1Hz CHOPPER TYPE QUADRUPOLE MAGNET POWER SUPPLY FOR SSRF BOOSTER

Z. X. Xu, C. L. Guo
Shanghai National Synchrotron Radiation Center, P.O. Box 800-204, Shanghai 201800, P.R. China

Abstract

A 1Hz-pulse chopper type power supply operated in PWM (pulse width modulation) mode is introduced. A power circuit with two parallel connected choppers which are operated by 180^o synchronizing phase shift was designed to improve response speed of the power supply. Analyses on its operation character and its regulator scheme are presented briefly. The performance of the converter prototype is described**.**

1. INTRODUCTION

The Shanghai Synchrotron Radiation Facility (SSRF) booster is operated with 1Hz repetition rate and accelerates the electron beam from 300MeV to 3.5GeV within 450ms. The 48 quadrupole magnets on the booster are divided into 2 families. Each family is fed by a single power supply rated by 450A/380V and 450A/350V respectively [1]. The key specification for the quadrupole magnet (Q-magnet) power supply is the ramp tracking accuracy. The tracking accuracy should be better than 0.1% within 10~100% of the output full range. High tracking accuracy demands a low current ripple, a minor cycle-to-cycle jitter, and excellent transient performance as well [2]. To meet these requirements, a converter with two parallel connected chopper branches was developed for the Q-magnet power supplies. Since the time constant of Q-magnet is less than 0.1s, while the booster return period is as long as 0.55s, the energy store/dissipation circuit is unnecessary for the power supply.

2. CHOPPERS IN PARALLEL

The converter consists of two chopper branches. The two branches are connected in parallel through their inductors (Fig. 1). Both chopper branches are operated at the same switching frequency with synchronizing phase shifts of 180 degree from each other.

With this topology, the synthetic operation frequency of the converter is doubled. The variation of synthetic output current becomes smaller. It is less than half of either branch. As a result, action speed of the converter is doubled. Since the branch shares only 1/2 of the load current, we could select the IGBT with lower current ratings. Lower current rating means higher switching frequency could be used, that again contributes to the fast action speed of the converter. For the current smoothing inductors, low current rating means easy for fabrication with commercial magnetic core products.

In our case, IGBT rated by 600A/1200V was selected for each chopper branch. The operation frequency was set to be 20kHz. The inductors and capacitors of the output filter were designed to be 100μH / 300A and 100μF /1000V respectively.

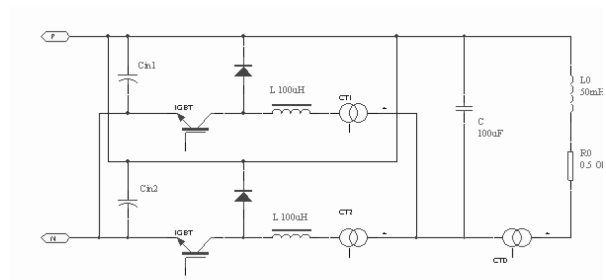

Fig. 1 Schematic of the converter

The current variation in each of the smoothing inductor has the expression,

$$\Delta I_L = \frac{D(1-D)\cdot E_{IN}T}{L}$$

where D is the duty cycle; E_{IN} is the DC input voltage; T is the switching period; L is the value of the inductor.

When the two branches run in the phase shifted PWM mode, the two current variations add up together with the DC components and forms a new semi-triangular current ripple, the amplitude of the semi-triangular current has a similar expression to that of a single branch,

$$\Delta I = \frac{\mathrm{D}'(1-\mathrm{D}')\mathrm{E}_{\mathrm{IN}}\mathrm{T}'}{\mathrm{L}}$$

where, T' =T/2; D'=2D for D<0.5, and D'=2D-1 for D>0.5. Obviously, the variation amplitude is reduced.

This ripple current sunk by the filter capacitor determines the output voltage ripple. At this point, the two branches are equivalent to a single chopper with a switching frequency of $f_s'=2f_s$. While the filter parameters are L and C. The voltage ripple in our case is less then 1%.

It is noticeable that the identity of component and circuit parameters between the two branches is important for balance operation. The bus and the cable connecting the two branches as well as the IGBTs and the inductors should be arranged identically, especially the values of the two inductors. However, slightly difference doesn't matter very much. For example, a difference less than 5% between the inductors are permitted.

