Analysis and Design of Controllable Class E Low *dv/dt* Synchronous Rectifier

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Abstract **-Class E synchronous rectifier regulating the output voltage at a fixed switching frequency is presented, analyzed and experimentally verified. This rectifier is derived from a class E low *dv/dt* rectifier by replacing a rectifier diode with a controlled switch. The rectifier is driven by a sinusoidal current source, and the output voltage is regulated by vary the conduction time of the controlled switch. The ZVS condition of a switch can be maintained from full-load to open-load operation. The experimental results measured at switching frequency 1 MHz were good agreement with the theoretical prediction.**

1 Introduction

Class E zero-voltage switching rectifier [1]-[9] has been used in high-frequency converter circuits to reduce its size, weight, EMI noise and increase rectification efficiency. Many published papers [1]-[7] have been presented many topologies of the class E rectifier, in which the operating frequency is varied against the variation of load or line voltage. To avoid problems accompanied by variation of operating frequency, we present the current driven class E low *dv/dt* synchronous rectifier regulating the output voltage at a fixed switching frequency.

2 Circuit Operations

Figure 1(a) shows the basic circuit of class E low dv/dt rectifier and (b) shows the proposed rectifier. The proposed rectifier consists of a transformer (T), switch (S_1) with its body diode (D_1), shunted capacitor (C_1), output capacitor (C_o) and the output load (R_L)

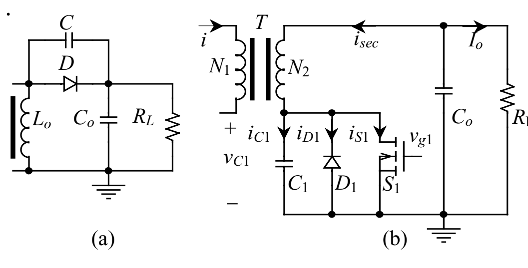

Figure 1: Class E low *dv/dt* rectifier. (a) Basic circuit. (b) Controllable synchronous rectifier.

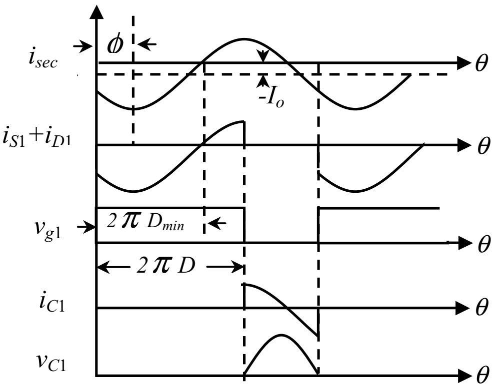

Figure 2: Idealized operating waveforms of class E controllable low *dv/dt* synchronous rectifier.

The proposed rectifier is modified from the basic rectifier by replacing the rectifier diode (D) with the controlled switch (mosfet S_1 with its body diode D_1). The secondary coil inductance of the transformer (T) is to operate as the output choke (L_O) forming the dc output current loop. The output voltage is filtered by first-order low-pass output filter, which is formed by the output capacitor (C_o) and the load (R_L). The filter attenuates the output voltage ripples, so that the output voltage (V_o) is supported approximately constant. Figure 2 shows the idealized operating waveforms of the proposed rectifier. The secondary coil current (i_{sec}) caused by the induced current from the driving input current (i') and the output dc current (I_o). The switch (S_1) is driven by V_{gs} from 0 to $2\pi D$. The conduction time of switch (S_1) begins at the time of the origin of the graph of Fig. 2, when the cathode of D_1 reaches zero volts with respect to the anode, after having been positive with respect to the anode. The shunt capacitor (C_1) shapes the voltage (v_{C1}) across switch (S_1) so that the switch turn-on and turn-off at zero-voltage.

The control interval of D is $D_{\min} \le D < 1$. The regulation of the output voltage can be described as follows.

- $D=D_{min}$: S_1 and D_1 conduct the negative current only. The conduction time of S_1 is equal to the conduction time of D_1 and I_o is the maximum.
- $D=1$: S_1 and D_1 conduct all cycle and I_o equal zero.
- $D_{\min} \le D < 1$:part of the positive current of i_{S1} flows through S_1. The averaged current through S_1 and D_1 is between 0 and the values corresponding to D.

