

Active control of a driving circuit by a derivative with respect to di/dt of the output current

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Abstract. The paper proposes a method, as well as a schematic diagram of a driving circuit for controlling a MOSFET. The mathematical model of the driving function of the circuit has been developed and analyzed. A particular schematics solution is described as a principle of operation. The experimental results from a working mode for controlling a MOSFET by an active-inductive load are considered. The transient processes at the moments of turning the transistor on and off are investigated. They are conditionally divided into three intervals. The losses of power at turning on and off are investigated as well. Another purpose of this paper is to evaluate a strategy to reduce the EMI noise by controlling di/dt of the source current during switching of a MOSFET. A parallel is drawn between the transient processes, employing the newly proposed and a commonly used driver. Conclusions and analyses are drawn.

I. Introduction

The proper choice of a MOSFET driver to a power MOSFET and IGBTs is essential for optimized switch performance. Designing for adequate gate drive, resulting in fast rise and fall times of the MOSFET, reduces MOSFET switching losses [1,2]. To turn-on, the gate on state voltage is switched to the MOSFET gate via the turn on gate pre-resistance and in the analogous way for switching off. Techniques are often desired or actively controlling the output terminal dv/dt and di/dt of insulated gate power devices such as MOSFETs and insulated gate bipolar transistors (IGBTs) in hard-switched converters in order to reduce electromagnetic interference (EMI) and voltage overshoots without requiring bulky and lossy snubber circuits [3]. With the di_c/dt feedback control, shown in Figure 1, the di_c/dt of the collector current i_c is sensed and fed back to the gate control path. In this way a control of the rise of the collector current is possible. The standard solution for gate drivers for MOSFETs nowadays is mostly done with pure resistive control. The gate current can be controlled by the multistep switching of gate pre-resistors. In a two step version, for example, low resistance allows low delay time; soft di_c/dt is achieved by means of higher resistance values [4,5].

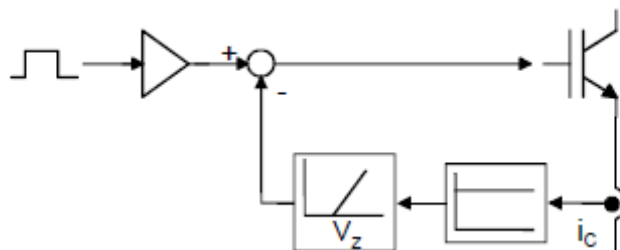


Fig.1. Basic concepts for active di/dt gate drive control.

The gate resistors can be rated to reduce EMI emission, but such fixed value would increase losses.

These different constraints would lead to different values of the gate resistors during operation [6,7]. The switching losses increase relatively strong with higher gate resistors.

The EMI noises caused by hard switching are produced by parasitic elements like stray inductance's, which naturally exist in series with main elements of the circuit and/or parasitic capacitance's existing in parallel with magnetic elements and inherent capacitance's of insulated gate switches. These parasitic elements produce voltage and current spikes when di/dt or dv/dt expose to them [8,9]. To reduce EMI noise, dv/dt and di/dt should be reduced. Reducing these parameters means longer switching transient and higher switching loss. Switching behavior of insulated gate transistor is determined by charging and discharging of internal capacitors. These capacitors are shown in a high frequency model of an insulated gate transistor (Fig.2) [10]. A simplified switching behavior of the switch is given in Fig.3.