3. CURRENT REGULATORS

Two levels of current regulation loops are designed for the converter: the load current loop and the branch current loop (Fig. 1, Fig. 2).

The load current loop with an integral element regulates the output current to the required tracking accuracy. The load current loop employs a bi-zero, bipolar compensator. The compensator increases the system response band to obtain a high response speed.

The two branch current regulation loops respond directly to the output of the load current regulator and insure that the two branch current track the converter reference and share the load current equally. Each branch regulator utilizes a proportion controller. Since the feed back signal is the branch current, very swift response to the outer loop could be obtained.

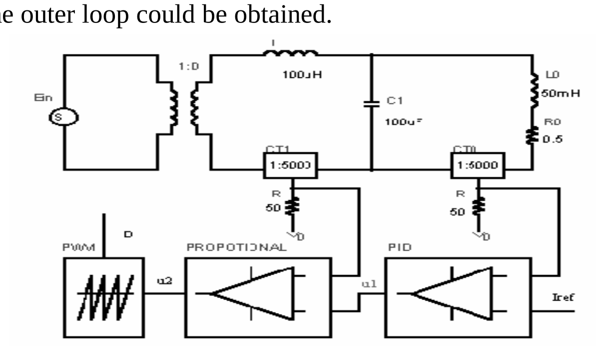

Fig. 2 The converter and the regulators scheme

For small signal and long term variation, the chopper can be simplified as a transformer with the ratio of 1:D [3]. We take the two branches in whole as a transformer. The equivalent block diagram of the converter is shown in Fig. 2. The regulation transfer structure diagram of inner loop is shown in Fig. 3.

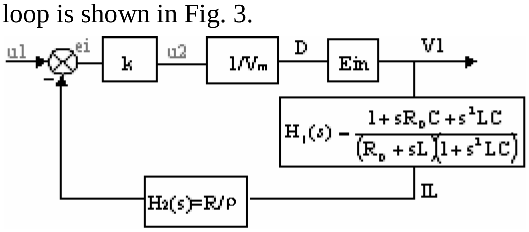

Fig. 3 Structure diagram of the inner loop

where, u1 is the input signal of the inner loop from load current regulator; V1 is the inner loop regulator output signal; k=5 is the gain of the proportional controller; E_{IN}=500V is the source voltage; and V_m=5V is the sawtooth wave amplitude of the PWM comparator. D is the duty cycle. D has an expression of $D=u_2/V_m$. And kE_{IN}/V_m represents the transfer function of the chopper together with the PWM comparator and the preamplifier.

$H_1(s)$ transfers the output voltage to inductor current. $H_2(s)$= R/ρfeeds the inductor current back. R is the shunt resistor, ρ is the ratio of the current transducer. The transfer function of V1/ u1 is $G_2(s)$,

$$G_2(s)=\frac{100k(1+s\tau_0)(1+s^2LC)}{1+2k+s\tau_0+s^2\cdot 2kL_0C+s^3\tau_0 LC}$$

where, $\tau_0=L_0/R_0$ is the time constant of the magnet load.

With the inner loop transfer function $G_2(s)$, we have the structure diagram of the load current loop. The structure diagram is shown in Fig. 4.

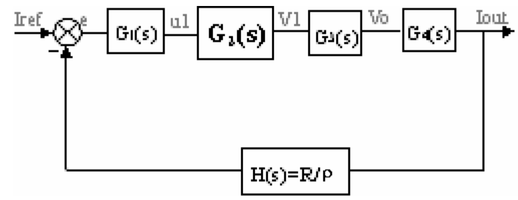

Fig. 4 System structure diagram

where, $G_3(s)=1/(s^2LC+1)$ represents the filter section, $G_4(s)=1/(R_0+sL_0)$ is the magnet load transfer function, and H(s)=R/ρ represents the current feed back transfer function.

The system, except the compensate part, has the transfer function:

$$G_2(s)G_3(s)G_4(s)H(s)=\frac{2k}{1+2k+s\tau_0+s^2\cdot 2kL_0C+s^3\tau_0 LC}$$

In order to obtain a better transient property, we choose to set the unit gain bandwidth frequency ω_c at 4000rad/s , ~2/5 of the filter character frequency. The phase margin is set to be 50 degree. We employ a bi-zero, bipolar regulator to accomplish the job. The regulator has the transfer function $G_1(s)$,

$$G_1(s)=\frac{29.39\times 10^3(0.930\times 10^{-3}s+1)(0.905\times 10^{-3}s+1)}{s(64.35\times 10^{-6}s+1)(64.53\times 10^{-6}s+1)}$$

With the compensator, the system open-loop frequency response is shown in Fig. 5.

