Further Development of Resonant Converter Employing Saturable Inductor

Keiju Matsui a,*, Eiji Oishi a, Masayoshi Umeno c
Mikio Yasubayashi b, and Masaru Hasegawa b

aMinna-denryoku Ltd., Setagaya-Monozukuri-Gakko, room 210, Tokyo 154-0001, Japan
bChubu University, Kasugai city 487-8501, Japan

*Corresponding Author: keiju@isc.chubu.ac.jp

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 electromagnetic 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 electromagnetic 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 electromagnetic 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 $\phi_2$ due to $I_2$ and $\phi_1$ due to $i_1$ 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 $\phi$ becomes almost zero, so the inductance of SI becomes zero. During $-B_m < B < +B_m$ differentiation of magnetic flux $\phi$, $d\phi/dt$ becomes extremely large. Consequently, as the inductance of SI becomes large, the inflowing primary current can be suppressed by secondary current $I_2$.

$$B = NI$$

$$H = NI$$

$$+B_m$$

$$-B_m$$

$$\frac{vL}{v_{\phi 1}} n_1 n_2$$

$$\phi_2$$

$$\phi_1$$

$$i_1$$

$$i_2$$

$$v_c$$

$$v_c$$

$$H = NI$$

$$[A/m]$$

Fig.1. Fundamental Operation of Saturable Inductor.

2.2 Fundamental construction by saturable inductor

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 $I_i$ 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 $I_i$ through $D_3$, inflowing current $i_1$ can be suppressed by this construction. This current source is given by $I_i = I_o n_2 / m$, where $n_2 / m$ is turn ratio of SI.

$$I_i = \frac{I_o n_2}{m}$$

Fig.2. Current Resonant Buck Chopper Using 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, \( L_i \) 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 \( I_n + E_0\sqrt{C/L} \). During current reverse resonance, the reverse inductor current is given by \(-I_n + E_0\sqrt{C/L}\). 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 becomes favorably suppressed.

![Waveforms of Conventional Resonant and SI Buck Chopper](image)

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

### 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.

\[ i_1 = \frac{E_0}{L_4} t \] ... ...(2)

where \( E_0 \) is initial capacitor voltage, \( L_4 \) is circuit inductance including the leakage inductance of SI and \( i_1 \) SI circuit current.

(b) period 2 (t1-t2)

At \( t_1 \), \( i_1 \) reaches to \( I_s \) and furthermore is increasing toward the final value of \( I_s \) since \( I_s \) is larger than \( I_i \). Because of this relation of \( I_s>I_i \), 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 \( V_{cl} \). At the final time of this period, the capacitor current of \( C_1 \) starts to discharge, which is suppressed to constant current \( I_s \) determined by SI.

(c) period 3(t2-t3)

By means of role of SI, incoming current can be suppressed to \( I_s \) and is flowing as constant current. Since \( I_s \) is smaller than \( I_i \), the difference current \( I_s-I_i \) is delivered from \( C_1 \) as constant current \( I_s-I_s-I_i \), discharging as linear straight line. Thus,

\[ i_c = I_s - I_i \] ... ...(3)

\[ v_c = E_o - \frac{I_s-I_i}{C} t \] ... ...(4)

where \( V_c(0) \) is assumed to \( E_0 \).

(d) period 4 (t3-t4)

At \( t=t_3 \), the capacitor voltage reaches almost or near of zero, and by performance of the circuit resonance of \( L_s \), 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

\[ i_c = -C \frac{dv_c}{dt} \]

\[ v_c = L \frac{dt}{\sqrt{LC}} \]

\[ i_1 = I_s + i_c \] ... ... (5)

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

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 \( E = 100V \), switching frequency is 20kHz, \( L_1=12\mu H \), \( C_1=1\mu F \), \( C_o=2000\mu F \), \( R_o=40\Omega \), 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 \( I_1 = I_s n_2 / n_1 \). \( L_4 \) 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 (t0 - t1)

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 \( I_s \) as

\[ I_1 = \frac{I_s n_2}{n_1} \] ... ... (1)

The current is linearly rising as described by
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 $i_1$ can be obtained from (5) as

$$I_1 = I_i + i_c.$$  

As above described, the input current is commutating 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.

