Current Modulation in the Power Supply of Rapid Cycling Synchrotrons

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Abstract

In a 50 Hz pulse power supply for rapid cycling synchrotrons, a current modulation which affects current stability was observed. In this paper, the modulation behavior is examined by experiment and analysis, and the method of the modulation suppression is described.

1 Introduction

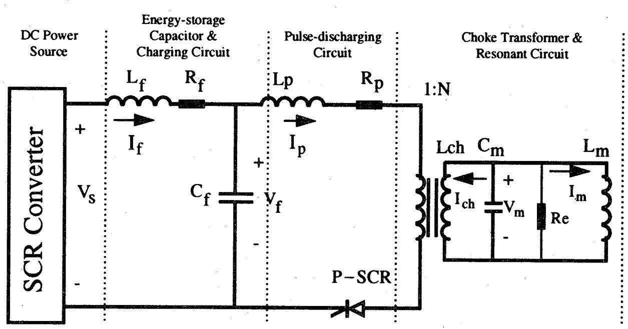

Fig.1 Pulsed power supply and resonant network for a rapid cycling synchrotron

In rapid cycling synchrotrons, a pulse power supply is usually used as the AC power source for the resonant network as shown in Fig. 1[1]. The DC power source is provided by an SCR converter, which produces both characteristic and non-characteristic harmonics due to "un-ideal" converter operation. The non-characteristic harmonics, also named subharmonics, are the components with lower frequencies than the fundamental frequency of the converter. These subharmonics will be transmitted to the resonant magnet-current I_m and cause a current modulation. This phenomenon has been reported and investigated by both computation and experiment[2]. Assuming that the line frequency is f_o, the switching frequency(= the resonant frequency) f_s and the frequency difference $\Delta f = |f_o - f_s|$, the modulation behavior can be summarized as follows.

(1). The current modulation appears when $\Delta f \neq 0$.

(2). Corresponding to a subharmonic of order h, the modulation appears as the sidebands with frequencies of $nf_s \pm h\Delta f$ around each harmonic of the resonant current with frequency of nf_s, n=1,2,3,..., accordingly, the modulation period is $h\Delta f$.

(3). The modulation amplitude decreases with the increase of the order of the subharmonics.

In this paper, we make a further measurement to examine the results above and give a demonstration to suppress the current modulation.

2 Experimental Observation

Firstly, we give a measurement result shown in Fig. 2 to examine the modulation frequency.

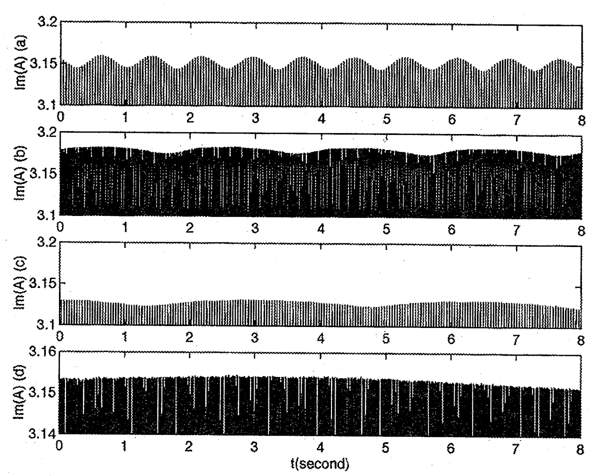

Fig.2 Measured resonant current I_m at difference f_s, (a) 49.35, (b) 49.75, (c) 50.13 and (d) 50.00 Hz.

The currents I_m are sensed with a DCCT (1500A/10V) and sampled near the peaks. The component of 100 Hz is dominant in the subharmonics of the source voltage. Therefore, the modulations are arisen chiefly by the 2nd-order subharmonic in this measurement. As a result, the modulation periods are $2\Delta f$ approximately as shown in the figure.

Secondly, a measurement (Fig. 3) is shown to confirm the correlation between the sidebands and the order of the subharmonics. We set the resonant frequency f_s=49.75 Hz and measured the spectrum of the source voltage V_s and the sidebands around f_s in the pulse current I_p. In measurement (1), the sidebands $f_s \pm 2\Delta f$ are the most prominent since the 2nd-order subharmonics of the source voltage is the highest one. In contrast, in measurement (2) the sidebands $f_s \pm 2\Delta f$ disappear when the 2nd-order subharmonic is made absent intentionally by means of the feedback control to be introduced in Sec. 3.

This proves that the 2nd-order subharmonic causes the sidebands $f_s \pm 2\Delta f$. Extending of this result leads to the general statement (2) made in Sec.1.

