Resonant dc/dc Converter with Class DE Inverter and Class E Rectifier Using Thinned-Out Method (Deleting Some of the Pulses to the Rectifier)

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Abstract—The Class DE inverter offers high-efficiency power conversion under high operating frequency (megahertz order) with low switching noises and low switch voltage stress. It has been applied to dc/dc converters as high-density power sources. Conventional converters with the Class DE inverter are controlled by varying the operating frequency, the switch duty ratio or the phase difference with two inverters. However, in general, frequency-modulated control requires a complex control unit. Changing the switching duty ratio puts the switch-voltage waveforms out of shape, and the phase shift control needs the double space of inverters, which is not suitable for the low output power circuit. As a remedy to these problems, we propose to combine the Class DE inverter with the Class E rectifier using the thinned-out method (deleting some of the pulses to the rectifier). The dc/dc converter’s output power is controlled in the rectifier by eliminating its diode-voltage pulse at a desirable rate. The operating frequency is fixed and the waveforms keep the characteristics of Class DE. An experimental circuit was designed at 1-MHz operating frequency and in the optimum operation, the measured dc/dc power conversion efficiency was over 80% with 2.2-W output power at 1 MHz. Characteristics of the converter for the line and load variations are given by circuit experiments. It is shown that the proposed circuit has good characteristics with high power conversion efficiency in a wide range of these variations.

Index Terms—Class DE inverter, resonant converter.

I. INTRODUCTION

Class DE circuits [1]–[9] realize highly efficient power conversion under high operating frequency (megahertz order) by means of Class E switching conditions [10]–[13]. In addition to this, they have low-switching noises and low-switch voltage stress. However, the first Class DE converter needs frequency-modulated (FM) control to regulate the output power [2], [5], [6]. In general, FM control requires a complex control unit. Then, phase-modulated (PM) control [4] and pulselwidth-modulation (PWM) control [8] are applied to Class DE inverters. PM control can be justified in full-bridge converters used for high-output power, however in the case of small output power, small-sized half-bridge converters are better, because PM control needs two Class DE inverters so its volume becomes about twice as large as the basic one. The PWM controlled Class DE inverter reported in [8] does not keep the switch voltage waveform which satisfies Class E switching conditions and zero-voltage switching.

On the other hand, the Class E rectifier realizes highly efficient ac/dc conversion at high operating frequency with low switching losses and noises [13]–[15]. In recent papers [16], [17], it is reported that output power is easily regulated at a fixed operating frequency by applying the thinned-out method to the Class E rectifier (deleting some of the pulses to the rectifier).

In this paper, we propose to combine the Class DE inverter with the Class E rectifier using the thinned-out method. Controlling only the rectifier’s diode-voltage pulses, the output power or voltage can be easily regulated with high power conversion efficiency at a fixed operating frequency. The experimental results of the thinned-out control are given. In the optimum operation, the measured dc/dc power conversion efficiency was over 80% with a 2.2-W output power at 1 MHz. Characteristics of the converter for the line and load variations are given by the circuit experiments.

II. CIRCUIT DESCRIPTION

A. Class DE Inverter

The circuit topology of the proposed converter is shown in Fig. 1(a). The input impedance of the Class E rectifier is regarded as an R-C series circuit for its fundamental frequency component [18]. This is shown in Fig. 1(b) as an equivalent circuit which is useful for analysis and used in the design of the inverter. The Class DE inverter consists of a series of resonant output circuits, two active devices, with a shunt capacitor and a load resistance. The active devices $S_1$ and $S_2$ are operated as switches at the operating frequency by the gate–source voltages of $D_{s1}$ and $D_{s2}$. Each switch has a shunt capacitor $C_{s1}$, $C_{s2}$ in parallel, which includes the parasitic capacitance of the active device. The series resonant circuit $L_C$ is composed of an inductance $L$ and an ideal tuned circuit $L_C$. The input of the Class DE inverter is dc voltage $V_l$ and the output is sinusoidal current $i_l$. The loaded quality factor $Q$ is assumed to be high enough to feed the sinusoidal current to the rectifier.

Fig. 2(a) shows the waveforms on the Class DE inverter and relationships between the switch voltage waveforms and their driving patterns. The switches turn on and off alternately at the operating frequency. There is a dead time between one switch’s turning off and the other one’s turning on. During the dead time, the sinusoidal current
i_o charges a shunt capacitor, and discharges the other. Therefore, the voltage across the switch goes to zero or V_i. This operation is the same as the zero-voltage-switching (ZVS) Class D inverter [19], [20]. At the end of the dead time, the switch voltage is equal to zero or V_i and its slope is also zero because of Class E switching conditions [10]–[13]. The dead time duty ratio D_f of the Class DE inverter can be specified by any values from 0 to 0.5 [9]. The smaller D_f is, the larger becomes the power output capability [9]. Here, we specify D_f = 0.25, as shown in Fig. 2(a), for the simplification of our driving circuit [6].

