Configurations of Magnet/Power Supplies for a Rapid-Cycling Synchrotron

Fengqing ZHANG, Toshikazu ADACHI, Hirohiko SOMEYA, Hikaru SATO, Yoshiro IRIE
High Energy Accelerator Research Organization (KEK)
1-1, Oho, Tsukuba-shi, Ibaraki 305-0801, Japan

Abstract

Configurations of magnet/power supplies for a rapid-cycling synchrotron (RCS) are investigated in this paper. Two fundamental magnet configurations, namely, parallel resonance (PR) and series resonance (SR), are described. Benefited from the advances of power switches, such as IGBT, power sources for RCS magnets are being developed to be lower in harmonics. Therefore, phase synchronization between multi-network in separated function RCS can be facilitated. While conventional White circuit powered by pulsed ac source is examined, IGBT PWM inverter and IGBT PWM converter are proposed respectively as ac power sources of PR and SR configurations for the RCS booster in JAERI-KEK joint project. The PR and SR performances are evaluated by circuit simulation.

1 Introduction

In a rapid-cycling synchrotron (RCS), magnets are commonly configured as resonant circuits, i.e. "White circuit", and powered by ac power sources [1]. The resonant current is generally dc-biased to achieve a full use of the sinusoidal waveforms for the injection and acceleration in one magnetic cycle. This general configuration of RCS avoids the generation of large amount of reactive power in magnet strings. The magnets are then grouped into meshes to work at moderate resonant voltages. Each mesh is connected in series so that a uniform waveform in each magnet is achieved.

One-mesh magnet/power supply in RCS comprises an ac power source and a parallel resonant circuit as shown in Fig. 1.

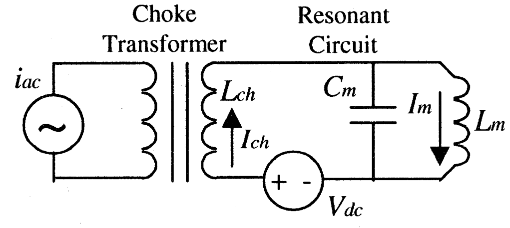

Fig. 1 RCS magnet/power supply in parallel resonance

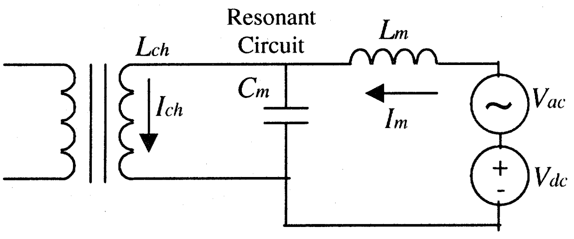

Fig. 2 RCS magnet/power supply in series resonance

An equivalent variation shown in Fig. 2 gives the series resonant circuit for RCS magnet excitation. Assuming the resonant frequency is ω_0 and turns ratio of the choke transformer is 1:1 for simplicity, we get equivalent resonant performances at

$$V_{ac} = j\omega_0 L_m \cdot i_{ac}, \text{ where } \omega_0 = \sqrt{\frac{L_m + L_{ch}}{L_m L_{ch} C_m}}.$$

The above two circuits are the fundamental configurations for RCS magnets and power supplies, where choke inductor provides the path of bias current and composes the resonant network together with the magnet (*L*m) and the capacitor (*C*m) as well. The ac power sources provide the power dissipated in the resonant circuits where large amount of stored energy is exchanged between the capacitor and inductors.

In the following sections, the characteristics of the two configurations and their power sources are described. Then, we investigate the possible options of RCS magnet/power supply system for large separated function RCS, where a close B/Q tracking is required to reduce beam losses in acceleration.

2 RCS Configurations

RCS can be configured as parallel or series resonant network with many meshes distributed along the ring. There are various types of ac power sources. They can be catalogued into continuous and pulsed ones. Recent development of power electronics, especially the power switch devices like IGBT, has provided flexible options for RCS to use continuous ac power sources adopting IGBT PWM inverter or IGBT PWM converter.

2.1 Parallel Resonance vs Series Resonance

Configurations of parallel resonance (PR) and series resonance (SR) are equivalent in circuitry, but they feature very differently in practice as described below.

(1). Both PR and SR require the choke inductors to provide a path for dc current. In PR identical coupling factors close to unity should be maintained. But in SR the primary windings are dispensable. Cutting the unwanted primary choke winding yields a very simple SR configuration.