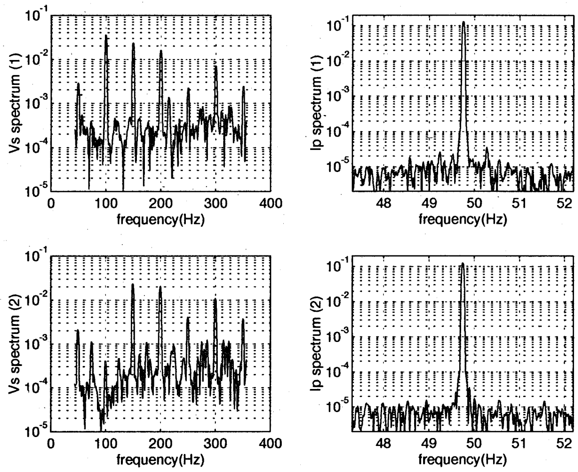

Fig. 3 Correlation between the sidebands and the order of the subharmonics for I_p

Finally, let us evaluate the transmission from the source voltage subharmonics to the resonant current.

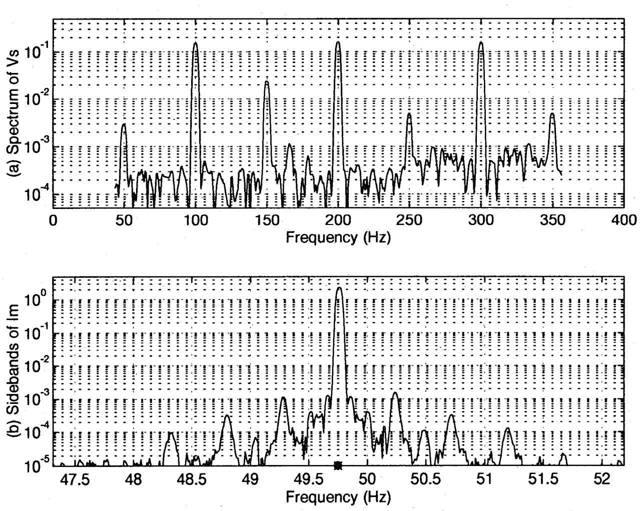

Fig.4 Spectrum of the source voltage (a) and sidebands of the resonant current (b)

To do this, we measured the spectrum of the source voltage [Fig. 4(a)] and the sidebands of I_m [Fig. 4(b)] around f_s, then normalized the sidedbands with the corresponding subharmonics. Note that a divider with the factor of 781V/5.1V is used for the measurement of V_s and a DCCT with the coefficient of 1500A/10V for the measurement of I_m. A numerical computation has been made to evaluate this transmission[3]. A comparison is made between the measurement and computation (see Table 1).

Table 1 Evaluation of the sidebands in I_m

Frequency	$f_s + 2\Delta f$ / $f_s - 2\Delta f$	$f_s + 3\Delta f$ / $f_s - 3\Delta f$	$f_s + 4\Delta f$ / $f_s - 4\Delta f$
Measured ($\times 10^{-2}$)	1.03 / 0.73	0.469 / 0.296	0.206 / 0.204
Computed ($\times 10^{-2}$)	1.21 / 0.93	0.48 / 0.40	0.23 / 0.21

The errors between the measured values and the computed ones are due to the dynamic changes in source voltage subharmonics and measurement uncertainty. Taking into account these error factors, we regard the measurement and computation are in fairly good agreement. A further calculation gives the estimated modulation for 1% subharmonics as shown in Table 2.

Table 2 Estimated modulation for 1% subharmonics at $\Delta f = 0.25$Hz

Subharmonics in V_s	Modulation in I_m
50 Hz	1.12×10^{-3}
100 Hz	2.8×10^{-4}
150 Hz	1.19×10^{-4}
200 Hz	5.61×10^{-5}

It is seen that the modulations, especially those with lower orders, affect the current stability noticeably.

3 Modulation Suppression

Having explicated the behavior of the modulation and evaluated its affect, we proceed to introduce a scheme to suppress this undesirable variation in the resonant current.

As the modulation is usually related to some predominant subharmonics in the source voltage in practice, we proposed a voltage feedback loop with one or two passband amplifiers tuned to the frequencies interested. In the model power supply under discussion, the main subharmonics are 50, 100 and 150 Hz components among which the 100 Hz is dominant while the 50 Hz is

negligible. Therefore, we designed a feedback loop mainly for the rejection of the 100 and 150 Hz components as shown in Fig. 5, where we have:
the input-output parameters as
V_r =voltage reference
V_d =voltage output, the full voltage is V_{d0} =781/5.2
V_p =perturbations including the subharmonics ;
the regulation element as
H=5.2/781 is the feedback coefficient
$G = 1/s\tau_i$ is an integration regulator