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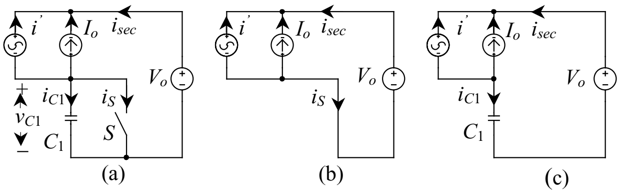

Figure 3: (a) Modeled of class E low *dv/dt* controllable synchronous rectifier, (b) when switch turn-on (c), when switch turn-off.

3. Circuit Analysis

The analysis of the rectifier begins with the following assumptions.

- The controlled switch (S_1) and diode (D_1) form an ideal switch. (S)
- The transformer (T) is ideal and secondary inductance (L_O) is large enough that the dc component current is constant and equals I_O.
- The rectifier is driven by an ideal sinusoidal current source (i).
- The passive components in circuit are ideal.

The driving input current (i') of a rectifier is

$$i' = \left(\frac{N_1}{N_2}\right) \cdot i = I_m \cos(\theta - \phi) \tag{1}$$

where N_1,N_2 are the number of transformer winding , i is the transformer primary current, I_m is the current peak value, and ϕ is phase angle. If the transformer (T) is ideal, the induced current (i') will be directly connected in parallel to equivalent dc current source (I_o).The transformer secondary current is equal to

$$i_{sec} = -\left(i' + I_o\right) \tag{2}$$

where I_o is the dc component of secondary current and equal to the dc output current. The shunt capacitor voltage (v_{C1}) is

$$v_{C2} = \frac{1}{\omega C_2}\int_{2\pi D}^{\theta} i_{sec} d\theta = \frac{V_O}{\omega C_2 R_L}\left[2\pi D - \theta - \frac{\sin(\theta-\phi) - \sin(2\pi D - \phi)}{M}\right] \tag{3}$$

where $M=I_o/I_m$ and $I_o=V_o/R_L$. Since $v_S=v_{c1}$ and $i_S=i'+I_o$, the switch voltage and current waveforms normalized with respect to V_o and I_o respectively expressed as

$$\frac{v_S}{V_O} = \begin{cases} 0, & 0 < \theta \le 2\pi D \\ \dfrac{1}{\omega C_2 R_L}\left[2\pi D - \theta - \dfrac{\sin(\theta-\phi) - \sin(2\pi D-\phi)}{M}\right], & 2\pi D < \theta \le 2\pi \end{cases} \tag{4}$$

$$\frac{i_S}{I_O} = \begin{cases} -1 - \dfrac{\cos(\theta-\phi)}{M} & 0 < \theta \le 2\pi D \\ 0, & 2\pi D < \theta \le 2\pi \end{cases} \tag{5}$$

From (3), the boundary condition of C_1 voltage when $\theta=2\pi$ is $v_{c1}(2\pi)=0$, yields

$$M = \frac{I_O}{I_m} = \frac{\sin(2\pi D - \phi) + \sin\phi}{2\pi(1-D)} \tag{6}$$

Because the secondary winding of the transformer has no dc voltage drop and the average value of v_{c1} is equal to V_o

$$V_O = \frac{1}{2\pi}\int_{2\pi D}^{2\pi} v_{C1} d\theta \tag{7}$$

Rewrite the result of (7), then we have

$$\frac{I_O}{I_m} = 2\frac{\cos\phi - \cos(2\pi D - \phi) - (2\pi D - 2\omega C_2 R_L)\sin(2\pi D - \phi)}{4\pi\omega C_2 R_L + 4\pi^2(1-D)^2} \tag{8}$$

Solving ϕ by using (6) and (8), yields

$$\phi = \tan^{-1}\left[\frac{\left[4\pi^2(1-D)^2 - 4\pi\omega R_L C_2\right]\sin 2\pi D + 4\pi(1-D)(1-\cos 2\pi D)}{\left(4\pi\omega R_L C_2 + 4\pi^2(1-D)^2\right) + \left[4\pi^2(1-D)^2 - 4\pi\omega R_L C_2\right]\cos 2\pi D + 4\pi(1-D)\sin 2\pi D}\right] \tag{9}$$

The ac-to-dc current transfer function of rectifier is defined as

$$K_I = \frac{I_O}{I} = \frac{\sqrt{2}I_O}{I_m} = \sqrt{2}M \tag{10}$$

where I is the rms value of input ac current. Substitute (9) into (10) and we obtain K_I as function of $\omega C_1 R_L$ and D shown in Fig. (4). Figure 5 shows the behavior of the maximum K_{I_max} which occurred when $\omega C_1 R_L = \omega C_1 R_{L\min}$ and $D=D_{\min}$. To obtain the relationship between $\omega C_1 R_L$ and $D_{\min}$ when K_{I_max} occurred, we substitute $D=D_{\min}$ in (6), $\theta=2\pi D_{\min}$ in (5) and use the boundary condition of switch current $i_S(2\pi D_{\min})=0$ in (5).

