Input Filter Design for Current Source PWM GTO Converter

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Abstracts - The current harmonics, occured in the input side of power converter system became big issue. This paper studied CS PWM GTO Converter system in the view of the current harmonics. First, two kinds of switching methods are analyzed by comparison. Second, a novel type of LC filter configuration named LRC filter, is proposed and analyzed. Simple design method and design data for the proposed filter configuration are presented and compared with the serial damping resistor type. The steady state and dynamic performances of the system are investigated. The simulation and experimental results are also presented in the paper.

1. Introduction

Recently, the attenuation of the harmonics, occuring in the input side of the converter system, has been considered very important. PWM control strategy is one of the typical method to avoid the low order current harmonics inherently. However, the higher harmonics resulted from the switching of the converter are increasing, so some external input filter is still necessary to suppress the harmonics.

PWM converters can be divided into CSC(current source converter) and VSC(voltage source converter) by the charateristics of DC link output. PWM-CSC has good dynamic characteristics on the current response and has an appropriate structure in the applications of superconductive energy storage system. This type of converter has a demerit with larger filter capacity than PWM-VSC.

In the paper, current source PWM GTO converter is designed as the purpose of the development of high power converter system.

A new type of L-C filter configuration which is necessarily installed in the AC input side of PWM-CSC is proposed. It is a L-C filter configuration named LRC filter, where damping resistor is connected in parallel with filter inductance. Compared with the LCR filter[2], althogh the harmonic attenuation factor is slightly decreased, the power loss in the damping resistor becomes very small and filter inductor is also protected from the high order current harmonics. Simple and optimal filter design is introduced into the paper.

Two kinds of PWM switching algorithms, which are the triple-triangle comparison method and the sawtooth comparison method, are analyzed. Through the simulation, the sawtooth method is chosen as the suitable PWM control scheme. This scheme is superior to that scheme in THDi and power utility. And also, its control circuit is simple.

Simulations are performed to analyze the charateristics of the steady state and the transient state. Good correspondence between simulated and experimental results confirmed the validity of the proposed theoretical results.

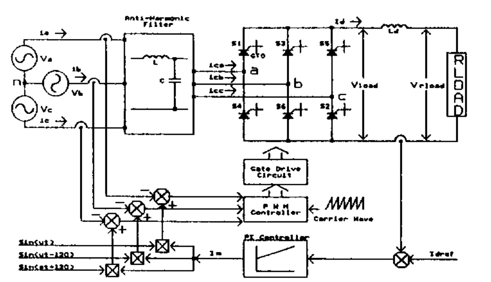


Fig.1. Power circuit of CS GTO converter with input/output filter.

2. Current source PWM GTO converter

Fig.1 shows the proposed scheme of current source PWM GTO converter system with anti-harmonic input and output filter. GTO thyristors are used as switching devices S1-S6. PWM-CSC has a constant current in the DC link side and the switching functions must be determined not to be shorted among the switching devices.[3]-[5] One of the upper and another of the lower devices must be simultaneously conducted for it. However if more than two among the upper or the lower devices are simultaneously conducted, the short circuit occurs. And if there is no conducting device among the upper or the lower, the circuit is opened and the device may be destroyed by the induced high voltage of DC link reactor. The freewheeling of load current occurs if two devices of the same leg are conducted. If the load current I_d is assumed to be ideal, any one of the three converter input line currents I_{cx} is given by;

$$I_{cx} = S_x(\omega t)\cdot I_d \quad : x=a,b,c \qquad 1)$$

where, $S_x(\omega t)= 1$ => S1, S3, S5 is on-State
$S_x(\omega t)=-1$ => S2, S4, S6 is on-State
$S_x(\omega t)= 0$ => Both switchs in leg x are on-States (i.e., freewheeling mode)

If V_a, V_b, and V_c are the source phase voltages, then converter output voltage V_{load} is given by;

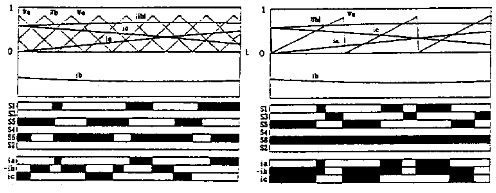
$$V_{load} = \sum_{k=0}^{2} S_a(\omega t-2\pi k/3)\cdot V_a(\omega t-2\pi k/3) \qquad 2)$$

