1. Introduction

Thyratron and hard-tube switch are used typically for control of high voltage and high current at the field of the pulsed power and plasma applications.

In the case of designing and using hard-tube, pulse generator has wide range of impedance matching with better rectangular pulse shape, high duty cycle and long life time. It is needed the isolated driver and the additional power to control hard-tube with low efficiency due to high voltage drop.

Thyratron which is widely used for commercial high power switch, has good property of high d/dt, high peak current allowance with reliable performances. Thyratron, however, has also many drawbacks poor rectangular pulse shape generating, narrow impedance matching, and short life time [1].

There are presented to replace Thyratron and hard-tube switch to overcome these drawbacks, using power semiconductors such as IGBT, MOSFET, Thyristor, GTO, and etc. There also have been proceeded many papers and academic researching to connect power semiconductor in series connect as high voltage switch since a decade.

Obviously, series connecting method of Power semiconductor has good advantages at the aspect of wide impedance matching, high duty cycle, good rectangular pulse shape generating with reliability.
Most of IGBT’s parameters are found indirect calculation from IGBT’s switching on/off waveform and time with gate driving waveform and datasheet. These calculations are set to 1kV sharing at each IGBT and 10 μs pulse generating condition with variable frequency as following equations of each switching phase in Figure 3. Table 1 indicates calculated internal circuit parameter of IGBT at the condition. [3] [4]

![Figure 3. Switching waveform of IGBT](image)

(a) Turn on phase  (b) Turn off phase

\[ V_{c_1, \text{on}} = L_s \times \frac{di}{dt}, \quad t_2, t_3 \text{ region} \]

\[ V_{c_2} = \frac{V_{c_2, \text{off}} - V_{c_2, \text{on}}}{R_{c_p}} \], t4 region

\[ C_{\text{es}+}\text{reverse transfer capacitance, } C_{\text{c}}\text{) calculation:} \]

\[ \frac{dv_{c_2}}{dt} = \frac{V_{c_2, \text{off}}}{C_{\text{es}} + R_{c_p}} \], t7 region

\[ C_{\text{es}+}\text{input capacitance, } C_{\text{es}} = C_{\text{es}+} + C_{\text{ac}}\text{) calculation:} \]

\[ \frac{dv_{c_2}}{dt} = \frac{V_{c_2, \text{off}}}{C_{\text{es}} + R_{c_p}} \], t8 region

Table 1. Internal Circuit Parameters of IGBT in series connected, compared with single switching experiment. \( R_s \) was set to 1Ω.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Single IGBT</th>
<th>IGBT in series connected</th>
<th>IGBT in Datasheet</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{c} + C_{c_2} ) input capacitance</td>
<td>3700pF</td>
<td>2500pF</td>
<td>4000pF</td>
</tr>
<tr>
<td>( C_{ac} ) gate-collector capacitance</td>
<td>250 pF</td>
<td>166 pF</td>
<td>300 pF</td>
</tr>
</tbody>
</table>

As auxiliary circuit components, \( R_s \) and \( C_s \) in Figure 1 are necessary to hold static and dynamic voltage balance. \( R_s \)-connected parallel to IGBT is necessary to prevent switch from being forced into avalanche at IGBT that has the lowest leakage current at steady state and \( C_s \) is needed not to be forced into voltage breakdown at the lowest IGBT among series connected. It is able to be altered \( C_s \) into RCD snubber or RC snubber circuit that depends on power semiconductor’s switching property whether normally off or on switch state.

### 2.2 Asymmetry factors of Series Connected IGBTs of voltage equalization based on Experiment Data

Though transient or dynamic voltage equalization in series connection of power semiconductor is mentioned very simply at section A, it is very hard to obtain due to difference of IGBT that are connected in series, and different delay time of a gate driving output at each IGBT.