We have phase angle ϕ when K_{I_max} occurred as

$$\phi = -\tan^{-1}\left(\frac{\sin 2\pi D_{\min} + 2\pi(1-D_{\min})\cos 2\pi D_{\min}}{1 - \cos 2\pi D_{\min} + 2\pi(1-D_{\min})\sin 2\pi D_{\min}}\right) \tag{11}$$

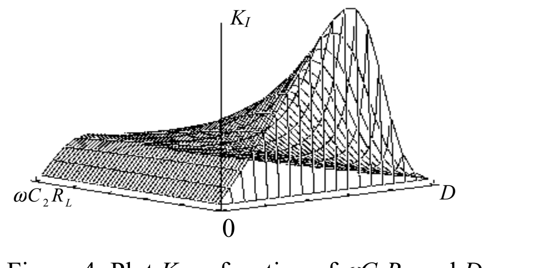

Figure 4: Plot K_I as function of $\omega C_1 R_L$ and D.

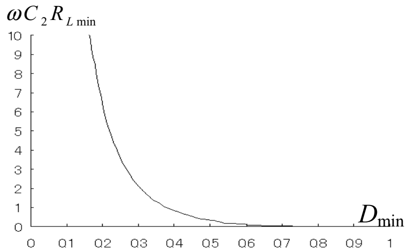

Figure 5: Relationship between $\omega C_1 R_{L\min}$ and $D_{\min}$.

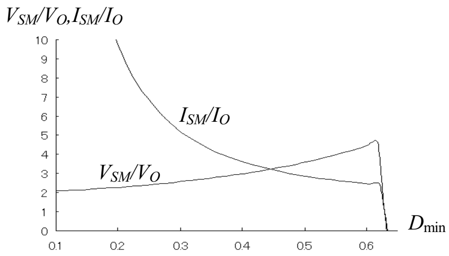

Figure 6: Normalized values of switch stress voltage and currents at any $D_{\min}$

Substitute D=$D_{\min}$ and $\omega C_1 R_L$= $\omega C_1 R_{L\min}$ into (9), and solving $\omega C_1 R_{L\min}$ from (9) and (11) yields

$$\omega C_1 R_{L\min} = \frac{1}{4\pi \sin^2 2\pi D_{\min}} \{(2\pi - 2\pi D_{\min})(2\sin 4\pi D_{\min} + 4\sin 2\pi D_{\min}) + 2(2\pi - 2\pi D_{\min})^2 (1+\cos 2\pi D_{\min}) - ((2\pi - 2\pi D_{\min})^2 - 4)\sin^2 2\pi D_{\min}\} \qquad (12)$$

We use this equation to select C_1 and $D_{\min}$ when the maximum load is given. We can see that, the maximum switch current occurred when $\theta = \phi$ in (5). By substitution this angle in (5), we obtain

$$\frac{I_{SM}}{I_O} = 1 + \frac{(2\pi - 2\pi D_{\min})}{\sin(2\pi D_{\min} - \phi) + \sin\phi} \qquad (13)$$

Similarly, the normalized switch stress voltage when $K_{I\_\max}$ occurred at any $D_{\min}$ can be calculated by substitution $\theta = \phi + \pi + \cos^{-1} 1/M$ into (4). This yields

$$\frac{V_{SM}}{V_O} = \frac{-1}{\omega C_2 R_{L\_\min}} \left\{ \theta_{vS\_\max} - 2\pi D_{\min} + \frac{(2\pi - 2\pi D_{\min})(\sin(\theta_{vS\_\max} - \phi) - \sin(2\pi D_{\min} - \phi))}{\sin(2\pi D_{\min} - \phi) + \sin\phi} \right\} \qquad (14)$$

