2017 International Symposium on Nonlinear Theory and Its Applications,
NOLTA2017, Cancun, Mexico, December 4-7, 2017

Steady-State Analytical Expression of Voltage Shift in Resonant Drivers With Clamp Diode

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Abstract—Resonant drivers are effective and useful for driving MOSFET at high frequencies. In resonant drivers, a clamp diode is often added between the gate and source terminals of the driven MOSFET. The driving voltage is, however, not clamped but just shifted with bias voltage by adding the diode. The mechanism of the voltage shift has not been explained analytically yet. This paper gives an analytical explanation of the voltage shift. The class-E driver is considered as a concrete example. By carrying out steady-state analysis, it is clarified that the voltage shift occurs due to coexistence of resonant and gate capacitances. The explanations are valid for not only the class-E driver but other resonant driver circuits. Therefore, it is expected that the given theory can be applied resonant driver designs widely and effectively. The validity of the analysis is confirmed by comparisons with PSpice simulation and experimental results.

1. Introduction

The developments of silicon carbide (SiC) and Gallium Nitride (GaN) MOSFETs, it is required that power converters operate at high frequencies with any level of powers[1]-[3]. It is important to design high frequency driver. A resonant driver is a good candidate of the high-frequency drivers because it can satisfy soft-switching conditions. Additionally, the resonant driver circuit includes parasitic capacitances of a driven MOSFET in its resonant filter. Therefore, the strain of driving voltage due to the parasitic capacitance can be mitigated at resonant drivers[4].

Because of the resonant filter, resonant drivers provide a sinusoidal waveform as a driving signal, which includes negative voltage. A clamp diode is often added to the gate-to-source terminals of the driven MOSFET in parallel for avoiding negative voltage. Intuitively, the clamped half-wave voltage appears on the gate terminal by adding the clamp diode. The sinusoidal voltage is, however, not clamped but just shifted [5],[6]. The added diode never turns ON in the circuit operation. As far as we know, there is no analytical explanation of this phenomenon. The analytical explanation may give effective design guidelines of resonant driver circuits.

This paper gives[1] an analytical explanation of the voltage shift in the resonant driver with clamp diode. The class-E driver [4] is considered as a concrete example of the resonant driver. It is explained from the steady-state analysis that the voltage shift is caused by simultaneous presence of resonant capacitance and gate capacitance of the driven MOSFET. The explanation is valid for not only class-E driver but other resonant driver circuits. Therefore, it is expected that the given theory can be applied resonant driver designs widely. The validity of the analysis is confirmed by comparisons with PSpice simulation and experimental results.

2. Circuit configuration and its operation

In this section, the class-E amplifier and a resonant driver based on the class-E amplifier, which is called the class-E driver, are introduced briefly.

2.1. Class-E Amplifier

Figure 1 shows a circuit topology of the class-E amplifier [7],[8] and its nominal waveforms. The class-E amplifier consists of dc-supply voltage V_{DD}, input inductance L_C, MOSFET S as a switching device, shunt capacitance C_S, and $L-C-R$ series resonant circuit. During MOSFET is in OFF state, the current flows through the shunt capacitance, which generates pulse-shape voltage. The switch turns ON when both the switch voltage and the derivative of switch voltage are zero as shown in Fig. 1(b). These switching conditions are called the class-E zero-voltage switching and zero-derivative switching (ZVS/ZDS) conditions. By applying the class-E ZVS/ZDS conditions to switch voltage, switching losses are reduced to be zero. Therefore, the class-E amplifier can achieve high power-conversion efficiency at high frequencies. The fundamental-frequency component of the switch voltage v_S passes through the resonant filter and sinusoidal output current can be obtained.

2.2. Class-E Driever

By connecting the output of the class-E amplifier to the gate terminal of the driven MOSFET, the class-E amplifier can be used as a driver circuit, which is called the class-E driver. Figure 2(a) and (b) show the circuit topology of the class-E driver and its equivalent circuit model, respectively. The driven MOSFET includes the parasitic input capacitance and resistance at the gate terminal. Therefore, the driven MOSFET is a modeled by the gate capacitance C_g

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[1] This paper is an extended version of [9].

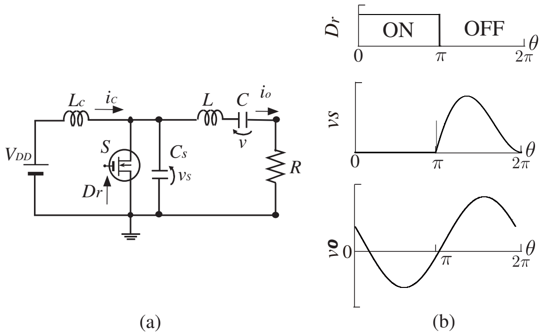


Figure 1: class-E amplifier(a)Circuit configuration. (b)Operating waveform

and the gate resistance R_g ,which are connected in series as shown in Fig. 2(b) [4],[5]. When the class-E amplifier is applied as a driver circuit, a sinusoidal voltage is provided as a driving signal. The sinusoidal voltage includes a negative value, which is not preferred as a driving signal of the MOSFET. For avoiding the negative voltage, a clamp diode is often added to gate-to-drain terminals in parallel as shown in Fig. 2(a).

