Performance of Pulsed Power Generator Using High-Voltage Static Induction Thyristor

Ryoji Hironaka, Masato Watanabe, Eiki Hotta, Member, IEEE, Akitoshi Okino, Member, IEEE, Mitsuaki Maeyama, Member, IEEE, Kwang-Cheol Ko, Member, IEEE, and Naohiro Shimizu

Abstract—In a present pulsed power generator system using semiconductor switches, saturable magnetic switches are usually connected in series to compress the output pulse because the current rise-time of semiconductor switches are generally not short enough. However, the magnetic switches are heavy and they reduce the energy transfer efficiency. So we propose a pulsed power generator system using a 5500-V static induction thyristor (SI-Thy), a Blumlein line for pulse formation, and a step-up pulse transformer. The fundamental characteristics of the generator are evaluated. From experiments using only one SI-Thy, turn-on time of several tens of nanoseconds and the maximum rise rate of the output voltage of 115-kV/μs are obtained. It is confirmed that an SI-Thy will have sufficient performance as a main switch of the pulsed power generator for the flue gas treatment and decomposition of hazardous gases when several SI-Thys are connected in series.

Index Terms—Blumlein line, energy transfer efficiency, static induction thyristor (SI-Thy), turn-on time.

I. INTRODUCTION

FOR environmental applications, high-power, high-voltage (∼100 kV) short pulse (voltage rise-time is less than a few hundred nanoseconds, and pulsewidth is less than 1 μs) generators are required for flue gas treatment and decomposition of hazardous gases [1]–[3]. The switch elements used in such generators are required to have long lifetimes. Because the semiconductor switches have semi-infinite lives as long as they are used within the rated values, they are potential candidates. However, the current rise-time of semiconductor switches are generally not short enough. Therefore, saturable magnetic switches are usually connected in series to compress the output pulse. It is desirable to develop a compact generator without magnetic switches because the magnetic switches are heavy and reduce the energy transfer efficiency. To realize compact pulsed power generators, semiconductor switches that have a very short rise-time are required.

Manuscript received December 2, 1999; revised June 23, 2000.
R. Hironaka, M. Watanabe, and E. Hotta are with the Department of Energy Sciences, Tokyo Institute of Technology, Yokohama, 226-8502 Japan (e-mail: ehotta@es.titech.ac.jp).
A. Okino is with the Department of Electrical and Electronic Engineering, Tokyo Institute of Technology, Tokyo, 152-8552 Japan.
M. Maeyama is with the Department of Electrical and Electronic Systems, Saitama University, Saitama, 338-8570 Japan.
K.-C. Ko is with the Department of Electrical and Computer Engineering, Hanyang University, Seoul, 133-791 Korea.
N. Shimizu is with the Corporate Research and Development Group, NGK INSULATORS, Ltd., Nagoya, 467-8530 Japan.

Fig. 1. Photograph of the static induction thyristor.

We are evaluating a high-voltage static induction thyristor (SI-Thy), RT-201 (NGK Insulators, Ltd., Nagoya, Japan). The specification of the SI-Thy is as follows: the rated repetitive peak OFF-state voltage is 5500 V, the rated direct OFF-state voltage is 4400 V, the effective ON-state current is 600 A, and the surge ON-state current is larger than 1200 A. Using the SI-Thy as a switch, a pulse generator that consists of a Blumlein line and a transformer connected in series was tested.

The SI-Thy shown in Fig. 1 has a buried gate structure. This enables higher on-currents and higher hold-off voltages than do the other devices, such as IGBTs [4]. In addition, because a depletion region disappears faster when supplying gate current of higher rise rate, the turn-on time becomes shorter [5], [6]. Moreover, the ON-state voltage of SI-Thy quickly decreases and is low compared with those of other devices, so that an anode reactor usually connected in series [4] can be omitted. Therefore, the buried gate SI-Thy is suitable for pulsed power applications.

II. EXPERIMENTAL PULSED POWER GENERATOR SYSTEM

An experimental circuit of a pulsed power generator system in which an SI-Thy is used as a switch is shown in Fig. 2. As stated in the previous section, magnetic pulse compression circuits reduce the energy transfer efficiency. Therefore, using a Blumlein line for pulse formation and a step-up pulse transformer, a pulsed power generator system without saturable magnetic switches was proposed. Two cables (RG-8 U: characteristic impedance is 52 Ω, length is 30 m) are used as a Blumlein line. It generates an output voltage pulse with a pulsewidth of 300 ns. The Blumlein line is charged to the maximum voltage of 3 kV when only one SI-Thy is used.