The phase angle (ϕ) in (11) continues its sign in the range $0 \le D_{\min} \le 0.628$ and will change in the sign inverse when out of this range; In practice, it is sufficient to use this range for design of the rectifier because the optimum circuit parameters occur around $D_{\min}$=0.5 (see Table 1). The ac-to-dc voltage transfer function (M_R) of the rectifier is given by

$$M_R = \frac{V_o}{V_{Ri1}} = \frac{I}{I_{O1}} = \frac{1}{\sqrt{2}M}. \qquad (15)$$

The equivalent input resistance (R_i) of the rectifier is

$$\frac{R_i}{R_L} = \frac{I_O^2}{I^2} = 2M^2 \qquad (16)$$

The fundamental component of equivalent input capacitance (C_i) voltage is expanded by using the Fourier series, yields

$$v_{c1} = -V_O + V_{Rim}\cos(\theta - \phi) - V_{Cim}\sin(\theta - \phi) \qquad (17)$$

where V_{Rim} and V_{cim} are the amplitudes of voltage across the equivalent input resistance (R_i) and capacitance (C_i) respectively. V_{Cim} is calculated by

D_{min}	ϕ	$\omega C_1 R_{L\min}$	I_{SM}/I_O	V_{SM}/V_O	c_p	R_i/R_L	C_i/C_1	K_I	M_R
0	-1.571	∞	∞	2	0	0	1	0	∞
0.05	-1.265	125.4	129.40	2.022	0.004	0.001	1.003	0.011	90.79
0.1	-0.973	29.99	33.73	2.079	0.014	0.002	1.023	0.043	23.14
0.15	-0.696	12.41	15.96	2.164	0.029	0.009	1.074	0.094	10.58
0.2	-0.430	6.337	9.717	2.273	0.045	0.026	1.166	0.162	6.164
0.25	-0.174	3.590	6.805	2.407	0.061	0.059	1.316	0.244	4.104
0.3	0.073	2.151	5.211	2.565	0.075	0.113	1.547	0.336	2.977
0.35	0.314	1.328	4.243	2.753	0.086	0.190	1.899	0.436	2.293
0.4	0.548	0.829	3.610	2.975	0.093	0.294	2.442	0.542	1.846
0.45	0.777	0.518	3.175	3.240	0.097	0.423	3.3	0.650	1.538
0.5	1.003	0.319	2.863	3.560	0.098	0.576	4.717	0.759	1.318
0.55	1.225	0.192	2.634	3.953	0.096	0.749	7.184	0.866	1.155
0.6	1.444	0.112	2.461	4.444	0.091	0.937	11.792	0.968	1.033

Table 1: Rectifier design parameters

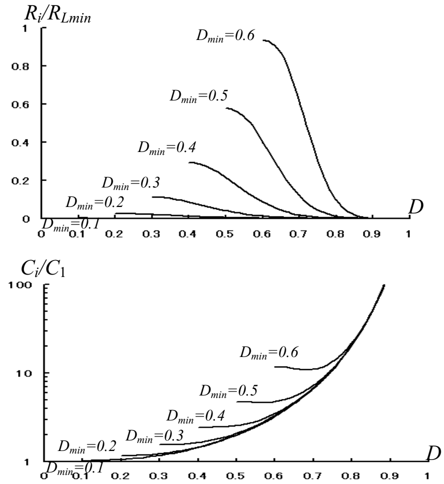

Figure 7: Normalized input resistance $R_i/R_{L\min}$ and input reactance C_i/C_1 versus $D_{\min}$ when D is varied from $D_{\min}$ to 1.

$$V_{Cim} = \frac{1}{\pi}\int_{2\pi D}^{2\pi} v_{C2}\sin(\theta - \phi)\,d\theta = \frac{I_m}{\pi\omega C_2}\left\{[2\pi(D-1)\cos\phi - \sin\phi - \sin(2\pi D - \phi)]M + \frac{1}{2}\left[\left(\frac{1}{2} - \cos^2\phi\right)\sin 4\pi D - (1-\cos 2\pi D)\sin 2\phi\cos 2\pi D + 2\sin 2\pi D\cos^2\phi + 2\pi(1-D)\right]\right\} \qquad (18)$$