Equations 1) and 2) imply that I_{cx} and $S_x(\omega t)$ posses the identical spectrums. Also if $S_x(\omega t)$ can be made ideally sinusoidal, input and output filters will be eliminated since I_{cx} would be ideally sinusoidal. Under practical considerations,[6] switching function $S_x(\omega t)$ is given by;

$$S_x(\omega t) = \sum_{k=0}^{\infty} A_k \cos(k\omega t) \quad : k=1,5,7,11,\cdots \qquad 3)$$

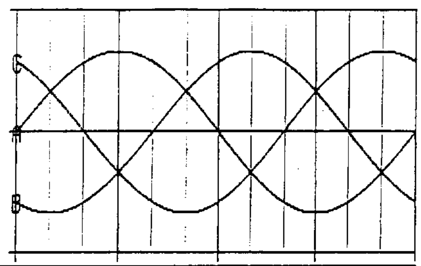
Practically, although the input filter cannot be eliminated, the size can be reduced if $S_x(\omega t)$ could be found with low A_k's.

Fig.2a) shows the triple-triangle comparison scheme which is composed of independently threefold carriers. The sawtooth comparison scheme is illustrated in Fig. 2b).[1] Within one period of sawtooth wave, the arm in which side the reference wave has the largest absolute value must be on-state. And switching states of another arms are determined by combinations of the waveforms that has the second and third largest values. This PWM scheme has not an optimal pulse pattern but has merits of no open- and short-circuit, in comparison with triple-triangle scheme. The short circuit -avoiding algorithm which is shown in Fig.3 must be



a) b)

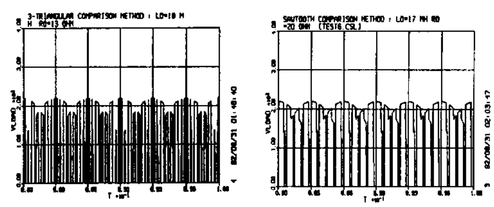
Fig.2. PWM control schemes; a) triple-triangle comparison method, b) sawtooth comparison method.



S1	①	1	1	1	1	①						
S2					①	1	1	1	1	①		
S3	1	①							①	1	1	1
S4							-①	-1	-1	-1	-1	-①
S5	-1	-1	-1	-①							-①	-1
S6			-①	-1	-1	-1	-1	-①				

Ref. : The number ① is the sacrificealbe switch.
The number 1 is the on-state switch.

Fig.3. Short circuit-avoiding algorithm.



a) b)

Fig.4. Output voltage waveforms of each switching algorithm; a) triple-triangle comparison method, b) sawtooth comparison method.

introduced into the triple-triangle scheme. The number marked with circles are the sacrificeable switches to avoid a short circuit. The output voltage waveforms according to two kinds of PWM control schemes is shown in Fig.4. Also the characteristics about two kinds of PWM control schemes are described in Table 1. As shown in Table 1, the sawtooth comparison method has the superior charicteristics under the same conditions (I_d=7.5A and RFi=4.8%). Even though the number of switching state are small, the sawtooth scheme has better characteristics in THDi and output power than triple-triangle scheme.

Table 1. Charateristic comparison of triple-triangle comparison method and sawtooth comparison method.

	3-Triangle Comparison	Sawtooth Comparison
RFi Output Current	4.8%	4.8%
Output Current	7.5A	7.5A
Swichging No. of each switch per one cycle	33	28
THDi Input Current	80%	60%
Output Power	832W	1280W
DC Reactor	18mH	17mH

3. Power passive filter

3.1 Conventional input power filters

Generally, L-C filters are used to suppress harmonic currents in the input side of the converter.[7] L-C filter has 2nd order transfer function so, makes resonant problem near the resonant frequency. To diminish the resonace related to PWM swithching, damping resistor can be connected in series with filter capacitor.[2] It is called LCR filter in the paper. The main problem of this type of filter is the power loss from the flow of the large harmonic current through the damping resistor. The damping effect can be also obtained with control loops.[1] The method is not simple.

This paper proposes a novel type of L-C filter configuration for solving the above mentioned problems.