Figure 2(c) shows the example waveforms of the class-E driver. It is thought intuitively that the driving signal becomes a clamped half wave because of the clamp diode. In actual operation, however the negative voltage disappears by shifting entire sinusoidal wave as shown in Fig. 2(c) [5],[6]. In this operation, the circuit works so that the diode is never in ON state. There is however, no analytical explanation of this voltage-shift phenomenon.

3. Steady-State Analysis Of Class-E Driver

This section shows the principle operation of the voltage shift at the class E driver with clamp diode through the steady-state analysis.

3.1. Assumptions

For simplifying the analysis, the following assumptions are given.

1. The MOSFET and the clamp diode work as ideal switches. Therefore, zero-switching time, zero on-resistances, and infinite off-resistances are assumed.
2. The duty ratio of the class-E driver is $D = 0.5$. The driver MOSFET turns ON and OFF at $\theta = 0$ and $\theta = \pi$, respectively, where $\theta = \omega t = 2\pi f t$ is the phase displacement and ω and f are angular operating frequency and operating frequency, respectively.
3. The loaded quality factor Q of the series resonant filter $L - C - C_g - R_g$, which is defined as

$$Q = \frac{\omega L}{R_g} \tag{1}$$

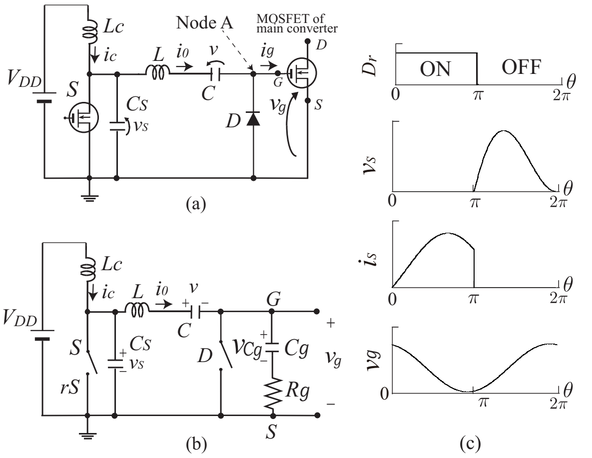


Figure 2: Resonant driver using class E amplifier (a)Circuit configuration (b)Equivalent circuit (c)Example waveforms

is high enough to generate a sinusoidal current through the resonant inductor. Namely, we have

$$i_L(\theta) = I_m \sin(\theta + \phi) \tag{2}$$

where I_m and ϕ are the amplitude and the phase difference of the resonant current.

4. The input inductance is high enough so that input current becomes direct a current I_c.
5. The class-E driver satisfies the class-E ZVS/ZDS conditions at turn-on instant. Namely, the switch voltage satisfies

$$v_S(2\pi) = 0, \tag{3}$$

and

$$\left.\frac{dv_S(2\pi)}{d\theta}\right|_{\theta=2\pi} = 0. \tag{4}$$

3.2. Waveform Equations

Now, it is important to show that the current i_L do not include dc component. If i_L is expressed by

$$i_{L_1}(\theta) = I_m \sin(\theta + \phi) + I_0 \tag{5}$$

the voltage across resonant capacitance is obtained as

$$v_{C0} = \frac{I_m}{\omega C_0}[\cos\phi - \cos(\theta + \phi)) + I_0\theta]. \tag{6}$$

where I_0 is the dc component of the resonant current. Because v_{c_0} is a periodic waveform, it is seen that I_0 should be zero. From the assumptions 1 and 4, the switch current flows through the MOSFET when the switch is in ON state. Therefore, we have

$$i_S(\theta) = \begin{cases} I_C - I_m \sin(\theta + \phi) & \text{for } 0 \le \theta < \pi \\ 0 & \text{for } \pi \le \theta < 2\pi. \end{cases} \tag{7}$$

Similarly, the current, which flows through the shunt capacitance, is

$$i_{C_S}(\theta) = \begin{cases} 0 & \text{for } 0 \le \theta < \pi \\ I_C - I_m \sin(\theta + \phi) & \text{for } 0 \le \theta < 2\pi. \end{cases} \tag{8}$$