Figure 4–(a) shows 2kV switching output waveform of triple connected IGBT in series at terminal port of negative pulse generator that is used RCD snubber and C component in the condition of 10kHz operating frequency. Figure 4–(b) presents gate driving waveform at 2kV switching operation of IGBT switch. Though, most of oscillation factors that cause asymmetry of voltage balance stem from differences of gate drive circuit, over voltage stress is concentrated on high voltage side, IGBT side.

![Figure 4. Gate drive signal at the condition of Figure 4–(a)](image)

### 2.3 Proposed Control Method and Circuit

![Figure 5. Proposed additional auxiliary circuit that is connected in parallel to IGBT](image)

To diminish asymmetry of voltage balance, active voltage clamping at high voltage side is preferred. Figure 5 shows proposed additional active clamping circuit that consists of \( R \), C, and transistor when it detects over voltage, C will compensate \( C_{c2} \) of IGBT that takes over voltage.

Operation of proposed auxiliary circuit is divided into 4 modes that depend on switching waveform of IGBT. Though, switching waveform mode of IGBT is divided into 9 modes as shown in Figure 3, imbalance of voltage sharing is observed at the phase of mode 2, 3 in Figure 3.

Thus, key point of symmetric voltage balance at mode 2, 3 is achievable by equalizing input transfer capacitance, \( C_{es} \) by compensating \( C_{ac} \). Except different value of internal circuit value in IGBT and of delayed time in gate driver and gate signal oscillation, difference of external capacitance value also can be a factor of asymmetric voltage sharing. In experiment and simulation of proposed circuit, it is concentrated to transient phase of off switching in
IGBT and different delayed time and signal in gate driver.

Figure 6 shows simulation data of proposed circuit while gate signal delay time is changed from 300ns to 1us that is based on basic experimental data at section A, and simulated waveform is executed under the condition of $200 \cdot 10^{-9}$ seconds delay time. Simulation assumption is originated from gate driving delay time is dominant factor of asymmetric voltage sharing, and simulated output waveform is compared with parallel connected $R_s$ and $C_s$ components.

![Figure 9. Simulation waveform of typical C compensation and proposed active clamping method](image)

2.3 Output Waveform of Proposed Circuit

To verify output waveform of proposed circuit and method, verification is executed at the same condition of basic experiment, operating frequency is varying from 1Hz to 10kHz, pulse width is fixed at 10us.

There are two advantages of proposed circuit even in comparison of existing active clamping method. $R_s$, compensating resistor that is connected in IGBT for static voltage balance at on or off steady state of IGBT switch is selected to flow two or three times of leakage current in IGBT. At the proposed circuit, $R_1$ value is able to be selected as two times of $R_s$ at typical connection method to diminish energy loss of high side.

The other strong point is not to be needed additional calculation of snubber capacitance at the proportion to varying operating frequency at typical connection method, because $C$ in auxiliary circuit compensates $C_{ov}$ from on state to off state transition at the phase of mode 2, 3 in Figure 3.

Most of current active clamping methods are consist of zener diode that detect two expected over voltage with Capacitor to compensate $C_{ov}$.[5] Internal capacitance of he zener diode also can be a serious oscillation factor to hold high voltage zener breakdown voltage at series connected IGBT switch and cause much energy loss compared with proposed active clamping method.

It is necessary needed to calculate amount of charge compensating at $C_{ov}$ in IGBT, due to being transferred charge from IGBT side to gate side must also be a serious oscillation or distorted waveform.

![Figure 10. Switching waveform of series connected IGBT with proposed circuit at the condition of 1kHz operation frequency, at 50us pulse width at terminal 5kV output of negative pulse generator](image)

3. 결론

In this paper, there are performed two kinds of approach to design and improve negative pulse generator for WIPS (Wire Ion Plasma Source) both experiment and simulation.

Active clamping method of IGBT in series connection to synchronize voltage sharing at transient switching time shows improved result, compared to typical series connection method of IGBT. In proposed circuit, amount of being transferred charge to gate diver side have to be measured and calculated very carefully to design auxiliary circuit because it can cause oscillation waveform in gate driving waveform.

[참고문헌]