The input reactance (X_{ci}) at operating frequency is $1/\omega_{Ci}$ or equal to V_{cim}/i_{sec} and from (18) the normalized equivalent input capacitance (C_i) respect to C_1 can be expressed by

$$\frac{C_i}{C_1} = \pi / \left\{[2\pi(D-1)\cos\phi - \sin\phi - \sin(2\pi D - \phi)]M + \frac{1}{2}\left[\left(\frac{1}{2} - \cos^2\phi\right)\sin 4\pi D - (1-\cos 2\pi D)\sin 2\phi\cos 2\pi D + 2\sin 2\pi D\cos^2\phi + 2\pi(1-D)\right]\right\} \qquad (19)$$

Figure 7 shows the normalized equivalent input resistance $R_i/R_{L\min}$ and the equivalent input reactance C_i/C_1 versus $D_{\min}$ when D is varied from $D_{\min}$ to 1. After we known R_i and C_i, they will be transferred to the primary side of transformer by factor $(N_1/N_2)^2$.

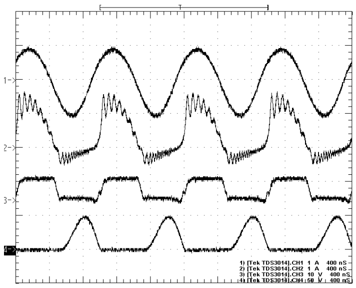

Figure 8: Rectifier operating waveforms at 1MHz. (ch.1 i 1A/div, ch.2 i_{sec} 1A/div, ch.3 v_{g1} , ch.4 v_{s1} ; horizontal 400nS/div.)

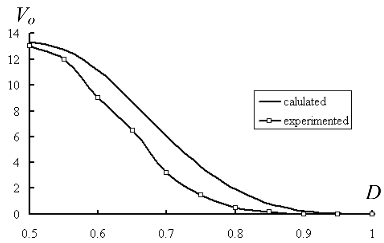

Figure 9: Output voltage control characteristic.

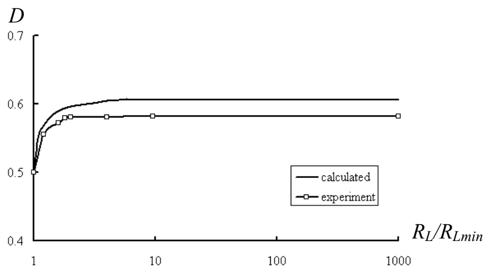

Figure 10: shows the output voltage regulation characteristic.

4. Design example

To show the design example of the proposed rectifier, a resistor R_L=25 Ω is given for the maximum output load. The class D inverter operates at switching frequency 1MHz with Q=10 with output current 1 A $_{peak}$ is used as the sinusoidal current source (i). From Table 1, we select D_{min}=0.5, we have $\omega C_1 R_{Lmin}$=0.319, I_{SM}/I_O =2.863, V_{SM}/V_O=3.650, R_i/R_{Lmin}=0.576, C_i/C= 4.717, K_I=0.759, M_R=1.318 and $\omega C_1(V_O/I_m)$ =0.171. The rectifier parameters are C=2.03nF, I_O=0.5367A, V_O=13.417V, R_i=14.4 Ω , C_i=9.575nF, V_{SM}=48.97V and I_{SM}=1.534A.

5. Experimental results

In experimentation, the high-frequency transformer with $N_1=N_2$ with secondary coil inductance (L_O) equal 100uH is used as T, capacitor 4.7uF as the output capacitor (C_O) and a Mosfet IRL640 is used as the controlled switch (S). Figure 8 shows the operating waveforms when rectifier is driven by sinusoidal current 1A $_{peak}$ at frequency 1MHz. The duty ratio (D) of driving signal (V_{gs}) is equal to 0.5 (or $D=D_{min}$) and loaded by resistor 25 Ω . The measured values are V_O=13V, V_{SM}=50V and I_{SM}=1.54A. Figure 9 shows the output voltage control characteristic of the rectifier when the output load was fixed at 25 Ω, by vary the duty ratio (D) from 0.5 to 1, the output voltage is decrease from 13V to 0V. Figure 10 shows the voltage regulation characteristic of the rectifier. By varying the duty ratio (D) from 0.5 to 0.585, the output voltage can be maintained at 13V when the output load was changed from R_L/R_{Lmin}=1 to 100.

6. Conclusion

The controllable class E low *dv/dt* synchronous rectifier can regulate the output voltage at fixed switching frequency by control the conduction angle or duty ratio. The switching is satisfied with zero-voltage switching condition from full-loaded to open-loaded

7. Acknowledgments

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