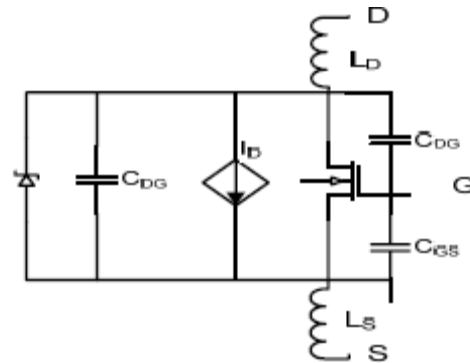


Fig.2. High frequency model of an insulated gate transistor

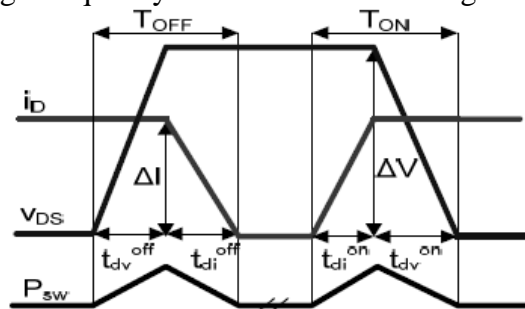


Fig.3. Switching pattern of insulated gate transistors

In a turn-off process, the drain-source voltage increases to V_{out} , the drain current reduces to zero, and then the turn-off process is completed. In a turn-on process, the drain current increases to inductor current (I_L) and then the drain-source voltage drops to V_{on} . The switching behavior of power MOSFETs are quite similar to the waveforms shown in Fig.3. [11]. Active Gate Signaling (AGS) has been used to reduce dv/dt in turn-on and di/dt in turn-off time which can minimize EMI noise more efficiently than the traditional method (increasing gate resistance). The EMI may be reduced by slow switching transient when load current is low and switching loss is negligible. On the other hand, a switching transient is getting faster when the load current is increased which reduces the switching loss. Instead of using a trapezoidal gate voltage in order to switch a semiconductor device, in this case a MOSFET, it is also possible to control the voltage in a more "curved" way, for instance a sinusoidal transition. In principle, it can be said that the trapezoidal shape corresponds to a "traditional" hard switching and the sinusoidal shape to a soft transition. Fig 4 presents a comparison between these two types of transitions. The time traces as well as the resulting frequency spectra are presented.

Both the pulses have a switching frequency of 1 kHz, amplitude of 1 p.u. (12 V) and a duty cycle of 50 %. The transition time i.e. the time for the pulse to go from low voltage level to the high or vice versa for the rising and falling edges respectively, is 50 μ s for both the trapezoidally and the sinusoidally shaped pulses.

Active di/dt control is achieved in modern research by feedback control of the gate current based on the device current. Sensing current is carried out by direct sensing (shunt resistor or Kelvin emitter). The goal of this active control is reduction of the EMI emission and reduction of snubber circuits. A three stage active gate drive is proposed for power MOSFETs.

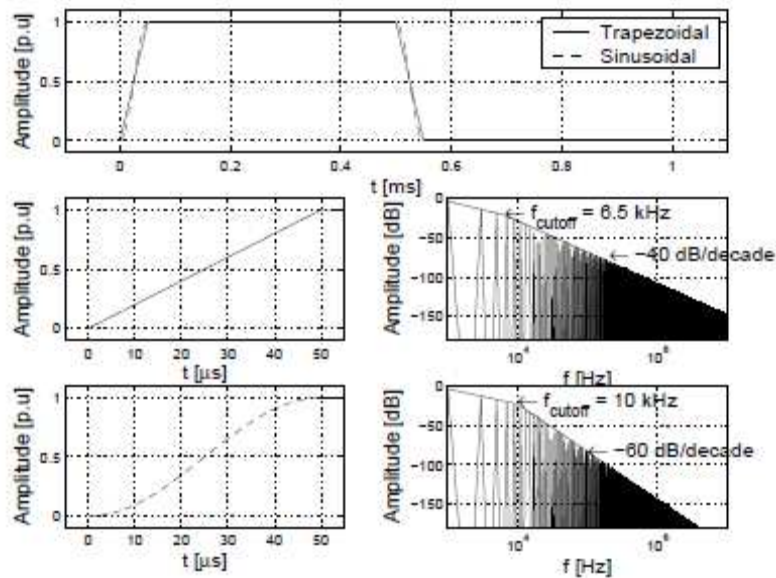


Fig.4. Comparison of frequency spectrums from PWM waveforms with trapezoidal and sinusoidal pattern.

