Further Development of Resonant Converter Employing Saturable Inductor

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Abstract

In various power converters, according to development of new devices and their application techniques having high performance, many superior conversion technologies have been also developed. One of main streams concerns a soft switching technology which can mitigate switching stress leading to the reduction of switching losses or electro-magnetic noise. On the other hand, as a characterized orthodox technology, the usual chopper circuit constructions are used, for example, for the electric vehicles and the like. It might be concerned that the further development due to new research cannot be expected. However, as present state of boost chopper for the battery controller in electric vehicles and the like, it is said that additional technical improvement is necessary. In such power controller, the bilateral function is required. With foregoing in mind, the authors have devised and analyzed the bilateral chopper using the soft-switch technology having resonant component. In bilateral chopper using resonant converter, a novel circuit topology having saturable inductors is proposed and discussed.

Keywords; resonant converter¹, saturable inductor², boost chopper³, soft switch⁴, buck chopper⁵

1. Introduction

Various power switching technologies are required to be improved with respect to switching losses and transient response, as this application of technology is widely employed. As a result, various devices and inventions to improve those characteristics have been presented and

investigated. As for the improvement in the devices for the reduction in forward voltage drop and in transient response, since the first invention of the power semiconductor device as SCR in 1957, consistent efforts have been made to obtain high performance devices. Also, for many converter applications, in order to realize a small system size or high response control, higher switching frequencies have been sought. The switching losses, however, increase in proportion to the switching frequency, presenting another problem that needs to be improved. With parallel development of devices for high performance, circuit technologies have been also required to reduce the electro-magnetic noise or to realize higher operational frequency. Hence, many useful results have been investigated and presented. One of main streams of investigation is in soft switching technology to mitigate the switching stress in devices. For investigating such switching technology, many researchers have reported scenarios in which the applied voltage or current across a device can be mitigated during a switching transient period, leading to the reduction in switching losses or electro-magnetic noise. On the other hand, amongst the significant developments in power electronics technology or the application example of characterized technologies, a chopper circuit had been developed for driving circuits of forklifts, electric trains and the like. Such technologies might have a tendency of going out of vogue because of very simple construction. Now, however, as a boost chopper for the battery charger of electric vehicle or for solar cells, such technologies have just begun to be applied extensively and become mainstream. Many examples of suitable applications or superior improvements are to be expected. Among such prospective

technologies, the boost converter for battery charger of an electric vehicle, being required to charge and discharge, must have a bilateral function, bringing the bilateral chopper into the mainstream. It is said that such technology is almost completed. However, when considering the efficiency improvement, even one percent improvement must be considered and must be pursued. With the above considerations, the authors have devised and analyzed a bilateral chopper using the soft-switching technology, whose inductor is replaced by saturable inductor. The resonant characteristic can be much improved which is applied as a battery charger for electric vehicles and the like. In such situation, as a resonant component, a novel saturable inductor is proposed and discussed.

2. Operational Principle of Circuit Performance

2.1 Fundamental operation of saturable inductor

Fig.1 shows basic element using in the proposed construction and magnetization characteristic as using novel resonant circuit. When switch S is turned on, the stored charge in C starts to discharge. During this period, it is assumed that the constant current is flowing through secondary winding of SI. The secondary circuit impedance is sufficiently large, so influence toward secondary circuit current due to secondary electromotive force can be negligible. Under such condition, the magnetic flux ϕ_2 due to I_2 and ϕ_1 due to i_c can be cancelled each other, and according to the turn ratio of windings, the increase of primary current is suppressed. By using this magnetizing characteristic in a case of $|B| > B_m$, magnetic core is saturated, so flux density can be kept constant. In this state, as differentiation of total magnetic flux ϕ becomes almost zero, so the inductance of SI becomes zero. During $-B_m < B < +B_m$ differentiation of magnetic flux ϕ , $d\phi/dt$ becomes extremely large. Consequently, as the inductance of SI becomes large, the inflowing primary current can be suppressed by secondary current I_2 .

Fig.1. Fundamental Operation of Saturable Inductor.

2.2 Fundamental construction by saturable inductor

Fig.2. Current Resonant Buck Chopper Using SI.

Fig.2 shows the fundamental circuit configuration with saturable inductor. The elementary construction is presented by buck chopper. The conventional inductor in LC resonance is replaced by SI. The secondary winding is connected to the load current. Usually, this load current is almost constant because the smoothing inductor is connected in series. When switch S is turned on, the LC resonance starts. In this situation, L is replaced by SI. For the usual LC resonance, the resonant current is increasing toward peak value in sinusoidal current. In order to suppress such peak current, the SI characteristic satisfies this requirement. Namely, by means of inductor current I_o , the resonant current does not increase over excessive value.

