}$. Thus, in case of the current system, area A is completely wasted. However, in case of the target system, the fast decrease of the loop voltage will produce an immediate plasma discharge.

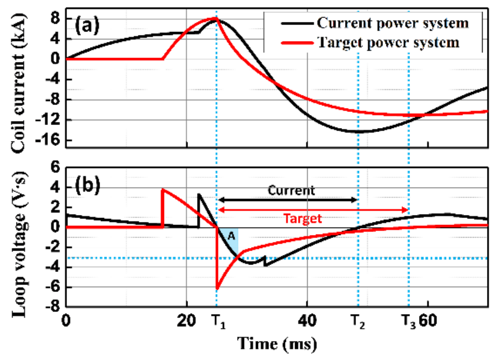

Fig. 2. Current evolution CS (a) and the loop voltage (b). Black lines: current power system, Red lines: target power system.

3. Optimization of the circuit simulation code

A test circuit which is exactly same design as the target circuit was made, but with a reduced capacitance and charging voltage, to test the IGBTs and optimize the simulation. Test was carried out using 5SNA 1200G450300 IGBT Modules which are going to be used in the target circuit. The transient voltage was measured under the various values of the snubber elements, and the results of the test circuit were used to optimize simulation.

The circuit simulation code by using MATLAB Simulink is written for estimating the transient voltage of the target circuit. However, the parasitic inductance in the circuit and the internal resistance in the IGBTs cause a large change in the simulation results. Accordingly, it is necessary to estimate these two values by matching the simulation results to the experiment results. As a result, an optimized IGBTs internal resistance is 1.02 mΩ and the parasitic inductance is 8.11 μH. Comparison between simulations and experiments of the transient voltages with the various snubber conditions is presented in Fig. 3. The peak value of transient voltage in the simulation is similar to that of the experiment within 7.41%.

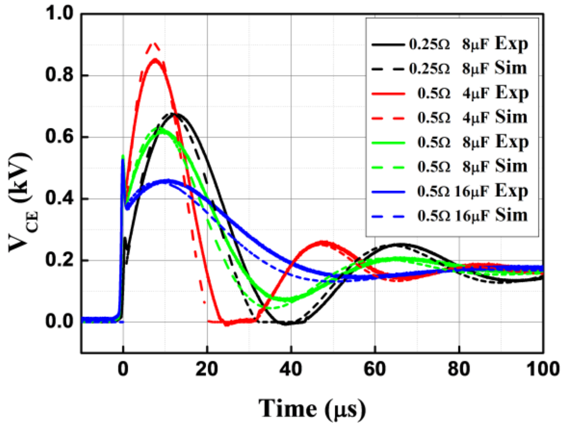

Fig. 3. The transient voltage of simulation and experiment results in various values of the snubber elements.

4. Determination the value of the snubber elements

4.1 Snubber resistance

The transient voltage was estimated from the optimized simulation applying the charging voltage and the capacitance of the target circuit. The simulation was carried out assuming a stray inductance in the circuit to be a sufficiently large value of 10 μH which is about 1 % of CS inductance 1.4 mH. According to change the resistance, the transient current at switching on and the transient voltage at switching off are changed.

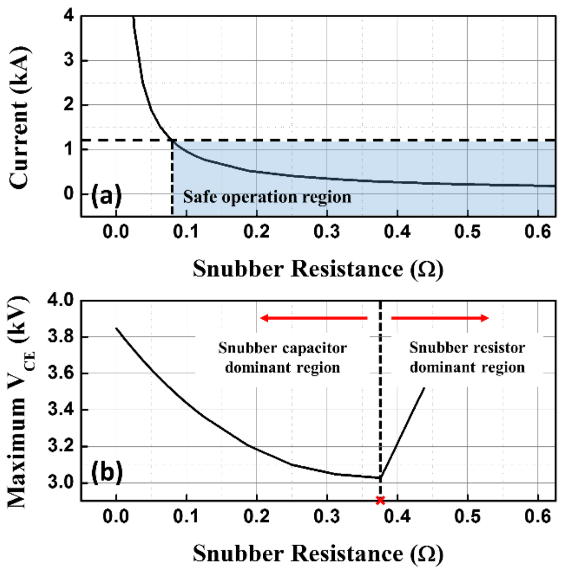

Fig. 4. The switching-on current (a) and the maximum transient voltage (b) as a function of the resistance.

Since the DC collector current limit for the IGBTs is 1.2 kA, it is necessary to choose a resistance that causes the transient current to be 1.2 kA or less. As shown in Fig. 4. (a), larger than the 79.9 mΩ condition is required for safe operation.

Fig. 4. (b) shows the maximum transient voltage according to the resistance. The maximum transient voltage decreases exponentially, but increase after a particular value of the resistance. Around this point, the left side is the capacitor dominant area and the right side is the resistor dominant area. The minimum value of the transient voltage appears at this point, so it is appropriate to choose 376 mΩ for resistance.

4.2 Snubber capacitance

The energy $\frac{1}{2}LI^2$ created by parasitic inductance is converted into the energy $\frac{1}{2}CV^2$ by the snubber. Because the parasitic inductance L and the current at switching off I cannot be changed, increasing the snubber capacitance C is very effective to reduce the transient voltage V. Fig. 5 compares the transient voltage over the capacitance of the snubber at different parasitic inductance. As the capacitance increase, it is likely to converge at almost 3.1 kV. This is because the transient voltage is offset by 1.5 kV from the C2 charging voltage and 1.6 kV from the damping resistor. Therefore, it cannot be suppressed less than 3.1 kV.

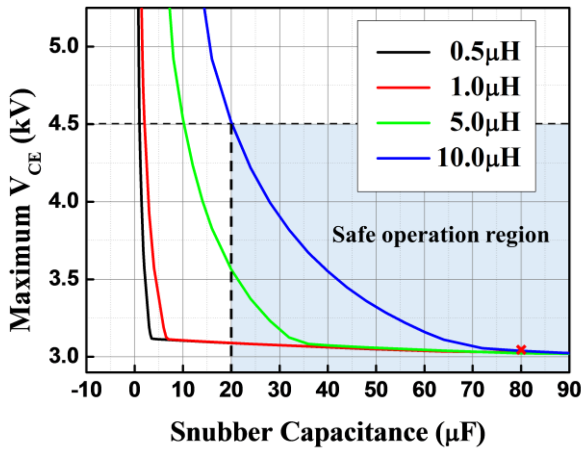

Fig. 5. The maximum transient voltage as a function of the snubber capacitance at various patristic inductance.

Since the allowable collector-emitter voltage of the IGBTs is 4.5 kV, a marginal condition for stable operation of the IGBTs can be made if the capacitance is 20 μF or more. If the snubber capacitance is too large, it will affect the load current waveform, thus the value that is infinitely large cannot be selected. 80 μF is selected for the snubber capacitance, and at 80 μF, the transient voltage almost saturate to 3.1 kV within 100 V, so it is still enough value for stable operation.

5. Conclusions

Optimal values of the snubber elements for safe operations of the IGBTs were obtained by the simulation. By creating a scaled down test circuit similar to the target circuit, the process of increasing the accuracy of the simulation was carried out. Using the simulation, reliable value of the resistance and the capacitance were obtained. It was confirmed that a resistance of 376 mΩ and a capacitance of 80 μF are suitable for stable operations of the IGBTs. Based on the values, the target system will be constructed and the transient voltage between the simulation results and the real values will be compared.

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