**B. Class E Rectifier Using Thinned-Out Method**

The circuit topology of a Class E rectifier using the thinned-out method is shown in Fig. 1(a). It consists of a diode D, a shunt capacitance C_3, a low-pass filter L_{f1} = C_{f1}, and an active switch S_r [16], [17]. A basic Class E rectifier [14] doesn’t have any controlled active devices.

The shunt capacitor contains parasitic capacitances of the diode and the MOSFET. When the ratio of the thinned-out pulses is zero, the rectifier performs as a basic Class E rectifier. The basic Class E rectifier is driven by a nearly sinusoidal current i = I_m \sin(\omega t + \phi) = i_o, where I_m is the amplitude and \phi is the phase angle. Assuming a large inductance of the output filter L_{f1}, the current through the inductance is approximately constant and equal to the dc output current I_o. Thus, the current i_s flowing through the parallel combination of the diode D and the capacitor C_3 is equal to I_o – i, that is, i_s = I_o – i = I_o – I_m \sin(\omega t + \phi). While the diode is on, the current i_s flows through the diode. While the diode is off, it flows through the capacitor C_3, producing the voltage v_d across the capacitor and the diode. Thus, the capacitor current is expressed as i_c = C_3 \cdot d v_d / dt. The capacitor current is zero at turn-off, so the slope of the diode voltage is also zero. Therefore, the rectifier also satisfies the Class E switching conditions [18].

Connecting an active switch S_r in parallel with the diode, the thinned-out method is applied to the basic Class E rectifier [16], [17]. The thinned-out of a diode-voltage pulse is done with the active switch’s turning on by the “thinned-out pulse” that is the gate-source voltages of D_{r1} while the diode is supposed to be off. Fig. 2(b) shows the diode voltage waveform and the relationship between the pulses on the rectifier and a driving pattern of the switch. While the switch is on, the current i_s flows through it. So, the voltage across the diode is kept at zero, that is, one pulse of the diode voltage is extinguished. The input resistance and capacitance of the rectifier are changed by the switch’s operation. If the amplitude of the input sinusoidal current and the diode duty ratio are constant, the output voltage is reduced in proportion to the ratio of thinned-out pulses [17].

In the case when the impedance of the rectifier is varied, the Class DE inverter does not keep the Class E switching conditions. However, it can keep the ZVS, so the inverter performs as a ZVS Class D inverter for any thinned-out ratio [19], [20]. Therefore, the inverter operates with high-power conversion efficiency and low switching noise. The power dissipation in the switch during the switch-on time is small because of the small saturation resistance of MOSFETs. The ratio of thinned-out pulses is defined as S = N_f / (N_r + N_s), where N_r is the number of remained pulses, and N_s is that of thinned-out pulses. We use this parameter in the following description. The thinned-out cycle is (N_r + N_s) \cdot f^{-1}. In the case of circuit design, we have to prepare for the lowest frequency noise caused by the thinned-out control.

In case the required response time is sufficiently longer than a thinned-out cycle, we can select a lot of patterns of thinned-out pulses. Therefore, discreteness of the output power can be negligible, however the output filter must be designed to have a lower corner frequency. In cases when quick response is required, the thinned-out cycle has to be small. In such cases, we cannot ignore the discreteness. The designer’s choice depends on the specific application.

**III. DESIGN PROCEDURE**

The details of analytical descriptions are given in [5], [6] and [17]. To design an experimental circuit of the proposed converter, the following conditions are given: the operating frequency f = 1 MHz, the input voltage V_i = 18.0 V, the output voltage V_o = 5.0 V, the loaded quality factor Q = 10, and the load resistance R = 10 \Omega. We assume the overall converter efficiency \eta = 80\%. When the thinned-out ratio is zero, Class E switching conditions are satisfied. From the power relationships [5], we have P_o = V_o^2 / R = 6.0^2 / 10.0 = 2.5 W; P_i = P_o / \eta = 2.5 / 0.80 = 3.13 W; P_r = P_i / V_i = 3.13 / 18 = 0.174 A; I_o = V_o / R = 5.0 / 10.0 = 0.5 A.

For the inverter, we yield the following values of elements [5], [6]:

- C_{i1} = C_{i2} = 1 / 4 \pi^2 f R_i = 1 / 4 \pi^2 f 1 \times 10^6 = 5.0 nF; L = \pi R_i / 4 \pi f = \pi \cdot 5 / 4 \pi 10^6 = 1.27 \mu H; L_s = Q R_i / \omega = 10 / 5 / 2 \pi 10^6 = 8.06 \mu H; L_j = L - L_s = 6.79 \mu H; C_j = 1 / 4 \pi^2 f L_j = 1 / 4 \pi^2 1 \times 10^6 = 6.79 \cdot 10^{-9} = 3.73 nF.

The dc/dc voltage transfer function is M = V_o / V_i = M, M, \sqrt{\eta} = 0.225 \cdot 1.414 \cdot \sqrt{0.80} = 0.25 [5].

