A NEW HIGH PERFORMANCE ZERO-VOLTAGE ZERO-CURRENT MIXED MODE SWITCHING DC/DC CONVERTER

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ABSTRACT

A new high performance DC/DC converter which has good DC characteristic and operates on constant frequency, variable duty mode in a wide load range is proposed. It has also low switching loss, low voltage stress and low EMI. Owing to these features, the proposed converter overcomes most of the limitations of resonant converters and quasi-resonant converters such as high VA rating of resonant elements, variable frequency operation and limited load range and improves the efficiency and DC characteristic of the pseudo-resonant converter. Proposed converter is thought to be suitable for high power applications above several KVA as well as low power range with high power density and high performance. Simulation results are shown under the conditions of 100 KHz and 1 KVA load.

I. INTRODUCTION

The demand for small size and light weight converter in a variety of industrial and aerospace applications can be satisfied employing high frequency operation with zero-voltage or zero-current switching. Resonant converters and quasi-resonant converters can operate on high frequency with low switching loss and low EMI. Therefore these converters are becoming widely used in many areas. However, these converters have well-known problems such as high VA ratings, variable switching frequency and complex control. To overcome these limitations, several new concepts are proposed. Recently, a new easy control method of quantum series resonant converter (QSRC) is proposed [2]. One of the main disadvantages of the QSRC is that the output voltage levels are quantized. Another converter, zero-voltage switching multi-resonant converter reduces the device voltage stress compared with that of zero-voltage switching quasi-resonant converter in an improved load range [5]. This converter, however, is not suitable for higher power applications. D. M. Divan has proposed pseudo-resonant converter to reduce the VA ratings of devices and passive elements [8]. This converter has good features such as simple control, wide load range and constant frequency operation. However, there are other demerits such as additional L-C tank energy loss and load dependent DC characteristic.

To overcome these problems, a new converter is proposed in this paper. The operation of the proposed converter is very similar to that of the conventional PWM DC/DC converter except the zero-voltage and zero-current switchings. Therefore the DC conversion-ratio characteristic of the proposed converter is linear in a wide range similar to the conventional PWM DC/DC converter and has the features of constant frequency and variable duty control with reasonable VA ratings. Besides, it has low switching loss and low EMI due to the zero-voltage and zero-current switchings. Owing to these ideal characteristics, proposed converter has high power density and high performance and is suitable for higher power applications. Basic idea, operation, characteristics and analysis of the proposed converter are described.

II. BASIC IDEA OF PROPOSED CONVERTER

Ideal DC/DC converter would be such a converter having low switching loss, good DC characteristic, constant frequency operation, easy control, reasonably rated reactive elements and wide control and load range. To obtain the above ideal characteristics, many improved resonant and quasi-resonant converters are proposed. The more effective approach to

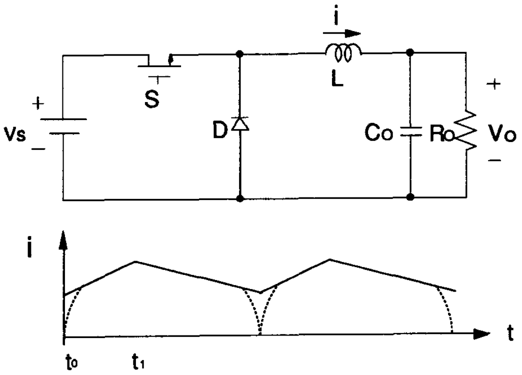


Fig. 1 Inductor current(solid line) of the conventional PWM DC/DC converter and desired current(dotted line) for soft switching

CH2721-9/89/0000-0902 $1.00 © 1989 IEEE

obtain the ideal characteristics, however, is to improve the hard switching conditions in the conventional PWM DC/DC converters because the conventional PWM DC/DC converters have the ideal characteristics except high switching loss.

Such an improvement can be done by providing soft switching conditions with resonant operation during switching operations only as shown in Fig. 1. The solid line is the inductor current waveform of the conventional PWM DC/DC converter and the dotted line denotes the desired inductor current waveform to obtain the zero-current switching condition at time t_0. The soft switching condition at time t_1 can be obtained with zero-voltage switching. This combined zero-current and zero-voltage switching operation enables to obtain the good features of the conventional PWM DC/DC converter as well as the soft switching condition. Furthermore the VA rating of the resonant capacitor becomes reduced significantly compared with that of resonant and quasi-resonant converter because the capacitor does not involve in the primary power transfer. Thus similar characteristics to the conventional PWM DC/DC converter can be realized with low switching loss and low VA rating of the resonant elements.