$$G_{b1}(s) = \frac{k_{b1}(1+\frac{s}{2\pi f_{b1}})}{1+\frac{s}{Q_{b1}2\pi f_{b1}}+(\frac{s}{2\pi f_{b1}})^2} \quad \text{and}$$

$$G_{b2}(s) = \frac{k_{b2}(1+\frac{s}{2\pi f_{b2}})}{1+\frac{s}{Q_{b2}2\pi f_{b2}}+(\frac{s}{2\pi f_{b2}})^2}$$

are two passband amplifiers with $f_{b1} = 100\text{Hz}, f_{b2} = 150\text{Hz}$, $k_{b1} = k_{b2} = 0.25$ and $Q_{b1} = Q_{b2} = 50$ for a design to achieve a gain above 20 dB at the central frequencies f_{b1} and f_{b2}.

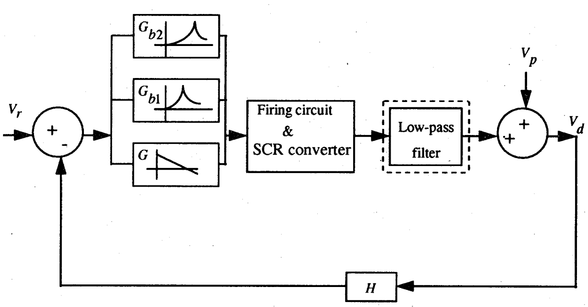

Fig. 5 Feedback loop with passband amplifiers

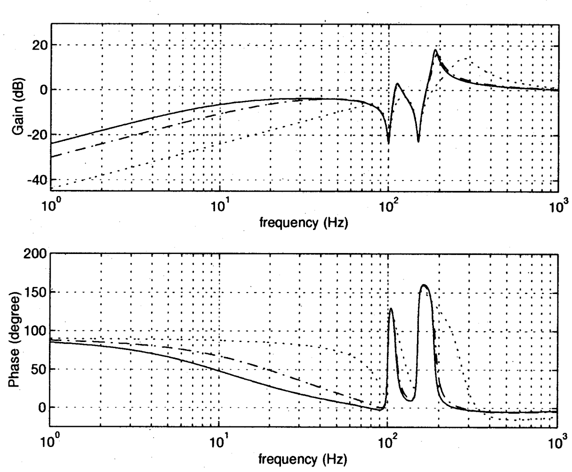

Fig. 6 Bode plots of V_d / V_p,
τ_i : __0.01, ---0.005, ...0.001

The Bode plots of V_d / V_p in Fig. 6 shows the rejection characteristic of the loop. With this scheme, we obtain an attenuation of over 20 dB at 100 and 150 Hz.

Experimental result is presented in Fig. 7 where we see that the experiment demonstrates an effective suppression of the subharmonics interested.

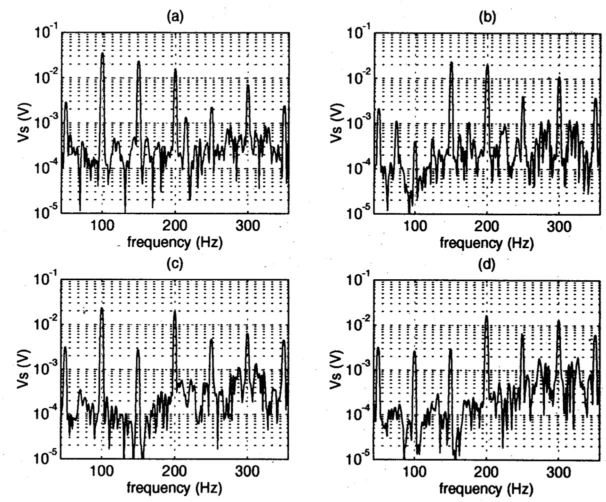

Fig. 7 Experimental results of the voltage feedback with the passband amplifier(s): (a) none, (b) 100 Hz, (c) 150 Hz and (d) both 100 and 150 Hz

Since the subharmonics are reduced effectively, the resonant current reaches a high stability of $\pm 1.56\times10^{-4}$, where the stability is defined as: $\pm\frac{I_{m,peak(\max)} - I_{m,peak(\min)}}{I_{m,peak(\max)} + I_{m,peak(\min)}}$.

4 Conclusion

We have described the phenomenon of the current modulation in the 50 Hz power supply. The behavior of modulation has been explained and confirmed. By diminishing the subharmonics in the source voltage, the modulation is suppressed effectively.

References

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[2] F.Q. Zhang, T. Adachi, K. Endo, "Effect of Source Voltage Subharmonics on a Rapid Cycling Synchrotron Power Supply," Proc. 1997 Part. Accel. Conf., Vancouver, B.C., Canada (1997).
[3] F.Q. Zhang, "Study on Power Supply for 50 Hz