Second, for the rectifier, R_i / R = 5 / 10 = 0.5, which gives D_{r1} = 0.476 from [5], [17]. Using this value of D_{r1}, we have \omega C_3 R = 0.403 and
Fig. 3. Observed waveforms in the experimental circuit. (a) For optimum operation at $f = 1.00$ MHz, $V_j = 18.0$ V, $V_O = 4.64$ V, $R = 10 \Omega$ and $P_{out} = 2.2$ W, (b) for ratio of thinned-out pulses 0.25 at $f = 1.00$ MHz, $V_j = 18.0$ V, $V_O = 3.99$ V, $R = 10 \Omega$ and $P_{out} = 1.6$ W. Vertical: 20V/div ($V_{D1}, V_{D2}$), 5V/div ($V_{O}, D_{T1}, D_{T2}$); horizontal: 500 ns/div.

IV. EXPERIMENTAL RESULT

The resonant dc/dc converter using the thinned-out method of Fig. 1 was built using the design values calculated in the design example given in Section III. Three 2SK982 MOSFETs (Toshiba) were used as switches $S_1, S_2$ and $S_3$. One Schottky barrier diode 11DQ04 was used as the diode $D$. Filter elements were $L_{fj} = 320 \mu H$ and $C_{fj} = 16 \mu F$.

Fig. 3 shows the experimental waveforms: (a) for optimum operation at $f = 1.00$ MHz, $V_j = 18.0$ V, $V_O = 4.64$ V, $R = 10 \Omega$, (b) for ratio of thinned-out pulses 0.25 at $f = 1.00$ MHz, $V_j = 18.0$ V, $V_O = 3.99$ V and $R = 10 \Omega$. At the optimum condition, the waveforms agree well with theoretical predictions shown in Fig. 2 and the measured efficiency was 80.3%. As shown in Fig. 3(b), the waveforms maintained the characteristics of Class DE. In this time, the output voltage was reduced to 3.99 V with 74.1% measured efficiency.

Fig. 4 shows the power conversion efficiency and output voltage as functions of ratio of thinned-out pulses for $V_j = 18.0$ V, $R = 10 \Omega$, $f = 1.00$ MHz.

Then, the dc output filter $L_{fj}, C_{fj}$ has to be designed to suppress ripples in the output voltage, which are caused by the thinned-out control, and the same applies to the input capacitance which stabilizes the input voltage $V_j$.
= 10Ω and f = 1.00 MHz. When the normalized input voltage changed from 1.0 to 2.8, the output voltage was kept 4.64 V by varying the ratio of thinned-out pulses from 0 to 0.75. Especially, in the range between 1.0 and 1.4 of V\textsubscript{i}/V\textsubscript{i,opt} the measured power conversion efficiency was maintained at over 70%. It is equal to the range from 0 to 0.5 of the thinned-out ratio, which agrees with the characteristics observed in Fig. 4.

Fig. 6 shows the power conversion efficiency and ratio of thinned-out pulses as functions of R/R\textsubscript{i,opt} for R\textsubscript{i,opt} = 10 Ω, V\textsubscript{o} = 4.64 V, V\textsubscript{i} = 18.0 V and f = 1.00 MHz. When the normalized load resistance changed from 1.0 to 1.53, the output voltage was kept 4.64 V by varying the ratio of thinned-out pulses from 0 to 0.5. In this range, the power conversion efficiency was maintained at over 66%. In this test, the maximum value of the thinned-out ratio was limited by the maximum load resistance which is open circuit. That is, the output voltage of the open circuit can be reduced.

V. CONCLUSION

We have proposed a resonant dc/dc converter with the Class DE inverter and the Class E rectifier using the thinned-out method. The additional element is only one active device connected in parallel to the rectifier’s diode. The regulation is carried out in the rectifier with high-power conversion efficiency at a fixed frequency.

We showed the design procedure and experimental results of the converter. Characteristics of the converter for the line and load variations are given by the circuit experiments. The measured dc/dc power conversion efficiency is over 80% with 2.2 W at 1.00 MHz. The output voltage can be reduced from the designed voltage to 11.4% of it with the changing of the thinned-out ratio from 0 to 0.94. The power conversion efficiency is kept at over 68% between 0 and 0.5 of the ratio of thinned-out pulses. Against the line variation, between 100% and 280% of the designed input voltage, the designed output voltage can be maintained with changing the ratio of thinned-out pulses from zero to 0.75. The power conversion efficiency is over 70%, when input voltage is between 100% and 140% of the designed one. Against the load variation, between 100% and 153% of the designed load resistance, the output voltage can be kept by controlling the ratio of thinned-out pulses from 0 to 0.5 with over 66% of power conversion efficiency.

The operating frequency is fixed, so the control circuit can be miniaturized or reduced.

The experimental results show that the converter is suitable for a high-efficiency high-frequency power conversion.

ACKNOWLEDGMENT

The authors wish to thank Dr. T. Suetsugu of Fukuoka University for his helpful and significant comments related to this work.

REFERENCES