III. OPERATIONS AND CHARACTERISTICS OF PROPOSED DC/DC CONVERTER

Proposed circuit configuration is shown in Fig. 2, which is composed of four switches, one inductor, two capacitors and one isolation transformer. In this case, S1 and S3 are bidirectional switches and S2 and S4 are unidirectional switches. Fig. 3 shows typical waveforms of the inductor current and device voltages during one cycle switching operation of the converter. During one period, the converter operates in five topological modes as shown in Figs. 5(a)-(e), which is described as follows.

Mode I : resonant mode

This mode begins when switch S4 is turned-on at time t_0 while switches S1, S2 and S3 are off state. Initial inductor current is zero and initial lower side capacitor voltage V_{co} is slightly higher than the supply voltage as shown in Figs. 3(a), (b) and (d), respectively. Because the switch S4 is turned-on at zero-current, turn-on switching loss is very low. During this resonant mode, the current flows through the path comprizing voltage source, capacitors, inductor L, transformer and switch S4 as shown in Fig. 5(a). Inductor current i and lower side capacitor voltage v_c have resonant waveforms as shown in Fig. 3(b) and (d), respectively. When v_c is reduced to the supply voltage V_s, this mode ends.

Mode II : Powering mode

This mode starts by turning on S1 at time t_1 when the lower side capacitor voltage v_c becomes equal to the supply voltage V_s. At this instant the upper side capacitor voltage v_c^* is zero as shown in Fig. 3(e). Therefore S1 is turned-on under zero-voltage switching condition which results in low switching loss. During this powering mode, the current flows through the path comprizing voltage source, switch S1, inductor, transformer and switch S4 as shown in Fig. 5(b). The inductor current increases linearly and lower side capacitor voltage holds the supply voltage as shown in Fig. 3(b) and (d), respectively.

Mode III : resonant mode

The powering mode ends and resonant mode begins when the switch S1 is turned off at time t_2. In this case, the switch S1 is turned-off under zero-voltage condition also. During this mode, the current path is the same as that of the resonant mode I. The inductor current i and lower side capacitor voltage v_c have partially resonant waveforms as shown in Fig. 3(b) and (d), respectively. When the capacitor voltage v_c is decreased to zero, this mode ends.

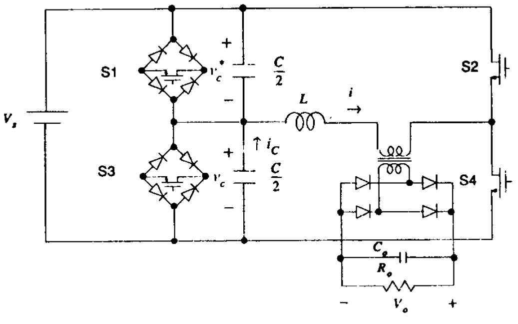


Fig. 2 Circuit diagram of proposed DC/DC converter.

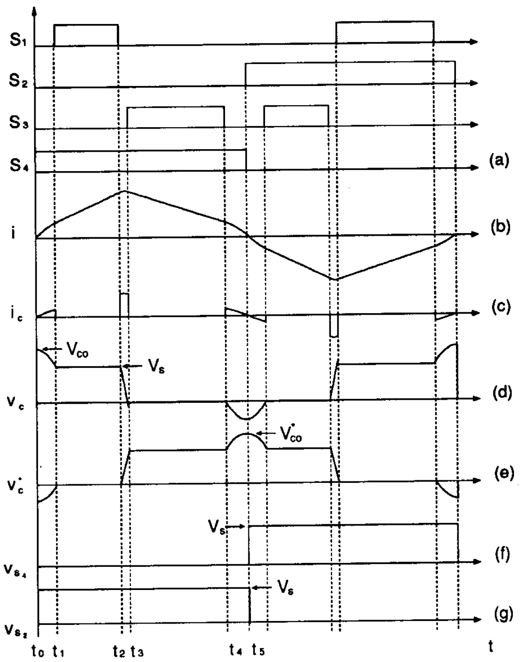


Fig. 3 Typical waveforms of proposed converter.