2.3 Proposed configuration using saturable inductor, SI.

Fig.3 shows the equivalent circuit when the circuit simulation is executed. The input current is suppressed to I_1 due to SI. Consequently, in the equivalent circuit, the saturable inductor can be replaced by constant current source I_1 accompanied by reverse parallel connected diode. In such a way, SI can be replaced by constant current source and the reverse parallel diode. The reason of this circuit model can be described as follows; by means of circulating current I_1 through D_3 , inflowing current i_l can be suppressed by this construction. This current source is given by $I_1 = I_o n_2 / n_1$, where n_2 / n_1 is turn ratio of SI.

Fig.3. Equivalent Circuit for Circuit Simulation.

By means of this performance, even if inflowing current tends to over due to resonant operation, such current can be suppressed by SI, whose operation can be expressed by constant current source. In the figure, L_l is small leakage inductance of SI.

2.4 Fundamental characteristics of buck chopper by SI

Fig.4 shows simulation results for the conventional current resonant buck chopper in Fig.4(a) and the current resonant buck chopper using proposed SI in Fig.4(b), respectively.

In Fig.4.(a), by means of current resonant, the flowing switch current is given by the sum of input current and resonant current, that is $I_{in} + E_0\sqrt{C/L}$. During current reverse resonance, the reverse inductor current is given by $-I_{in} + E_0\sqrt{C/L}$. In these equations, in the first half equation, it is undesirable state that is peak current value is extremely large which condition is presented in the figure. For example, in present day, power converters are spread to apply also larger capacity areas like EV battery charger and the like. Thus, peak current suppression becomes very important. In Fig.4(b), the mentioned peak current is favorably suppressed.

Fig.4. Waveforms of Conventional Resonant (a) and SI Buck Chopper (b).

3. Development toward Boost Chopper

In this section, let us consider about some developing circuit with boost chopper using saturable inductor under consideration. In a case of boost chopper, the fundamental consideration is the same compared to the one of buck chopper. Thus, the saturable inductor is equipped to the place of the inductor for buck chopper. That is, resonant inductor is replaced by resonant saturable inductor. By means of this operation, resonant

peak current for conventional boost converter is much suppressed, leading to improvement of switching characteristic. With respect to the secondary winding circuit, in a case of buck chopper, secondary current is provided by load current. In the case of boost chopper, however, secondary current is provided by input current as shown later. In both cases, secondary currents do not much vary in a short period, because of including large filtering inductor. For the buck chopper, the capacitor voltage is varied on the base of input voltage. On the

other hand, for the boost chopper, the capacitor voltage is varied on the base of output voltage.

Fig.5. Boost-chopper with saturable inductor.

3.1 Analysis Development of Boost Chopper

Fig.5 shows the circuit for boost chopper with saturable inductor. Each circuit parameter in simulation is that input voltage $E = 100\text{V}$, switching frequency is 20kHz , $L_1=12\mu\text{H}$, $C_1=1\mu\text{F}$, $C_o=2000\mu\text{F}$, $R_o=40\Omega$, and the duty factor $d = 0.5$. Under such conditions, circuit operation was confirmed. The input current was made smooth by input inductor L_1 , leading to constant current. As a result, the input current can be represented by constant current source in simulation. The current through saturable inductor can also be represented the current source as described in $I_l = I_i n_2 / n_1$. L_1 indicates the leakage inductance of SI. In addition, small leakage inductance is utilized for reversed operation, leading to soft switching function. The input current I_i at this circuit operation can be commutated toward the capacitor C_1 circuit, whose voltage approaches near of zero or slightly reversed voltage. As a result, the switch current is much suppressed or reversed, so that soft switch can be achieved. The circuit sophisticated analyses will be performed in Fig.5 and Fig.6 as follows;

(a) period 1 ($t_0 - t_1$)

For $t < t_0$, when the power from the input power supply is delivered toward the output power supply. At $t = t_0$, when the switch S is turned-on. The current starts to flow into switch S circuit. According to the turn ratio of primary winding and secondary one, the current is increasing toward the final value of I_1 as

$$I_1 = \frac{I_i \times n_2}{n_1} \quad \dots \dots (1)$$

The current is linearly rising as described by

$$i_1 = \frac{E_i}{L_1} t \quad \dots \dots (2)$$

where E_i is initial capacitor voltage, L_1 is circuit inductance including the leakage inductance of SI and i_1 SI circuit current.