Design is based on: reduced delay time at both turn-on and turn-off; reduced turn-on di/dt and the associated reverse recovery effects; controlled overvoltage at turn-off; reduced total switching losses at both turn-on and turn-off. In this paper active gate drive method di/dt control has been investigated. A new driving circuit of incessant control of derivative to the drain current of the MOSFET is created. The continuance of the transient processes is investigated for the cases of controlling the same transistor by means of a commonly used driver and by means of the proposed new circuit. Some measurements, carried out under equal conditions, are presented and analyzed.

II. Principle of operation of the driving circuit

The scheme contains a differentiating circuit, comprising the elements R_{12} , C_1 and R_{13} (Fig.5). The current sensor in the output circuit is the resistor R_2 . The output signal of the differentiating circuit is amplified by a single transistor stepped level – the transistor Q_4 . Two signals go into the non-inverter input terminal of the operational amplifier AR_1 – the input control signal for the driving gate with TTL level (V_{in}) and the output signal from the transistor amplifying stepped level. A signal from the source of supporting voltage V_{ref} goes to the inverter input terminal.

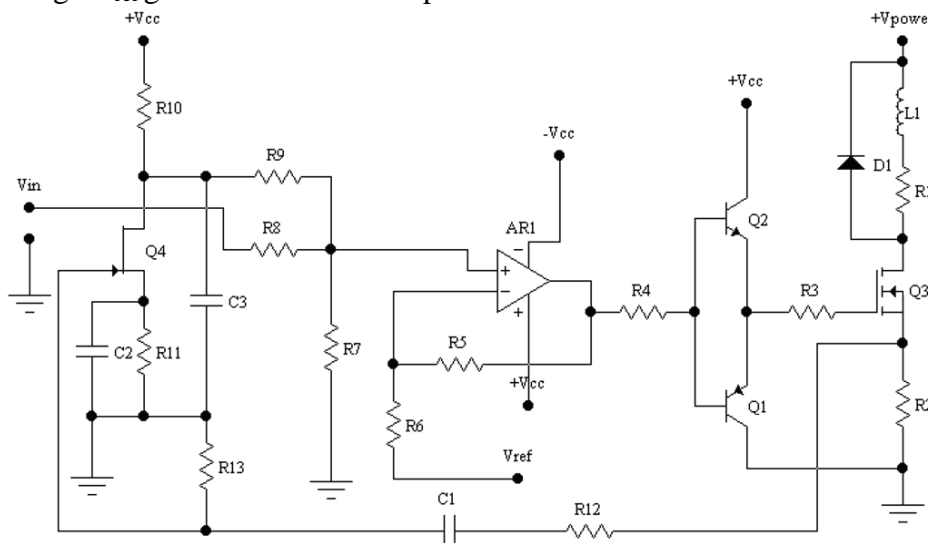


Fig. 5. Schematic circuit of the MOSFET driving circuit.

The operational amplifier controls the output transistor stepped level, which comprises the transistors Q_2 and Q_1 , for the purpose of charging and discharging the input capacity of the power

transistor Q_3 . The investigations are made at values of the load resistor $R_1 = 8\Omega$, inductivity $L_1 = 100\mu\text{H}$ and power supply voltage $V_{\text{power}} = 50\text{V}$. The power transistor Q_3 is IRF 350.

Mathematical model of the driver

The corresponding schematic diagram of the driver is shown in Fig. 6 together with the driving functions of the particular elements.