Because an SI-Thy is a normally-on device, the gate of SI-Thy must be negatively biased to −15 V to keep hold-off state. The switch closes when supplying a positive voltage.
pulse to the gate. Then, a voltage pulse with the maximum value of 3 kV appears on the primary winding of the pulse transformer. As the turn ratio of the pulse transformer is 2 to 6, the maximum pulse voltage of 9 kV appears on the secondary winding. A resistor of 900 Ω is used as a matched load.

The fundamental characteristics were evaluated by changing the turn-on gate trigger voltage to increase the rise rate of gate current.

### III. Experimental Results and Discussion

Fig. 3 shows typical waveforms of the voltage and current of SI-Thy and that of the load voltage: charging voltage is 3 kV, and turn-on gate trigger voltage is 100 V.

The on-state resistance of an SI-Thy is large because of the small switch current, and it leads to a reflection of current pulse from an SI-Thy and an on-state Joule loss. Therefore, the flattop current is smaller than the ideal value of 57.7 A, which is shown by the broken line in Fig. 3. Because the reflection rates of anode current were observed to be nearly constant under all conditions, the on-state resistance of an SI-Thy is considered to be constant.

Except the rise rate waveforms of load voltage are mainly affected by the characteristics of the pulse transformer. Because of a transfer energy loss, the peak load voltage is smaller than the ideal value of 9 kV, which is shown by the broken line in Fig. 3. In addition, since a pulse transformer cannot transmit dc power, and generally, this leads to droop of load voltage, the shorter pulsewidth is better for achieving a high energy transfer efficiency.

#### A. Turn-On Characteristics

Fig. 4 shows the dependences of turn-on time and the peak rise rate of switch current on turn-on gate trigger voltage. The turn-on time is defined as the time for the voltage of an SI-Thy to fall from 90% to 10% of the charging voltage. Because charge injected into the gate of SI-Thy increases when supplying a larger positive voltage pulse to the gate, the turn-on time decreases. On the other hand, the turn-on time becomes longer when switch current, which is proportional to charging voltage, becomes higher. However, the latter effect on the turn-on time is rather small, and the peak rise rate of switch current becomes larger when the charging voltage is increased. Because of the large characteristic impedance of Blumlein line, we obtained short turn-on rise-times.

#### B. Delay Time

The dependence of the delay time on the turn-on gate trigger voltage is shown in Fig. 5. The delay time is defined as the duration between the time when the gate voltage changes to positive and the time when the voltage of an SI-Thy begins to fall.
Fig. 5. Dependence of the delay time on the turn-on gate trigger voltage.

Fig. 6. Dependence of the peak rise rate of the output voltage on the turn-on gate trigger voltage.

The delay time does not depend on the charging voltage but on the turn-on gate trigger voltage. Since the depletion time, which decreases with increasing rise rate of the gate current, affects both the characteristics of the delay time shown in Fig. 5 and the turn-on time shown in Fig. 4, they resemble each other.

The minimum delay time of about 45 ns was obtained, and the jitter is a few nanoseconds, which is negligible in comparison with the delay time.

C. Output Characteristics

Fig. 6 shows the dependence of the peak rise rate of output voltage on the turn-on gate trigger voltage. It is easily understood that the peak rise rate of output voltage depends on a turn-on time, which is a function of the turn-on gate trigger voltage, as shown in Fig. 4.

Although the core of the pulse transformer is not saturated, the rise rate of output voltage exhibits a sudden change from high to low near its peak when a turn-on gate trigger voltage becomes larger, as seen in Fig. 3. However, the maximum rise rate of the output voltage of 115 kV/μs was obtained.

D. Energy Loss

Fig. 7 shows the dependences of switching loss and energy transfer efficiency on the turn-on gate trigger voltage. A switching loss and a turn-on time decrease with increasing a turn-on gate trigger voltage. Therefore, the dependence of switching loss on the turn-on gate voltage is similar to that of the rise rate of the current of SI-Thy shown in Fig. 4.