The current through the shunt capacitance generates the switch voltage, which is expressed as

$$v_S(\theta) = \begin{cases} 0 \quad \text{for } 0 \le \theta < \pi \\ \dfrac{I_C(\theta - \pi) - I_m[\cos(\theta + \phi) - \cos\phi]}{\omega C_s} \\ \qquad \text{for } \pi \le \theta < 2\pi. \end{cases} \tag{9}$$

From the assumption 1, the output voltage of the driver, which across the gate capacitance and resistance of the driven MOSFET is given by

$$v_g(\theta) = \begin{cases} 0 \quad \text{for } \theta_{ON} \le \theta < \theta_{OFF} \\ R_g I_m \sin(\theta + \phi) + \dfrac{I_m[\cos\phi - \cos(\theta + \phi)]}{\omega C_g} + V_{C_g} \\ \qquad \text{for other cases.} \end{cases} \tag{10}$$

where V_{c_g} is the bias voltage across the gate capacitance, and θ_{ON} and θ_{OFF} mean the instant the diode turn ON or OFF respectively. The output current, which flows through the gate terminal is expressed as

$$i_g(\theta) = \begin{cases} \omega C_g \dfrac{dv_{C_g}(\theta)}{d\theta} & \text{for } \theta_{ON} \le \theta < \theta_{OFF} \\ I_m \sin(\theta + \phi) & \text{for other cases.} \end{cases} \tag{11}$$

The clamp diode turns ON when the output voltage v_g is zero from positive value. Additionally, it turns off when the diode current becomes zero. Therefore, we obtain the relationships about θ_{ON} and θ_{OFF} as

$$\begin{aligned} & R_g I_m \sin(\theta_{ON} + \phi) + \tfrac{I_m[\cos(\phi) - \cos(\theta_{ON} + \phi)]}{\omega C_g} + V_{Cg} = 0 \\ & \qquad \text{with } \left.\frac{dv_g(\theta)}{d\theta}\right|_{\theta = \theta_{ON}} = 0, \end{aligned} \tag{12}$$

and

$$\begin{aligned} & i_D(\theta_{OFF}) = i_g - i_L \\ & = -I_m \sin(\theta_{OFF} + \phi) + \omega C_g \left.\tfrac{dv_{C_g}(\theta)}{d\theta}\right|_{\theta = \theta_{OFF}} = 0 \\ & \text{with } \left.\frac{di_D(\theta)}{d\theta}\right|_{\theta = \theta_{OFF}} = 0, \end{aligned} \tag{13}$$

respectively. It is seen from (10) and (12) that the diode has an opportunity to turn ON when V_{cg} satisfies

$$\begin{aligned} V_{C_g} \le \ & -RI_m \sin[\tan^{-1}(-\omega C_g R_g)] \\ & - \frac{I_m \cos\phi - I_m \cos[\tan^{-1}(-R_g \omega C_g)]}{\omega C_g}. \end{aligned} \tag{14}$$

4. Analytical Explanation of Voltage Shift

It can be stated that the gate current i_g, flowing through $C_g - R_g$, does not have any dc component where voltage is a periodic waveforms. This is because there is the gate capacitance C_g between gate and source terminals. When KVL is applied to the closed circuit consisting of $D - C_g - R_g$ for ON state of the clamp diode. We have

$$R_g \omega C_g \frac{dv_{C_g}}{d\theta} + v_{C_g} = 0 \quad \text{for } \theta_{ON} \le \theta \le \theta_{OFF}. \tag{15}$$

By solving (15), v_{C_g} is expressed by

$$v_{C_g}(\theta) = -RI_m \sin(\theta_{ON} + \phi) \exp[-\frac{(\theta - \theta_{ON})}{\omega R_g C_g}] \tag{16}$$

Namely, the dc component of diode current is

$$\begin{aligned} & \int_0^{2\pi} i_D d\theta = \int_0^{2\pi} (i_g - i_L) d\theta \\ & = \int_{\theta_{ON}}^{\theta_{OFF}} \left[\omega C_g \frac{dv_{Cg}}{d\theta} - I_m \sin(\theta + \phi)\right] d\theta = 0 \\ & = -RI_m \omega C_g \sin(\theta_{ON} + \phi)\{\exp[-\frac{(\theta_{OFF} - \theta_{ON})}{\omega R_g C_g}] - 1\} \\ & +I_m[\cos(\theta_{ON} + \phi) - \cos(\theta_{OFF+\phi})] = 0 \end{aligned} \tag{17}$$

From (13) and (16), we obtain

$$\sin(\theta_{ON} + \phi) = 0 \tag{18}$$

From (17) , (18), we obtain

$$\cos(\theta_{OFF} + \phi) - \cos(\theta_{ON} + \phi) = 0 \tag{19}$$

The solution of (19) are $\theta_{ON} = \theta_{OFF}$ and $\theta_{ON} = \theta_{OFF} + 2\pi$. From (13), it is seen that the current of diode i_D never negative. This means diode never turns ON and only $\theta_{ON} = \theta_{OFF}$ is the solution in (19).