Mode IV : free-wheeling mode

When the lower side capacitor voltage v_c is reduced to zero, this mode begins by turning-on the switch S3. In this case zero-voltage switching of S3 also occurs. During this mode, the current flows through the path comprizing switch S3, inductor, transformer and switch S4 as shown in Fig. 5(d). The inductor current decreases linearly and lower side capacitor voltage v_c holds zero as shown in Fig. 3(b) and (d), respectively.

Mode V : resonant mode

At the instant of t_4 when the switch S3 is turned-off, resonant mode operation begins, which is mode V. Also the switch S3 is switched-off with zero-voltage switching condition. During this mode, the current path is the same as that of mode I, as shown in Fig. 5(e). When the inductor current is reduced to zero, the switch S4 is turned-off with zero-current switching condition as shown in Fig. 3(b). During this mode, the upper capacitor voltage v_c^* increases up to V_{co}^* which is slightly greater than the supply voltage as shown in Fig. 3(e).

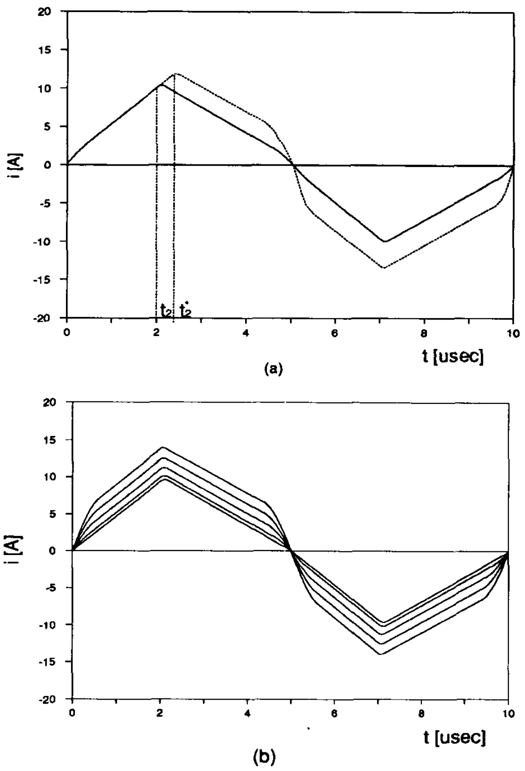
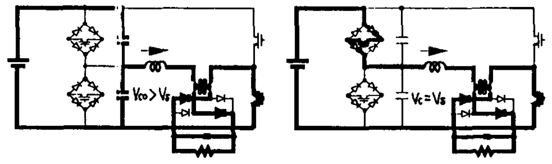


Fig. 4 Waveforms of inductor current with load variations:
(a) a method of inductor current increase,
(b) variation of inductor current at fixed duty.

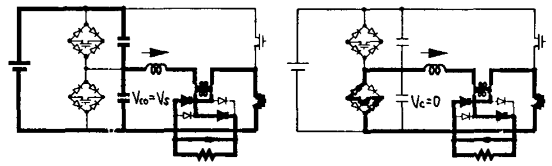
By this over charged energy, the next resonant mode (mode I) occurs.

The capacitor current i_C is very small compared with the power transfer related current i as shown in Fig. 3(c). This results in low VA rating of the capacitor. Fig. 3(b) shows that powering and free-wheeling mode inductor current waveform is the same as that of the conventional PWM DC/DC converter. Fig. 4(a) shows a control method when load is increased under a constant output voltage. The solid line denotes the steady state inductor current waveform before load increase. When load is increased during the first half cycle, t_2 should be extended to t_2^* to increase the inductor current as shown in the dotted line. This kind of control method is similar to that of the conventional PWM DC/DC converter. Fig. 4(b) shows the variations of the inductor current when load varies under a constant output voltage.

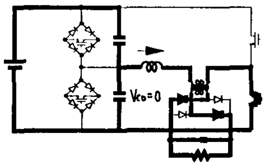
As described above, the proposed converter operates on mixed zero-voltage and zero-current switching modes and the operation resembles to the conventional PWM DC/DC converter having good DC characteristic, constant frequency operation, easy control and wide load range. Besides, this converter can operates up to high frequency because of the zero-voltage and zero-current switchings.



(a) Mode I (b) Mode II



(c) Mode III (d) Mode IV



(e) Mode V

Fig. 5 Topological mode diagrams in one switching cycle.