An energy transfer efficiency is defined as the ratio of the energy dissipation in the load resistance to the initial energy stored in a Blumlein line. The energy dissipated by the distorted part of output is included in the calculation of the energy transfer efficiency. The on-state loss increases with increasing a charging voltage; however, it is limited less than 10% of a switching loss. The ratios of the energy, including the switching loss, the on-state loss, and the output energy to the initial storage energy were observed to be nearly constant even if the condition is changed. Therefore, the decrease of a switching loss and an on-state loss improves an energy transfer efficiency. As a result, about 93% of the initial energy stored in a Blumlein line is delivered to the primary winding of the pulse transformer. The remaining energy is dissipated as the reflection loss caused by the impedance mismatching due to the low coupling coefficient of a pulse transformer and the losses caused in the pulse transformer.

IV. CONCLUSION

We designed a pulsed power generator system using a 5500-V SI-Thy and a Blumlein line for pulse formation, and the fundamental characteristics were evaluated by changing the turn-on gate trigger voltage. Because of an impedance mismatching, we could obtain no more than the maximum energy transfer efficiency of 88%. However, from the experiments using only one SI-Thy, a turn-on time of several tens of nanoseconds and the maximum rise rate of the output voltage of 115 kV/μs were obtained. It is confirmed that an SI-Thy has a sufficient performance as a main switch of the pulsed power generator for the flue gas treatment and decomposition of hazardous gases if several SI-Thys are connected in series. It is also necessary to improve the performance of the pulse transformer to increase an energy transfer efficiency.

REFERENCES


Ryoji Hironaka was born in Aichi, Japan, on February 13, 1976. He received the B.S. and M.S. degrees from Tokyo Institute of Technology, Tokyo, Japan, in 1998 and 2000, respectively. Since 2000, he has been with the Toshiba Corporation, Japan.

Masato Watanabe received the B.S., M.S., and Ph.D. degrees in mechanical engineering from Tohoku University, Japan, in 1988, 1990, and 1993, respectively. Since 1993, he has been with the Tokyo Institute of Technology, Tokyo, Japan, where he is a Research Associate in the Department of Energy Sciences. His research interests include plasma physics and laser applications.

Eiki Hotta (M’91) was born in Nagano, Japan, in 1951. He received the B.S., M.S., and Ph.D. degrees in electrical engineering from Tokyo Institute of Technology, Tokyo, Japan, in 1973, 1975, and 1981, respectively. He has been a Professor in the Department of Energy Sciences at Tokyo Institute of Technology since 1995. His current research interests include plasma engineering and pulsed power technology.

Akitoshi Okino (M’98) received the B.S. and M.S. degrees in applied physics from Osaka University, Osaka, Japan, in 1989 and 1991, respectively, and the Ph.D. degree in nuclear engineering from Tokyo Institute of Technology, Tokyo, Japan, in 1994. He is with the Department of Electrical and Electronic Engineering, Tokyo Institute of Technology. From 1998 to 1999, he was a Visiting Researcher in the Department of Chemistry, The George Washington University, Washington, DC. His recent research has included plasma engineering and pulsed power technology.

Mitsuaki Maeyama (M’99) received the M.S. and Ph.D. degrees in electrical and electronic engineering from Tokyo Institute of Technology, Tokyo, Japan, in 1984 and 1987, respectively. He has been an Associate Professor in the Department of Electric and Electronic Systems Engineering, Saitama University, Saitama, Japan, since 1994. His research interests include industrial applications of pulsed power and analysis/control of magnetically confined fusion plasmas.

Kwang-Cheol Ko (M’92) was born in Seoul, Korea, in 1959. He received the B.S. degree in electrical engineering from Hanyang University, Seoul, Korea, in 1982, and the M.S. and Ph.D. degrees from Tokyo Institute of Technology, Tokyo, Japan, in 1986 and 1989, respectively. From 1990 to 1995, he was with the Department of Electrical Engineering, Kyungwon University, Kyunggi-do, Korea. In 1995, he joined the faculty in the Department of Electrical and Computer Engineering, Hanyang University, Korea, where he is currently an Associate Professor. His research interests include pulsed power technologies and their applications for environment.

Naohiro Shimizu received the B.S. degree in engineering of physics from the University of Electro-Communications, Tokyo, Japan, in 1979. From 1979 to 1998, he worked at Toyo Electric Manufacturing Co. Ltd., and was engaged in the development of the power semiconductor devices. From 1989 to 1991, he studied the designing of the static induction thyristor at Semiconductor Research Institutes, Sendai. In 1998, he joined NGK Insulators, and has been working on the development of the high-power static induction thyristor, the process and the design.