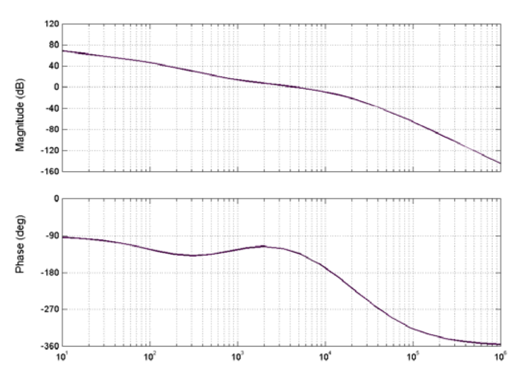

Fig. 5 System open-loop response

The compensated magnitude (top plot in Fig. 5) intersects the 0dB line at 4500rad/s with a slope of

–20dB/dec. The system has a phase margin of 48 degree and a magnitude margin of 12dB.

There is an integral element in the open loop transfer function. The static speed error factor is $K_v=26.71\times10^3$. Given slope reference, the static speed error will be a constant.

It is noticeable that the two levels of current regulation loops provide little suppression on the low frequency ripples of the chopper DC source.

4. PERFORMANCES OF THE PROTOTYPE

A prototype rated for 80A/40V has been designed and tested for the studies on the parallel chopper topology. The two IGBTs are operated at 20kHz. The synthetic frequency is 40kHz.

Fundamental ripple of the output voltage is twice the IGBT switching frequency. It indicates that the branch currents are well balanced (Fig. 6).

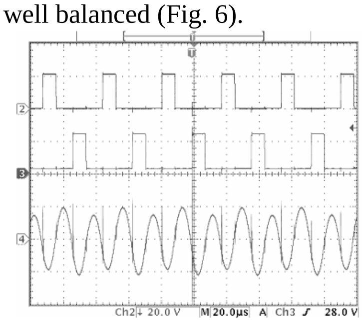

Fig. 6 The PWM signals and the voltage ripples

It is found out that the gain of the branch controller affects very little on the current balance.

A built in amplifier with a gain of 50 was utilized as the error detector. It senses the output current error signal based on the difference between the load current feedback and the current reference waveforms. Fig. 7 shows the waveforms measured by scope. Only ramp section was investigated. The error signal was set to zero during the return section.

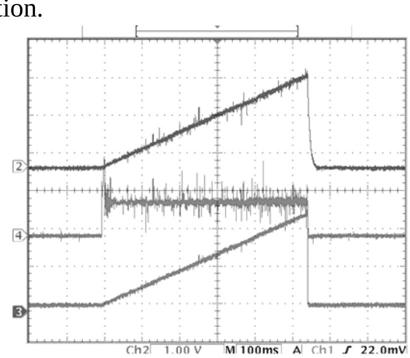

Fig. 7 Current regulating errors

We find that the error consists of two parts. The first part is the transient error at the ramp starting section. The second is a constant delay error (or static speed error) within the ramping section.

Since any repeatable deviation can be eliminated by modification on the delay time of the reference waveform in a computer-based control system, only transient determines the ramp tracking accuracy.

The transient property is sensitive to the variable of the reference start section. A soft turn and small positive bias at the start point are expected for a better transient property. Further study can be carried on by employ of the reverse response technique.

Based on the proper choice of the regulator parameters and the careful tuning of the small positive bias at the start point, an accuracy of 0.1% could be obtained throughout 10%~100% of the peak current.

The ripple component caused by the DC source was observed in the output load voltage without significant suppression. The ripples can be observed in the current error signals. A feed forward technique or voltage feedback might be used to suppress the ripples from the DC source.

5. CONCLUSION

Based on the system analysis and prototype tuning, we could draw the conclusions:

The parallel chopper topology of converter, which has a doubled action speed, is fit for the tracking requirements of the 1Hz quadrupole magnet power supplies.

The branch currents can be maintained equally with no difficulty.

The converter regulator with current regulation loops operated under the computer based tracking reference is suitable to insure the tracking accuracy.

The start section of the reference affects significantly on the transient, in turn, affects on the tracking accuracy.

Voltage ripple of the DC source should be small enough so as not to affect the tracking accuracy significantly.

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