IV. ANALYSIS OF THE PROPOSED CONVERTER

A. DC Conversion-Ratio Characteristic

The output capacitor C_o is assumed to be sufficiently large to be replaced by voltage source V_o. The isolation transformer turn-ratio is assumed one to one. The inductor current and capacitor voltages in each mode are described as follows.

Mode I :

$$i = \frac{V_{co} - V_o}{Z_r} \sin \omega t \tag{1.a}$$

$$v_c = V_{co} - (V_{co} - V_o)(1 - \cos \omega t) \tag{1.b}$$

where
V_{co} : initial capacitor voltage
V_o : output voltage

$$Z_r = \sqrt{L/C} \tag{1.c}$$

$$\omega = \frac{1}{\sqrt{LC}} \tag{1.d}$$

Mode II :

$$i = i(t_1) + \frac{V_s - V_o}{L} t \tag{2.a}$$

$$v_c = V_s \tag{2.b}$$

Mode III :

$$i = i(t_2) \cos \omega t + \frac{V_s - V_o}{Z_r} \sin \omega t \tag{3.a}$$

$$v_c = V_s - Z_r i(t_2) \sin \omega t - (V_s - V_o)(1 - \cos \omega t) \tag{3.b}$$

Mode IV :

$$i = i(t_3) - \frac{V_o}{L} t \tag{4.a}$$

$$v_c = 0 \tag{4.b}$$

Mode V :

$$i = i(t_4) \cos \omega t - \frac{V_o}{Z_r} \sin \omega t \tag{5.a}$$

$$v_c = V_o (1 - \cos \omega t) - Z_r\, i(t_4) \sin \omega t \tag{5.b}$$

The parameter values of the converter used in simulation are as follows :

L = 8.3 μH,
C = 0.027 μF,
V_s = 100 V.

The above equations (1) through (5) are used in the numerical procedure to obtain the DC conversion-ratio characteristic of the proposed converter as shown in Fig. 6. In this case, the conversion-ratio M is defined as

$$M = \frac{V_o}{V_s} \tag{6}$$

and d is the duty given by

$$d = \frac{t_{on}}{T}. \tag{7}$$

The conversion-ratio deviates slightly compared with that of the conventional PWM DC/DC converter according to the variation of load. In this case the variable duty range is from 0.148 to 0.852 due to the resonant operation for the zero-current switching. This duty range can be adjusted of course.

B. Explanation of the DC Characteristic

The average output voltage and the average lower or upper side capacitor voltage are the same. To explain the slight deviations in DC characteristic, the lower side capacitor voltage is divided into four sections A, B, C and D as shown in Fig. 7. Conventional PWM DC/DC converter operation results in section D only and the average output voltage V_o is given by

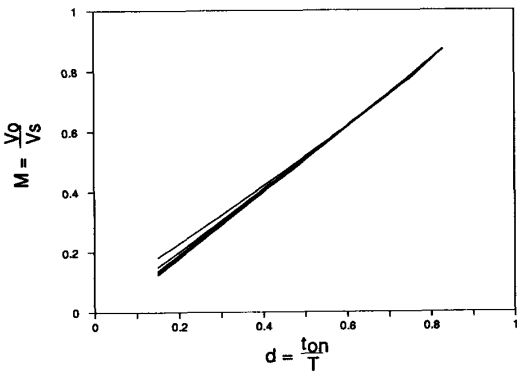


Fig. 6 DC conversion-ratio characteristics of proposed converter.

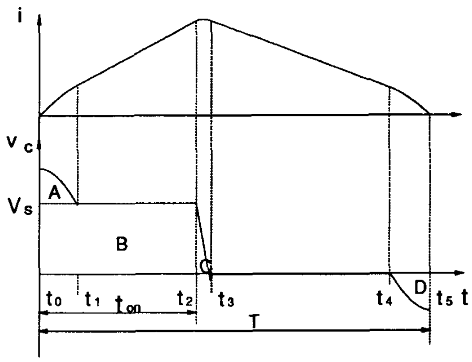


Fig. 7 Waveforms of inductor current and lower side capacitor voltage.

$$V_o = \frac{t_{on}}{T} V_s. \tag{8}$$

The resonant operations of the proposed converter result in sections A, B and C. In this case, the average output voltage becomes

$$V_o = d\, V_s + \alpha \tag{9}$$

$$d = \frac{t_{on}}{T} \tag{10}$$

$$\alpha = \frac{S_a - S_b + S_c}{T}. \tag{11}$$

where S_a, S_b and S_c are assumed to be the areas of A, B and C, respectively. The three areas depend on the resonant intervals t_{10}, t_{32} and t_{54}, respectively,