(b) period 2 ($t_1 - t_2$)

At t_1 , i_1 reaches to I_l , and furthermore is increasing toward the final value of I_l since I_l is larger than I_i . Because of this relation of $I_l > I_i$, the discharge of C_1 also begins. The discharge current of SI, which is the resonant current, determines the resonant period. This resonant period is calculated by the turn ratio of SI. As this transient time of rising is very short, the waveform is described by almost constant value as shown in brief period of V_c . At the final time of this period, the capacitor current of C_1 starts to discharge, which is suppressed to constant current I_l determined by SI.

(c) period 3 ($t_2 - t_3$)

By means of role of SI, incoming current can be suppressed to I_l and is flowing as constant current. Since I_i is smaller than I_l , the difference current $I_l - I_i$ is delivered from C_1 as constant current $I_c = I_l - I_i$, discharging as liner straight line. Thus,

$$i_c = I_l - I_i \quad \dots \dots (3)$$

$$v_c = E_o - \frac{I_l - I_i}{C} t \quad \dots \dots (4)$$

where $V_c(0)$ is assumed to E_o .

(d) period 4 ($t_3 - t_4$)

At $t=t_3$, the capacitor voltage reaches almost or near of zero, and by performance of the circuit resonance of L_l and C , the voltage goes toward negative polarity. As a result, the input current I_i begins to commutate to this capacitor loop from switch S circuit. This circuit equations are given by

$$\left. \begin{aligned} i_c &= -C \frac{dv_c}{dt} \\ v_c &= L \frac{di_c}{dt} \\ i_1 &= I_i + i_c \end{aligned} \right\} \quad \dots \dots (5)$$

By resolving the equation, each voltage and current equations can be obtained as follows;

$$\left. \begin{aligned} i_1 &= (I_1 - I_i) \cos \frac{t}{\sqrt{LC}} + I_i \\ i_c &= (I_i - I_1) \cos \frac{t}{\sqrt{LC}} \\ v_c &= (I_1 + I_i) \sqrt{\frac{L}{C}} \sin \frac{t}{\sqrt{LC}} \end{aligned} \right\} \dots\dots(6)$$

At $t=t_4$, the capacitor current becomes almost zero, so that the direction of current is reversed from charge to discharge. At this time, the switch current i_l can be obtained from (5) as $I_l = I_i + i_c$. As above described, the input current is commuting toward capacitor circuit of nearly zero or reversed voltage. Consequently, by means of this operation, the switch current is going toward zero current. As period 4 and 5 are commutation ones from switch S to capacitor C, this period 4 is represented by first half commutation and the later period 5 is by second half commutation.

Fig.6. Waveforms of SI Resonant Boost Chopper.

(e) period 5 (t_4 - t_5)

The direction of capacitor current in discharge mode is reversed, where the operational circuit is identical with the former period, so that (5) and (6) can be applied also to this period. In such a way, the current of switch S is going rapidly toward zero according to the current equation presented by i_l . At $t=t_5$, when the input current is completed to commute, so the switch current becomes zero and this period comes to an end. During this period, the capacitor voltage becomes slightly negative voltage by means of the resonant operation between the leakage inductance voltage of SI and C, where the capacitor voltage is shown in (6).

(f) period 6 (t_5 - t_6)

When the commutation from switch current to capacitor current is completed, the input current is flowing exclusively as capacitor current. During this period, the switch is made to turn-off. The circuit equation is shown by

$$I_i = \frac{dv_C}{dt} \dots\dots(7)$$

The equation can be resolved as

$$v_C = \frac{I_i}{C} \times t \dots\dots(8)$$

where $i_c = I_i$.

According to the increasing rate of capacitor voltage, the applied voltage across the switch is also increasing. When the capacitor voltage reaches to output voltage and the input and output circuit are connected, this period comes to an end.

4. Conclusions

One of defective characteristics of the soft switch with LC resonances is that a certain excess current due to resonant operations flows. A novel technique using saturable inductor has been proposed and discussed also for bilateral chopper, where it has only unity core having double circuits for primary and secondary, leading to concise and compact one.

For fundamental operation principle of circuit resonance using saturable inductor, at voltage reversion of SI, the capacitor voltage is also reversed. In the paper, however, this voltage reserved operation dose not utilize, so free wheel diode is equipped and capacitor voltage is suppressed around zero voltage. If the saturable inductor technique is utilized as it is, V_c voltage swings largely toward positive and negative polallity. As a result, useless and excess operation would be added in such a way. In actual simulation procedure, however, such equivalent circuit for SI can be represented by simple constant current source and its accompanied free wheel diode, so derivative effect can be achieved. The principal purpose is to reduce the radio noise, surge voltage and the like. By means of the proposed technique, the defective points of the soft switch would be improved regarding to additional excess voltage or current.

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