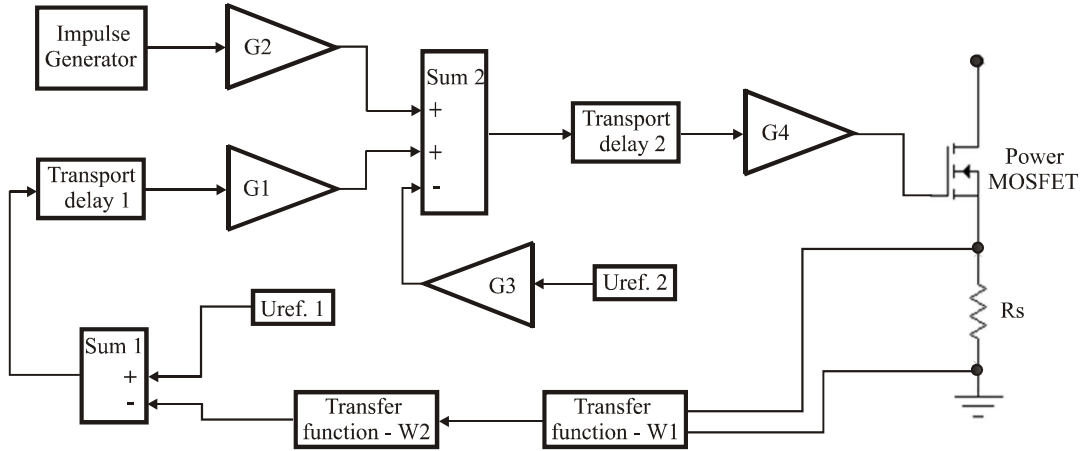


Fig. 6. Equivalent Blocks schematic of the MOSFET driving circuit.

Description of the driving functions of the elements in the block scheme in fig.3:
The passive differentiating circuit with a resistor in series has a driving function

$$W1 = \frac{p \cdot \tau_1}{1 + p\tau_2} \quad (1),$$

where the time constants have the values of

$$\tau_1 = R_{13} \cdot C_1 \quad (2)$$

$$\tau_2 = R_{12} \cdot C_1. \quad (3)$$

The driving function $W2$ represents the operation of the amplifying stepped level, realized by the transistor $Q4$

$$W2 = \frac{S \cdot R_{10}}{1 + p \cdot T}, \quad (4),$$

where the time constant is equal to

$$T = R_{10} \cdot C_3 \quad (5)$$

The voltage U_{ref1} is equal to the drain voltage of the transistor $Q4$ at a zero input signal. The delay, introduced by the transistor amplifier, is Transport delay 1. The driving function of the operational amplifier - ARI is expressed by the equation

$$W = V_f \cdot G1 + V_{in} \cdot G2 - U_{ref2} \cdot G3 \quad (6)$$

V_f is the signal, amplified by the feedback circuit, V_{in} – the control impulse signal for the driver, U_{ref2} – the source of supporting voltage. Transport delay 2 is the delay, caused by the operational amplifier. The coefficient of transmission of the gate driving power module, realized by the transistors $Q1$ and $Q2$ is denoted by $G4$.

III. Reduction in EMI by employing smooth transitions

The main idea behind the operation principle is that the gate voltage is controlled in such a way that the harmonic content in the desired output, either drain-source voltage or drain current, is reduced. The proposed way to do this is by reducing the sharp transitions in the output. Instead of using a trapezoidal shaped (can be seen as a square wave voltage with a finite rise time) gate voltage to switch the semiconductor, it is possible to control the desired output in a more curved way by applying a corresponding gate voltage. The desired output can take several shapes, e.g. a sinusoidal transition or a third degree approximation. The main purpose of this transition and what all applied curve forms

should have in common is the low harmonic content mainly due to rounding off sharp edges and avoiding sudden sharp transitions. A simulation model of the control circuit for a 12 V system was implemented in the circuit simulation software, OrCAD [12,13] and is presented in Fig. 5. Power supply voltage is 12 V. The control pulses V_{in} have a switching frequency of 1 kHz, amplitude of 5V, a duty cycle of 50 %, and rise and fall time of 10 ns. The transition time i.e. the time for the pulse to go from low voltage level to the high or vice versa for the rising and falling edges respectively, is about 60 ns for the applied curve shaped pulses, Fig.7 and 8. The slopes of the envelopes (in the frequency spectra) in the lower frequency region before the cut-off frequency are -20 dB/decade. The envelope for the pulse falls with a slope of -20 dB/decade, Fig. 9.