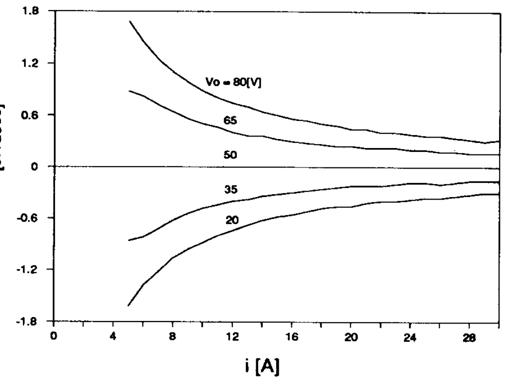


Fig. 8 Time difference between t_{10} and t_{54} with the variation of current at some output voltage, $V_s = 100V$.

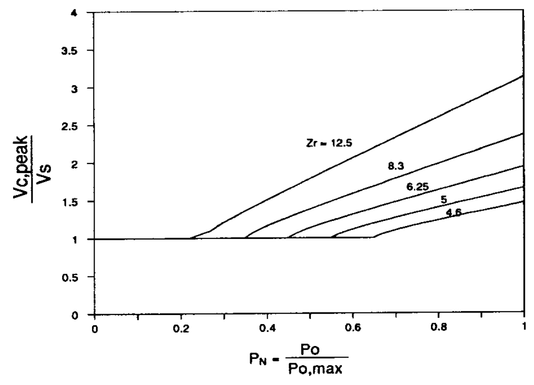


Fig. 9 Normalized voltage stress at $M = 0.5$, $V_s = 100\ V$ and $P_{o,max} = 1\ Kw$.

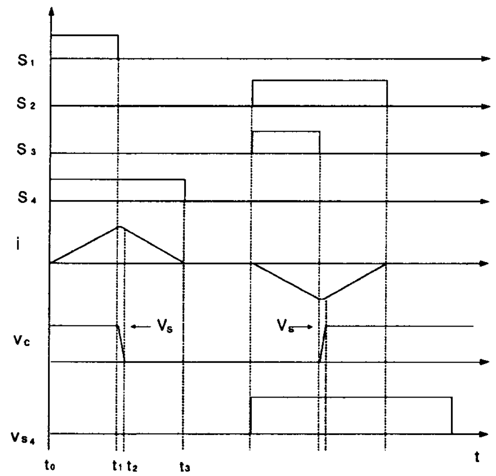


Fig. 10 Typical waveforms of proposed converter in discontinuous mode operation.

$$\begin{aligned} t_{10} &= t_1 - t_0 \\ t_{32} &= t_3 - t_2 \\ t_{54} &= t_5 - t_4. \end{aligned} \tag{12}$$

To find the deviation α, first consider S_a and S_b because S_c becomes small compared with S_a and S_b as load increases. If we define the difference between t_{10} and t_{54} as δt, then

$$\delta t = t_{10} - t_{54}. \tag{13}$$

Fig. 8 shows the difference δt as a function of inductor current and output voltage. For above half duty, the difference δt is positive. This means S_a is greater than S_b because t_{10} is greater than t_{54} and results in positive α. For under half duty, δt is negative. This results in negative α because S_b is greater than S_a. However at light load condition, although the duty is under half duty the deviation α is positive because S_c is greater than S_b. In summary,

$$\begin{aligned} &V_o = d\ V_s + \alpha \\ &\alpha \geqq 0 \quad \text{for} \quad d \geqq 0.5 \\ &\alpha < 0 \quad \text{for} \quad d < 0.5 \quad \text{and} \quad \textit{heavy load} \\ &\alpha > 0 \quad \text{for} \quad d < 0.5 \quad \text{and} \quad \textit{light load}. \end{aligned} \tag{14}$$

The degree of deviation is within 5 %.

C. Voltage Stress

Figs. 3(d) and (e) shows that the voltage stresses of the switches S1 and S3 are higher than the supply voltage. However, the voltage stresses of the switches S2 and S4 are clamped to the supply voltage. The voltage stresses of the switches S1 and S3 can be reduced by a proper design. Fig. 9 shows the normalized voltage stress of the switches S1 and S3 as a function of output power for several values of characteristic impedances of the resonant circuit. As the load and characteristic impedance increase, the voltage stress increases. The voltage stress becomes three times the supply voltage at 1 kw output power when the characteristic impedance Z_r = 12.5. Comparing with other similar resonant or quasi-resonant converters, the voltage stress is thought to be low. The flat line denotes the clamped device voltage to the supply voltage in discontinuous mode operation. The relations between voltage stress, characteristic impedance and the range of continuous mode operation is discussed in section V.

