ABSTRACT

This paper is concerned with the latest technologies on high-power switching dc-dc converters controlled by time-sharing high-frequency thyristor chopper with energy-storage and -transfer reactor coupling links, which can operate over an ultrasonic chopping frequency region in the extent of 20KHz or more than 20KHz. The possible circuit configurations of new thyristor type switching step-up and down dc-dc converters relating to magnetic-power semiconductor devices and their unique features are described and discussed from a practical point of view.

The general procedures of circuit analysis and performance evaluations to offer the desirable design data are presented, and the steady-state open-loop control characteristics and a closed-loop control policy are elucidated on the basis of the theoretical and experimental results. Thyristor type high-frequency switching step-up dc-dc converter using time-sharing control technique is also originally examined and discussed herein.

INTRODUCTION

Of late years, the static high-frequency chopper-fed switching dc-dc converters using power transistors, thyristors, and magnetic switching devices, which operate successfully over a certain chopping-frequency range from 20KHz to the extent of 100KHz or so, have attracted special interests in the field of power electronics. To authors' knowledge, there have been many recent studies on hardware and software of power transistor type switching dc-dc converters comprising energy-storage and -transfer reactor assemblies. At present, these switching dc-dc converters are generally considered to have already reached a new stage for practical use. A great number of technical reports relating to energy-storage switching dc-dc converters by power transistors will have been increased and this tendency must become much stronger in the future.

On the contrary, there are very few strong technical reports about fast response type thyristor chopper-fed switching dc-dc converters except the valuable papers reported by Dewan and Clarke [1],[2]. Many additional researches on high-power high-frequency inductive energy-storage switching dc-dc converters using the latest excellent high-speed thyristors should have been still investigated on the basis of the fundamental and applied researches concerned with usual switching dc-dc converters using power transistors and the latest circuit technique of thyristor commutation.

This paper deals with the recent significant system developments on energy-storage and-transfer type high-frequency chopper-fed switching dc-dc converters using relatively new load voltage commutation method [3],[4] and time-sharing control principle [5],[6]. This presentation describes the following items; (1) operating principle, (2) energy-storage and-transfer mechanism, (3) behavior analysis in steady-state, (4) theoretical consideration for overlapping commutation-mode, (5) performance assessments such as load characteristics and frequency characteristics, imituation of chopping-frequency and the forth. Theoretical results are generally put in order and explained by introducing the normalized chopping frequency variable and some circuit constants, and are compared with the experimental ones.

Finally, the thyristorized energy-storage and-transfer type switching dc-dc step-up converters using the load voltage commutation technique and time-sharing control scheme are originally proposed and discussed for a practical convenience.

CIRCUIT DESCRIPTION

Figure 1-(a) shows a concrete example circuit of time-sharing high-frequency thyristor switching regulator with multiple reactor coupled links.

This switching dc-dc converter is constructed by two sub-resonant choppers enclosing energy-storage and-transfer reactors. The main circuit configuration of this circuit is divided into six sections; thyristor resonant commutation circuits including energy-storage reactors, energy-transfer reactor coupled by energy-storage reactors, switching diode, smoothing capacitor stage and load circuit.

Figure 1-(b) shows another trial example of time-sharing high-frequency thyristor chopper-fed dc-dc converters. This circuit is constructed by combining the bridge type switched-capacitor sub-circuits with Clarke type energy-storage thyristor dc-dc converter. We describe concentretrately our study on dc-dc converter shown in Figure 1-(a).

CIRCUIT ASSUMPTION

This switching dc-dc converter is constructed by two sub-resonant choppers enclosing energy-storage and-transfer reactors. The main circuit configuration of this circuit is divided into six sections; thyristor resonant commutation circuits including energy-storage reactors, energy-transfer reactor coupled by energy-storage reactors, switching diode, smoothing capacitor stage and load circuit.

Figure 1-(b) shows another trial example of time-sharing high-frequency thyristor chopper-fed dc-dc converters. This circuit is constructed by combining the bridge type switched-capacitor sub-circuits with Clarke type energy-storage thyristor dc-dc converter. We describe concentrate our study on dc-dc converter shown in Figure 1-(a).
For simplicity, the following assumptions are accepted as follows: (1) thyristors and diodes are supposed to be the unidirectional ideal switches. (2) $C_2$ is much greater than $C_1$, i.e., $v_0(t)$ is equal to average voltage $V_0$. (3) Leakage inductances of reactor systems are neglected, i.e., $L=1$ (4) Loss resistances of commutation circuit and $C_2$ and circuit wiring are neglected. The third assumption will be properly changed when we analyze this circuit in current-overlapping commutation mode which will be minutely explained later.

**CIRCUIT OPERATION**

Figure 2 illustrates the typical operating waveforms of switching dc-dc converters shown in Figure 1-(a), 1-(b). For simplicity, the following assumptions are accepted as follows: (1) thyristors and diodes are supposed to be the unidirectional ideal switches. (2) $C_2$ is much greater than $C_1$, i.e., $v_0(t)$ is equal to average voltage $V_0$. (3) Leakage inductances of reactor systems are neglected, i.e., $L=1$ (4) Loss resistances of commutation circuit and $C_2$ and circuit wiring are neglected. The third assumption will be properly changed when we analyze this circuit in current-overlapping commutation mode which will be minutely explained later.

For steady-state, the operation in other main modes is tightly, no overlapping-commutation mode occurs between 1-A and 1-B. This instant commutation behavior will be proved later. Sub-mode 1 (O$\Omega$4$\Omega$3): thyristor and diode current to illustrate the commutation process in the case of $\delta=1$.