3.2 Proposed LRC filter configuration

In the paper, a novel type of L-C filter configuration named LRC filter, where damping resistor is connected in parallel with filter inductor, is proposed. Harmonic equivalent circuit and frequency charateristics about L-C filter with damping resistor are illustrated in Fig.5.

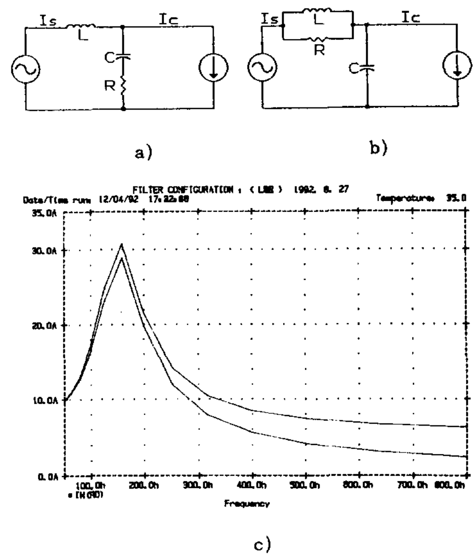


Fig.5. Harmonic equivalent circuit with damping resistor R and frequency characteristics: a) LCR filter, b) LRC filter, c) Gain curve.

The transfer function between the source current and the harmonic current of LCR filter is given by:

$$\frac{I_s}{I_c} = \frac{S\cdot \omega_c/(2\zeta) + \omega_c^2}{S^2 + S\cdot \omega_c/(2\zeta) + \omega_c^2} \tag{5a}$$

$$\omega_c = \frac{1}{\sqrt{LC}} \tag{5b}$$

$$Q = \frac{w_c L}{R} \tag{5c}$$

$$\zeta = 2Q \tag{5d}$$

In the case of LRC filter:

$$\frac{I_s}{I_c} = \frac{S\cdot (2\zeta\omega_c) + \omega_c^2}{S^2 + S\cdot (2\zeta\omega_c) + \omega_c^2} \tag{6a}$$

$$Q = \frac{R}{w_c L} \tag{6b}$$

$$\zeta = \frac{1}{2Q} \tag{6c}$$

If Q=2 then ζ = 4 (LCR filter) and ζ = 0.25 (LRC filter). In this case, the overshoot of each indicial response becomes about 44%.

In the LRC filter, the fundamental current mainly flows through the inductor, and the harmonic current over the cutoff frequency mainly flows through the damping resistor. So, the power loss in damping resistor is drastically decreased and the filter inductor is also protected from high order current harmonics. It behaves like a L-C filter under the cutoff frequency and R-C filter over the cutoff frequency.

3.3 Filter design

As the filter design constraints, THDi (total harmonic distortion of the AC source current) is limited within 5% and filter quality factor Q is fixed to 2. The constraint function of THDi and the optimal function of filter cost are given by;

$$\mathrm{THDi} = \frac{100}{I_1}\left\{\sum_{k}^{\infty}\left[\frac{I_k}{k}\right]^2\right\}^{1/2} \quad ;k=5,7,11,\cdots \qquad 7)$$

$$\mathrm{Cost} = 3\cdot \mathrm{TKVAL} + \mathrm{TKVAC} \qquad 8)$$

where, TKVAL : Capacity of inductor L
TKVAC : Capacity of capacitor C

This paper introduces a simple and optimal filter design method;

① Investigate local minimum filter cost for the resonably selected filter cutoff frequency.
② Obtain V curve by execution of step 1 for more then 4 cutoff frequency.
③ Find optimal filter values at the valley of the V curve.

4. Simulation

4.1 Conditions

Through the computer simulation using ACSL (advanced continuous simulation language), behaviour charateristics of the PWM-CSC and optimal filter design method are investigated. Phase voltage of 3-phase converter is 127[V]/50[Hz], MI(modulation index) is 0.8, and sampling frequency of sawtooth wave is 1.2[kHz]. As filter design constraints, RFi<5% and THDi<5%.

4.2 Results

Design results of LRC filter about CS PWM GTO converter according to the proposed design steps are shown in Fig.6. In Fig.6a), total cost curve versus filter reactance is shown when Q = 2 and fc =155[Hz]. It shows minimum point. Fig.6c) shows the curve of filter combinations which have minimum cost at each filter cutoff frequency. The locus forms as V curve. The valley of the V curve is the GMP (global minimum point) of the filter cost.