Discontinuous mode operation arises as the load decreases. Fig. 10 shows the inductor current and applied device voltages in discontinuous mode operation. No resonant operations appear at the instants of zero current switching of the switches S2 and S4, which exist in the continuous mode operation. Thus the applied voltage to the switches S1 and S3 is limited to the supply voltage in discontinuous mode operation. Since the inductor current is zero at the instant of switching operation, the switches S2 and S4 also have zero-current switching condition. The switches S1 and S3 have zero-voltage switching condition as in the continuous mode operation as well.

V. DESIGN CONSIDERATIONS

Characteristic impedance of the resonant elements affects the device voltage stress and continuous conduction mode (CCM) operation range as mentioned above. Normalized peak capacitor voltages for 10 A load current and CCM range as a function of the characteristic impedance are shown in Figs. 11 and 12, respectively. Voltage stress increases as the characteristic impedance increases and output voltage decreases. CCM range is represented by a normalized value R_N which is defined as

$$R_N = \frac{P_o - P_{min,CCM}}{P_o} \qquad (15)$$

where P_o is rated power and $P_{min,CCM}$ is minimum power in CCM. Normalized CCM range increases as the characteristic impedance increases and decreases as the output voltage increases as shown in Fig. 12. It is found that the voltage stress and CCM range should be compromised depending on the design condition.

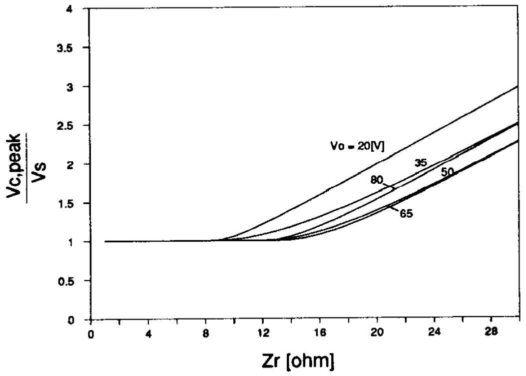


Fig. 11 Normalized device voltage stress with the variation of the characteristic impedance, Z_r at $i_o = 10\ A$, and $V_s = 100\ V$.

VI. CONCLUSIONS

A new zero-voltage zero-current mixed mode switching DC/DC converter is proposed to overcome the limitations of resonant converter, quasi- and pseudo-resonant converter. The new converter is very similar in operation to that of the conventional PWM DC/DC converter with added zero-voltage zero-current switchings. The features of the proposed converter can be summarized as follows:

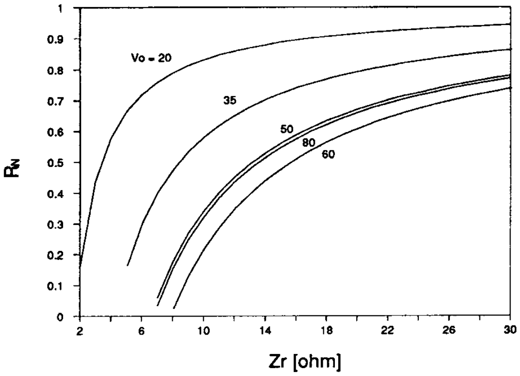


Fig. 12 Normalized range of CCM operation with the variation of the characteristic impedance, Z_r ($P_o = 1\ Kw$).

1) good DC conversion-ratio characteristic,
2) constant frequency operation,
3) easy control of variable duty,
4) wide load range,
5) low switching loss,
6) low EMI,
7) mixed mode zero-voltage zero-current switching operation,
8) low VA rating of resonant elements,
9) clamped device voltage to the supply voltage in discontinuous mode operation.

The proposed converter having these features overcomes many problems such as the limited load range, complex control, high VA rating of resonant elements and variable frequency operation of resonant and quasi-resonant converters and nonlinear DC characteristic of pseudo-resonant converter. Proposed converter is also thought to be suitable for high power applications above several KVA as well as low power range with high performance high frequency operation.

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