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ABSTRACT
A novel overvoltage driver is proposed to speed up the turn-on transition of series-connected MOSFETs module which serves as the main switch in high voltage pulse generator. In order to realize the overvoltage driver, a nanosecond pulse with the amplitude of hundreds of volts is superposed on a square driving signal by linear transformer driver scheme. The results show that, comparing to the commercial high current driver, the turn-on time of a 10kV MOSFETs module including ten devices with the proposed driving scheme can be shortened from ∼25ns to ∼7ns. The proposed overvoltage driver can be used to conveniently modulate the rise time and pulse width of high voltage nanosecond pulse generator constructed by MOSFETs. In addition, it is demonstrated that there is almost no influence of the overvoltage driver on the gate-source characteristics of device by analyzing the variation of C-f curves of input capacitances.

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I. INTRODUCTION

POWER MOSFETs have great potential as switches for high speed high voltage applications such as pulsed power technology.1,2 However, constrained by voltage-blocking capability of single device, it is necessary to connect many devices in series for high voltage applications at present.3,4 Generally, each device requires an independent driver circuit, and these drivers must be isolated from each other. With the increase of the number of MOSFETs in series, the driving synchronization of many devices is a challenging task especially for fast pulse applications, and the system will become so complicated that it is difficult to be constructed compactly.

For those problems, some solutions with devices series-connected has been reported in the previous researches.2,3 What they have in common is that only one external gate driver is required. Therefore, it’s favorable to compact design of fast pulse generator. However, the turn-on transition time of these modules becomes almost 200 ns to 300 ns, when the voltage is above ∼10 kV. Furthermore, with the similar solution, a 30kV Marx-type pulse generator with three 10kV series-connected MOSFETs module was developed,5 through optimizing topology, layout, trigger capacitor, etc. But still restricted by the turn-on transition of MOSFETs stack, the rise time is almost more than 40ns, which is not fast enough for some applications. With the increase of voltage-blocking capability of single device, this problem will become more prominent with a larger input capacitance. Obviously, the gate driver is the key part influencing the switching performance of series-connected MOSFETs module with single external gate driver.6 However, a commercial driver was normally utilized in the previous researches. Therefore, it still needs a further investigation on the fast switching characteristics of series-connected high voltage MOSFETs module by improving the performance of gate driver.

In this paper, to address the above problem, we develop a novel overvoltage driver scheme with inductive adder pulse for fast switching of series-connected MOSFETs module. The paper is organized as follows: the idea of the overvoltage driver is proposed and its working principle is described in section II; the experimental results and
II. THE PROPOSED OVERVOLTAGE DRIVER

As mentioned in section I, the typical solution with single external gate driver for series-connected module is illustrated in Fig. 1. Its operation principle has been described in detail previously. Briefly speaking, the first MOSFET in the module is directly driven by the external gate driver, and the rest of the MOSFETs is driven by the rapid changing potential of the emitter of each device. In fact, it is naturally an overvoltage driving scheme for the upper devices in the above series-connected MOSFETs structure. Therefore, the turn-on transitions of those upper devices are obviously faster than the lower ones. In such a way, a longer platform or even a transient rebound shall appear in the drain-source voltage waveform for the lower MOSFET devices especially the bottom one, which will charge the miller capacitor against the driver, leading to a slow turn-on transition. The simulation results corresponding to Fig. 1 can illustrate this phenomenon very clearly, shown in Fig. 2. Hence, we can find that the switching behavior of the bottom device is the key point influencing the turn-on transition of the whole series-connected MOSFETs module. However, this issue was ignored in the previous study. Accordingly, being similar to the driving scheme of the
upper devices, the idea of overvoltage driver is proposed to speed up the switching of the bottom device, to further improve the switching performance of the whole module with dozens of MOSFETs series-connected.