$$i_c = (I_1 - I_i) \cos \frac{t}{\sqrt{LC}}$$  

$$v_c = (I_1 + I_i) \sqrt{\frac{L}{C}} \sin \frac{t}{\sqrt{LC}}$$  

$$I_1 = I_i + i_c.$$  

---

(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 $i_1$. At $t=t_5$, when the input current is completed to commutate, 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).

$$i_1 = (I_1 - I_i) \cos \frac{t}{\sqrt{LC}} + I_i$$

$f)$ 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

$$I_i = \frac{dv_c}{dt}$$  

\( \cdots (7) \)

The equation can be resolved as

$$v_c = \frac{I_1}{C} \times t$$  

\( \cdots (8) \)

Fig.6. Waveforms of SI Resonant Boost Chopper.
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 does 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 polarity. 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.

References

(1) Keiju Matsui, Noriaki Sato: “A New thyristor Inverter with Improved Commutating Efficiency”, Trans IEEJ, Vol.97-B, No.7, pp.367-373 (1977)

(2) Keiju Matsui, Susumu Tanaka, Masaru Hasegawa: “Analysis and Improvement of Bilateral Chopper Having Current Resonant Soft-Switch”, The IEEE International Symposium on Circuits and Systems (ISCAS-2010), B6p-V, pp.2726-2729, 2010

(3) Takanori Asaba, Keiju Matsui, Masaru Hasegawa:” Proposal and Analyses of Resonant Bilateral Converter Employing Simple Zero Current Switches”, Proceeding of ICEE-2011, A534, pp.1-6, 2011

(4) Yukinori Tsuruta, Hisaichi Irie, Mutsuo Nakaoka, Mantaro Nakamura, Tamotsu Ninomiya, Seiya Abe, Eiju Hiraki, Shuji Watanabe: “Trends of Soft Switching Technology-dc-dc conversion” The 2007 Annual Meeting Record of IEE Japan, no.4-S20-2, pp.5-8, 2007

(5) Tamotsu Ninomiya: “Introduction to Recent Development of High-Frequency Soft-Switching Power Converters and their Applications”, The 2004 Annual Meeting Record of IEE Japan, no.4-S18-1, pp1-4, 2004

(6) N. O. Sokal, A. Sokal: “Class E-A new class of high-efficiency tuned single-ended switching power amplifiers”, IEEE J. Solid-State Circuit, vol.SC- 10, no.3, pp.168-176, (1975)

(7) Serguei Moisseev, Mutsuo Nakaoka: “Development of Novel Bidirectional Soft-Switching PWM DC-DC Power Converter”, The 2004 Annual Meeting Record of IEE Japan, no.4-066, p.9, 2004

(8) S.Cuk, R.D. Middlebrook, “Advances on Switched-Mode Power Conversion Part I”, IEEE Trans. On IE, vol. IE-30, no.1, pp.10-19, (1983)

(9) C. Hua, S. Leu, F.C. Lee: “Novel Zero-voltage-transition PWM Converters”, IEEE Trans .On Power Electronics, vol.9, no.2, pp.213-219,(1994)

(10) Yukinori Tsuruta, Martin Pabloyzky, Atsushi Kawamura: “Improvement of Mid-Power SAZZ Chopper for Very High Efficiency”, "Proceeding of the 2009 Japan Industry Applications Society, JIASC2009, pp.1-675-678 (2009)

(11) Keiju Matsui, Susumu Tanaka, Masaru Hasegawa:” Analysis and Improvement of Bilateral Chopper Having Current Resonant Soft-switch”, The IEEE International Symposium on Circuits and Systems (ISCAS-2010), B6p-V, pp.2726-2729, 2010-6

(12) Keiju Matsui, Takanori Asaba, Masaru Hasegawa:” Proposal and Analyses of Resonant Bilateral Converter Employing Simple Zero Current Switches”, Proceeding of Tencon, Premier Technical Conference of IEEE Region 10, pp.2454-2459, 2010-11

(13) Keiju Matsui, Eiji Oishi, Masayoshi Umeno, Mikio Yasubayashi, Yuuichi Hirate, Sudip Adhikari, Masaru Hasegawa, " DC Power Control Using Simple Inverters Constructed by Concise Circuit Configuration - Pursuit for photovoltaic simple power conditioner - " , ICDCM 2019 : The 3rd IEEE International Conference on DC Microgrids PS2-1,pp.1-6,2 019-5