Table 2. Characteristic comparison between LRC filter and LCR filter.

	LRC Filter	LCR Filter
L[mH]	11.5	16
C[μF]	91.68	63.42
R[Ω]	22.4	7.9
fr[Hz]	155	158
Q	2	2
TKVAL[KVA]	265.14	286.72
TKVAC[KVA]	525.77	461.54
Cost[KVA]	1421.18	1321.71
PLoss[%]	1.32	20

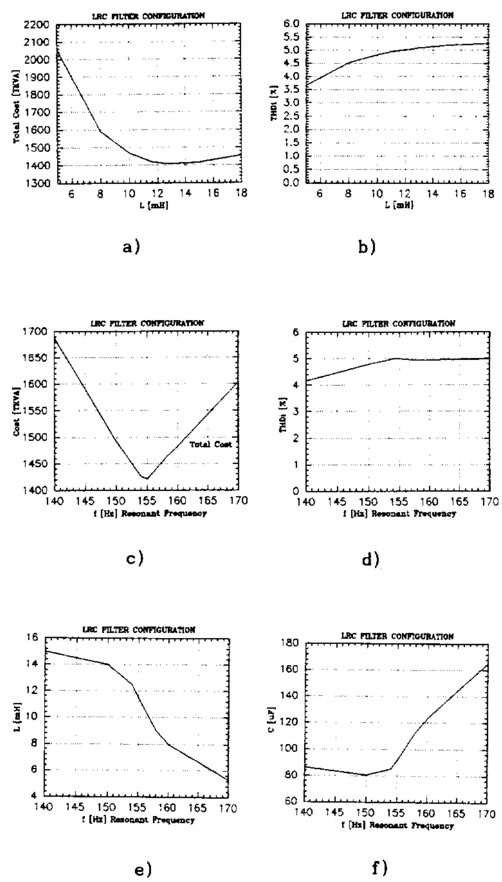
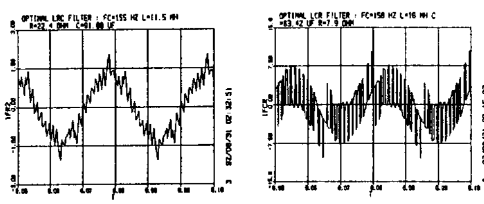
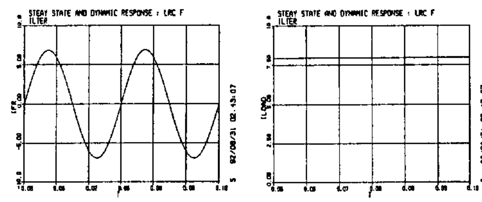


Fig.6. LRC filter design results for CS PWM GTO converter; a) Cost curve vs. L, b) THDi curve vs. L, c) Cost curve vs. fc, d) THDi curve vs. fc, e) Value of L curve vs. fc, f) Value of C curve vs. fc.



a) b)

Fig.7. Current waveforms through damping resistor; a) LRC filter, b) LCR filter.



a) b)

Fig.8. Input/output current waveforms in steady state; a) AC source current waveform, b) DC output current waveform.

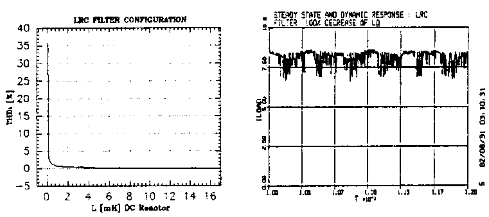


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Fig.9. Input/output characteristics vs. DC link smoothing reactance; a)THDi curve vs. DC link smoothing reactance, b) DC output current waveform when decrease L_d to 0.17mH.

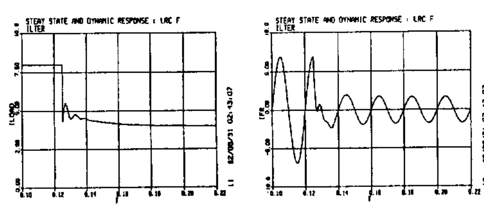

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Fig.10. Waveforms of the system with LRC filter on the change of DC current reference; a) DC link output current, b) AC source current.