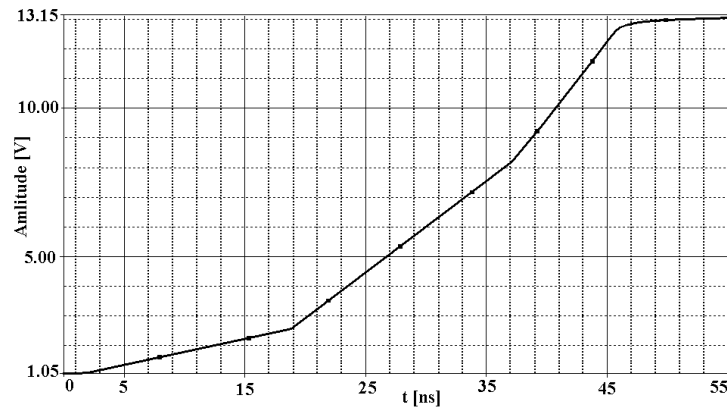


Fig.7. The time for the pulse to go from low voltage level to the high

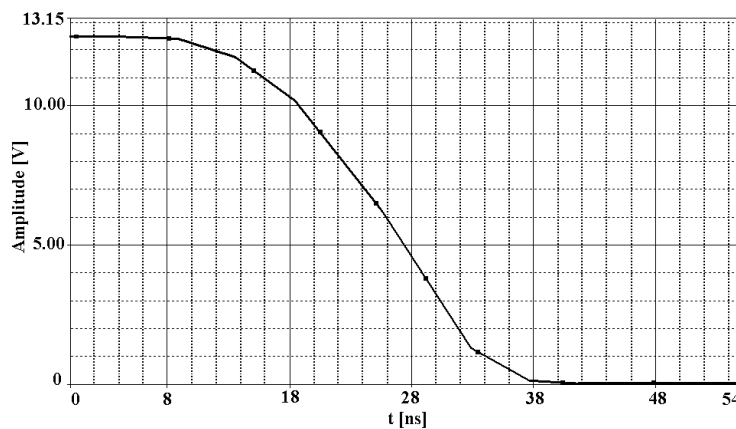


Fig.8. The time for the pulse to go from high voltage level to the low

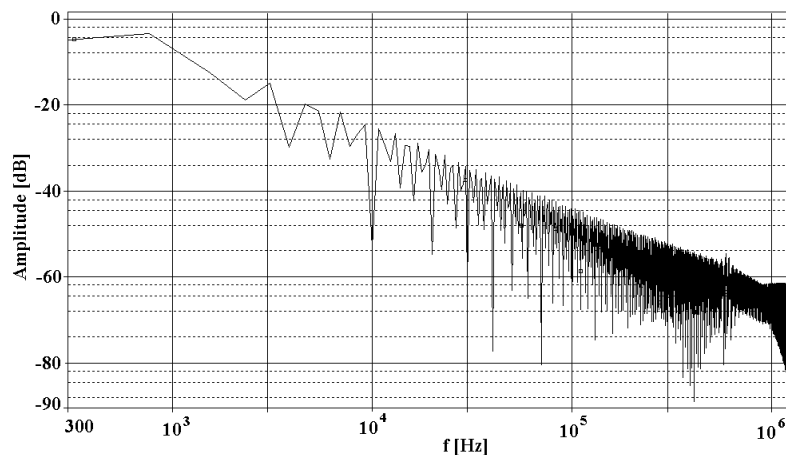


Fig.9. The frequency spectrums from PWM waveforms

Conclusion

Methods for active gate control of a MOSFET for the low and medium power range and the adaptation of the switching behavior to the requirements have been investigated. A limited number of

additional electronic elements have been used. Methods using the sensed drain current solution have been analyzed, selected, and implemented, and the behavior has been measured. The proposed new driver reduces power and energy losses during the transient processes of turning the power transistor on and off. The duration of the transient processes at the moment of turning on/off goes down. The suggested driving circuit is appropriate for controlling active-inductive loads. Thanks to the feedback with respect to a derivative of the drain current, the maximum current value at turn-on and the maximum voltage value at turn-off can be limited.

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Този доклад е финансиран по проект RES-OP-DEV „Romanian - Bulgarian joint cooperation for a long-term and sustainable development of the young human resources in the field of the renewable energy technologies, in order to overcome the socio-cultural barrier and to open common opportunities for getting a job and their employment along the cross - border area“, MIS-ETS code: 222.