**CIRCUIT ANALYSIS**

When $\delta=1$, thyristor commutation is instantly completed. There exists an overlapping commutation-mode between 1-A and 1-B in the case of $\delta=1$. Figure 3 shows the thyristor and diode current to illustrate the commutation process in the case of $\delta=1$.

![Figure 2 Operating waveforms in steady-state](image)

![Figure 3 Thyristor and diode currents in overlapping-commutation mode](image)

![Figure 4 Output voltage vs. chopping frequency](image)
From Figure 1-(a), the circuit equations in the overlapping mode are given by

\[
\begin{pmatrix}
\frac{d}{dt} x_1 \\
\frac{d}{dt} x_2 \\
\frac{d}{dt} x_3
\end{pmatrix} =
\begin{bmatrix}
0 & 0 & 1 \\
1 & 0 & 0 \\
0 & 1 & 0
\end{bmatrix}
\begin{pmatrix}
x_1(t) \\
x_2(t) \\
x_3(t)
\end{pmatrix} +
\begin{pmatrix}
E \\
-V_0 \\
0
\end{pmatrix}
\]

where \( M = L_1L_2 \), \( v_{C0L}(t) = V_0 \).

Considering the following relationships:

\[
\begin{pmatrix}
i_{OL}(t^+o) \\
i_{OL}(t+o) \\
v_{C0L}(t+o)
\end{pmatrix} =
\begin{pmatrix}
i_1(t^-o) \\
i_0(t^-o) \\
v_{C0L}(t^-o) = \frac{E}{n}
\end{pmatrix}
\]

where, \( n = \sqrt{L_2/L_1} \). We obtain the following solutions for the above equations:

\[
i_{OL}(t) = a_i \sin(\omega t + \theta),
\]

\[
v_{C0L}(t) = \frac{a_i L_2}{(1-o)^2} \sin^2(\omega t + \theta) - \frac{V_0}{n}
\]

where, \( \omega = 1/\sqrt{L_1C_1(1-o)^2} \).

From \( i_{OL}(t) = 0 \), \( t_{OL} \) can be estimated by,

\[
t_{OL} = \frac{\theta}{\omega} + \frac{1}{\omega} \sqrt{1-(1-o^2)},
\]

When \( o \) increases to approach so as to be 1, then \( t_{OL} \) will decrease to be zero. This means that no overlapping commutation-mode between 1-A and 1-B occurs when \( o = 1 \).

**OUTPUT CONTROL CHARACTERISTICS**

The average values of \( i_1(t) / 2 \) and \( i_0 \) are calculated as follows;

\[
I_0 = \frac{1}{2} I_1 \int_{t_0}^{t} \frac{V_C}{T_s} dt = \frac{C E}{T_s} \left( 1 + \frac{2V_0}{E} \right) V_0 = \frac{C E V_0}{T_s}
\]

Considering eq. (1) and \( I_0 = V_0 / R \), we obtain,

\[
V_0 = \frac{E R}{2} \left( 1 + \frac{1}{n^2} \right)
\]

where \( E = 2C V_0 / T_s \). As known from eq. (2), \( V_0 \) can be continuously regulated by controlling \( T_s \). The relationship expressed by eq. (2) is also derived from energy-storage and transfer conversion principle,

\[
\frac{1}{2} i_1(t_1 + o) = \frac{V_0}{R} \frac{T_s}{T_s}
\]

where \( i_1(t_1 + o) = \frac{V_0}{R} \frac{T_s}{T_s} \sin^2 t_1 \), \( n = 1/\sqrt{L_1C_1} \),

\[
v_0(t_1 + o) = -V_0 / R
\]

Moreover, it is proved by energy conversion principle that the relationship described by eq. (2) is able to expansively applied in the operating region of \( T_s \leq T_s^* \).

**OPEN-LOOP CHARACTERISTICS**

For simplicity and generality, we introduce the following defined parameters: (1) normalized chopping-frequency variable: \( \omega = \sqrt{L_1C_1 / T_s} \), \( fc = 1 / T_s \), (2) normalized circuit constants: \( \omega = R / M \sqrt{L_1C_1} \). Figure 4 shows the frequency control characteristics and Figure 5 shows the overlapping control characteristics. As can be seen, the implementation in open-loop can be impossible in practice

**DISTINCTIVE FEATURES AND CONVERTER APPLICATIONS**

This proposed switching dc-dc converters possess the following unique features: (1) The circuit components for commutation and output-filter can be designed so as to be smaller size, lighter weight, more efficient and high-reliable apparatus. (2) The maximum circuit turn-off time is not dependent of various load conditions. The circuit operation is extremely stable over a wide chopping frequency control. The converter circuits are flexibly available for all kinds of load patterns. (3) The output voltage can be regulated with a faster response because of much smaller low-pass capacitor configuration and linearly with a certain value proportional to the reference voltage. (4) The voltage conversion ratio is relatively wide. (5) \( dv/dt \) and \( di/dt \) capabilities for thyristor are very small and are not influenced for wide-range load variations. (6) The realization of dc isolation and multiple output configurations is concretely carried out. (7) These converters are available for large-scale switching power supplies. The overload capability is extremely high. (8) The stop-start sequential control is easily performed. In practice, these proposed circuits have been properly applying for faster response thyristorized chopper in order to control rapidly the output voltage of high-frequency inverters and high-power dc amplifying controller of a low-inertia high-power dc motor variable-speed drive.

**CONCLUSIONS**

Two types of thyristorized energy-storage and transfer dc-dc switching converters by load voltage commutation technique and time-sharing control scheme, which can operate over a chopping frequency range from 20KHz to 100KHz or so, were originally demonstrated and their effectivenesses were sufficiently confirmed by theoretical consideration and experimental results.

**REFERENCES**