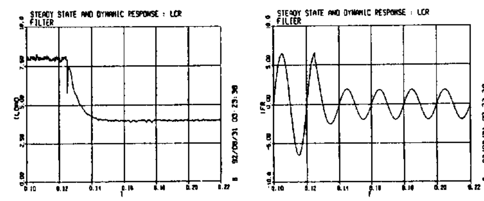

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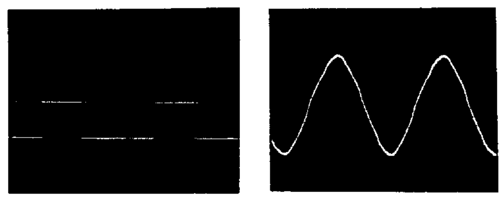
Fig.11. Waveforms of the system with LCR filter on the change of DC current reference; a) DC link output current, b) AC source current.



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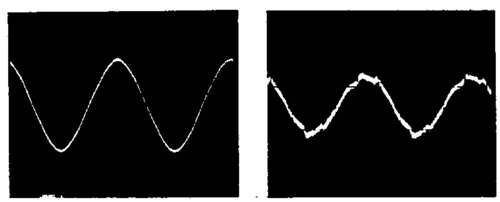
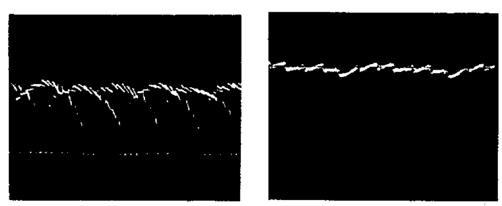


c) d)



e) f)

Fig.12. Experimental waveforms in LRC filter; V_p=60[V]/60[Hz], R_{load}=20[Ω], L_d=30[mH], L=13[mH], R=22[Ω], C=30[μF] (Δ connection), a) PWM output waveform of gate signal (S1) from ROM (5V/DIV), b) AC input current (0.2A/DIV), c) Input current of inductor L (0.2A/DIV), d) current of dampiing resistor R (20mA/DIV), e) Output voltage waveform of converter (10V/DIV), f) output current I_d (0.2A/DIV).

Fig.7 shows the current waveform through damping resistor. The current in LCR filter is relatively larger than that in LRC filter.

The characteristic comparisons between LRC filter and LCR filter are shown in Table 2. The cost of LRC filter is a little higher(7%). However, the power loss in the filter is drastically decreased more than 15 times and also it is about 1.7% larger in the output power than LCR filter.

Fig.8 shows the waveforms of the AC source current and the output DC current. By the control effect, the ripple components of output current in the DC side is drastically decreased. As a result, the THDi of the AC source current is much decreased near to 0.08%.

Fig.9a) shows the relation about THDi of the AC source current while decreasing DC link reactor. Even though reactor value is decreased 100 times, THDi remains below 5%. Fig.9b) shows the waveform of output current in the DC side with the same DC reactor.

Current and voltage waveforms in the system with LRC filter are shown in Fig.10 when DC current reference I_{dref} is changed from 8[A] to 4[A]. The transient response is a little longer (about a quarter of a period) than LCR filter in Fig.11.

5. Experimental results

As the switching devices of GTO, GFT50B12 was used. The experimental results of CS PWM GTO converter are shown in Fig.12.

Fig.12a) shows PWM output waveform of gate signal (S1) from ROM. Fig.12b) shows a source current with nearly sinusoidal. Fig.12c) and 12d) show each current waveform through inductor L and damping resistor R. Fig.12e) shows output voltage of converter. Fig.12f) shows output current I_d.

6. Conclusions

In the paper, PWM scheme and passive filter about anti-harmonics were described.

The sawtooth scheme was selected as superior switching algorithm which fumdamentally reduces filter size. Simple design method and design data of the proposed LRC filter were presented and compared with the LCR filter. The cost of the -LRC filter is a little higher(7%) and the transient response of the LRC filter is a little longer (about a quarter of a period) than that of the LCR filter. However, the power loss in the damping resistor is drastically decresed and the output power is increased a little (1.8%) in the LRC filter. Good correspondence between simulated and experimental results has confirmed the validity of the proposed theory.

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