Fig. 3(a) shows the schematic diagram of the overvoltage driver. It consists of a classical push-pull circuit and a nanosecond pulse generator, which are utilized to produce a square signal of variable width and a variable amplitude nanosecond pulse respectively. The above two functional parts are combined in a similar way to linear transformer driver. It should be noted that, in order to ensure the superposition of two signals at the front of square wave, it requires not only to control the time sequence of driving signals for the devices $S_1$ and $S_3$ accurately, but also to employ the devices $S_1$-$S_3$ with very fast switching speed. Thus, we use RF MOSFET IXYS DE275X2-501N16A with a typical turn-on time $\sim$2ns, which is driven by a special chip IXRFD631. High speed optical coupler APS1551S was utilized to isolate the control signals. Besides that, the winding number of pulse transformers $T_1$ and $T_2$ should be as little as possible to decrease the leakage inductance. In this paper, the numbers of primary and secondary winding for both $T_1$ and $T_2$ are both unity, with a leakage inductance being only $\sim$160nH. The material 1K107 is used as the magnetic core of pulse transformers to realize the coupling of fast pulse. The prototype of our homemade overvoltage driver with inductive adder pulse is shown in Fig. 3(b).

III. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 4 presents the output waveforms of the home-made overvoltage driver, corresponding to different charging voltage of $U_2$. We can find that a pulse with a half width of several nanoseconds is superposed onto the square signal at its front shown in Fig. 4(a), which exactly satisfies the requirements of time sequence. It should be noted that the waveform differences between Fig. 4(a) and Fig. 4(b) is mainly caused by the difference of the equivalent load. Corresponding to Fig. 4 (b), MOSFET C2M0080170P was taken as a load for this driver, with a typical input capacitance $\sim$2250pF. Hence, during the turn-on transition, the amplitude of driving signal will not exceed $U_{GS(max)}$ listed in device specification due to the clamp effect of Miller capacitance, even with a charging voltage $\sim$500V for $U_2$. Moreover, we can find that, with the increase of the charging voltage of $U_2$, the rise time of driving pulse on the gate to source of the device can be shorten significantly so that the turn-on transition is speed up.

Fig. 5 shows the turn-on transition of series-connected MOSFETs module with ten devices (MOSFET C2M0080170P), driven by the overvoltage driver with different charging voltage of $U_2$. If there is no overvoltage pulse at the front of the driving signal, the turn-on time is almost 30ns. When $U_2$ increases to $\sim$500V, it can be switched on within $\sim$7ns. It demonstrates that the improvement of fast switching behavior of series-connected MOSFETs module greatly depends on the turn-on transition of the bottom device, which further verifies the above analysis. However, it is worth noting
FIG. 6. The typical C-f curves of gate-source capacitances of the device driven by the overvoltage driver before and after.

that, when the charging voltage \( U_2 \) increases from \( \sim 400 \text{V} \) to \( \sim 500 \text{V} \), there is almost no improvement of fast switching performance any more. It is no necessary to further increase the amplitude of the overvoltage pulse, because the turn-on speed of the MOSFETs module has almost reached the limiting speed. Meanwhile, we can find that, comparing to a commercial high current driver KA103 manufactured by LMY Electronics, the turn-on time becomes 7ns from \( \sim 25 \text{ns} \) for a 10kV series-connected MOSFETs module driven by our home-made overvoltage driver.

Finally, in order to evaluate the influence of overvoltage driving method on the gate-source of MOSFET, the gate-source capacitance of MOSFET were measured by semiconductor device analyzer B1500A manufactured by Keysight Company. Figure 6 shows the typical gate-source capacitance C-f curves, corresponding to a new device and the one having continuously operated ten hours at 10 kHz repetition rate. From the measurement results, it is indicated that the gate-source capacitances are both around 1.6nF, almost having no change. It is easy to understand, because there is no overvoltage spike between the gate and the source, shown in Fig. 4(b), only with a high driving current flowing through the internal gate resistance.

IV. CONCLUSIONS

In summary, we have devised a way to improve the fast switching performance of high voltage MOSFETs module with dozens of devices series-connected. It has been demonstrated that the turn-on time of a 10kV MOSFETs module including ten devices can be shortened from \( \sim 25 \text{ns} \) to \( \sim 7 \text{ns} \). Meanwhile, despite that the overvoltage driver is in a special way, it can be considered reliable for the operation of devices. Moreover, this method can also be used for modulating the pulse front time conveniently in the nanosecond pulse generator constructed by MOSFETs.

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