This means that the clamp diode never turns ON in the class-E driver. It is seen from the above discussions that the voltage shift occurs due to coexistence of the resonant capacitance and gate capacitance. These capacitances do not allow the diode current to have a dc component. This is a fundamental mechanism of the voltage shift.

Considering that the charge in the capacitance must be minimize in time average. It is obtained from (16) that the bias voltage in the capacitance C_g is

$$\begin{aligned} V_{C_g} = \ & -R_g I_m \sin[\tan^{-1}(-\omega C_g R_g)] \\ & - \frac{I_m \cos\phi - \cos[\tan^{-1}(-\omega C_g R_g)]}{\omega C_g}. \end{aligned} \tag{20}$$

5. Design Example

In this section, the validity of the analysis is confirmed by comparisons with PSpice simulation and experimental results. The operating frequency $f = 7$ MHz, $Q = 5$ and duty ratio of the drive MOSFET $D = 0.5$ were given as a driver specifications. The SUD06N10 SiC MOSFET was supposed as the driven MOSFET. Therefore, the gate resistance and capacitance were obtained as $R_g = 22.9\ \Omega$ and $C_g = 1.11$ nF, which were measured by Impedance Analyzer of KEYSIGHT E4990A.

Because the clamp diode never turns ON from the theory in the previous section, it is possible to obtain the component value for satisfying the class-E ZVS/ZDS conditions from the design equation of the class-E amplifier in [8]. Table 1gives the obtained component values. We used SS2040FL schottky barrier diode for the clamp diode. For driving the MOSFET in the driver circuit, Intersil EL7104 was used. All the component values were measured by KEYSIGHT E4990A impedance analyzer. The experimental waveforms were measured by oscilloscope of Tektronix MDO3024.

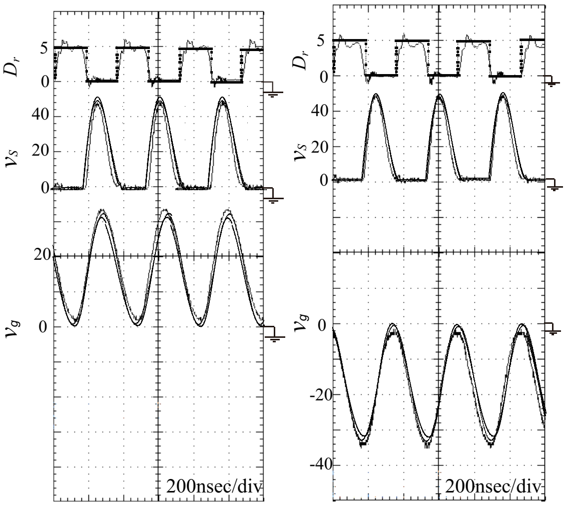
Figure 3 shows the analytical and experimental waveforms. When the clamp diode was connected in the positive direction as shown in Fig. 2(a), lower limit of the gate voltage of the driven MOSFET was zero. This is because the clamp diode did not work. Conversely, the upper limit of the gate voltage became zero when the clamp diode was connected in the negative direction, which can be confirmed from Fig. 3(b). Namely, the bias voltage changed depending on the direction of diode. The validity of the theory that the driver works so that the clamp diode never turns ON was confirmed from Fig. 3. It is also seen from Fig. 3 that analytical predictions showed good agreement with experimental results. All the waveforms satisfied the class-E ZVS/ZDS conditions. It can be stated that the analytical expressions were verified by the quantitative agreements with the circuit experiments.

Table 1: Component values of the designed class-E driver

	Analytical	Measured	Difference
L_c	40 μH	39.4 μH	1.5 %
L_1	2.60 μH	2.62 μH	0.85 %
C_1	377 pF	374pF	1.0%
C_s	183 pF	183 pF	0%
R_g	22.9 Ω	23.0 Ω	0.65 %
C_g	1110 pF	1112	0.9%

6. Conclusion

This paper has given analytical explanations of voltage shift. By carrying out steady-state analysis, it have been clarified that the voltage shifts occurs due to coexistence of resonant and gate capacitances. The validity of analysis was confirmed by comparison with experimental results.



(a) (b)

Figure 3: Analysis(line) and experimental waveforms (dotted line) of the class-E driver. (a)In the case that the clamp diode is connected in the positive direction as shown in Fig. 2 (a). (b) In the case that the clamp diode is connected in the negative direction.

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