(2). The ac and dc sources in PR are a current source and a voltage one, respectively, and have to be separated. But in SR, the ac and dc sources can be combined into a single one due to their same character of voltage source.

2.2 Ac Sources: Pulsed vs Continuous

An ac source supplying the resonant network is either pulsed or continuous. High harmonics are produced in pulsed ac sources, and pulse operation results in a phase difference between multi-network system. Efforts were made to avoid the disadvantages of pulsed ac sources and some continuous types of ac power sources were applied in RCS [2].

2.2.1 Pulsed Sources

Figure 3 shows a multi-network system powered with pulsed sources implemented with phase synchronization.

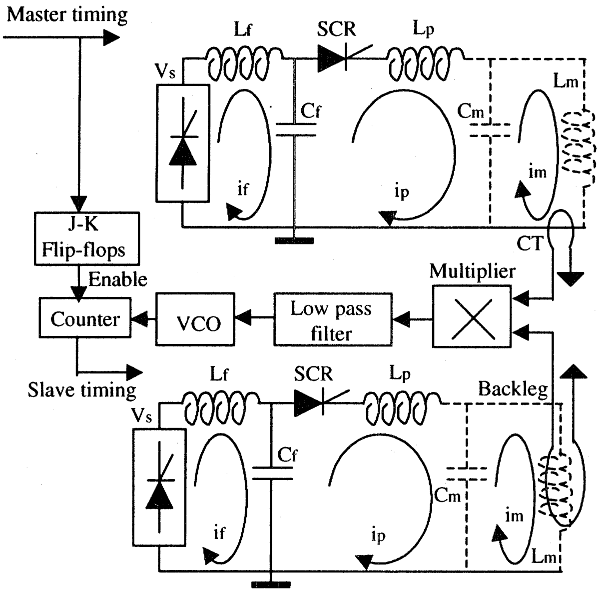

Fig. 3 A multi-network system with phase synchronization in the pulsed ac sources

This is an R&D experimental set consisting of a master and a slave system for the JHF 3-GeV booster planned to be a 25 Hz or an upgraded 50 Hz RCS. In this conventional configuration, choke transformers are omitted. The resonant currents (*I*m's) in the two networks are synchronized by adjusting the trigger timing of the pulse SCR in the slave system, and thus the phase of the pulse current (*I*p) is adjusted. Experimental test was carried out at the repetition frequency of 50 Hz and a phase synchronization was achieved with the phase difference less than 3 μs in long-term (8 hours) [3].

Though the phase synchronization can be established, the pulse operation is responsible for the phase deviation and high harmonics problem. So we turn to continuous ac sources.

2.2.2 Continuous Sources: Inverter and Converter

Motor generator (MG), cyclo-converter, resonant square-wave inverter and GTO PWM inverter, etc. were used in RCS for ac excitation previously, as reviewed by W. Bothe [4]. However, recent development of power electronics has brought new advances in continuous ac power sources.

Continuous ac sources can be divided into two classifications, namely, inverter and converter. Resonant square-wave inverter and GTO PWM inverter were precedent for powering RCS with inverters. On the other hand, a 12-pulse SCR converter (voltage source) was used in Fermilab 8-GeV booster, which is a 15 Hz series-resonance RCS [2]. We here present an IGBT voltage-source inverter (VSI) [5] for PR, and an IGBT PWM converter [6] for SR as follows.

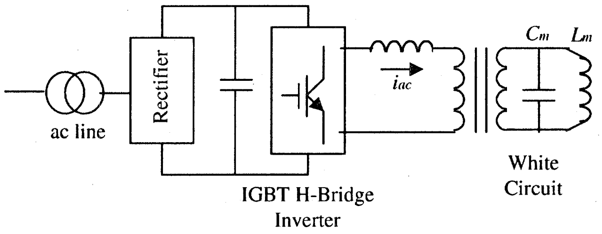

Fig. 4 Sinusoidal IGBT H-bridge PWM VSI

IGBT PWM inverter is sketched in Fig. 4. A model (628V/6A) has been built. Since it is a VSI type, voltage control is implemented in the inverter as an inner regulation loop, and a current loop will be added as an outer loop to control the resonant current.

In Fig. 5, IGBT PWM converter is presented as the combined ac+dc source for the resonant circuit in series. Since it is a voltage converter, the resonant current is regulated by voltage control. The major disadvantage of this configuration is its substantially higher peak power drawn by the resonant network, which will be shown in the next section.

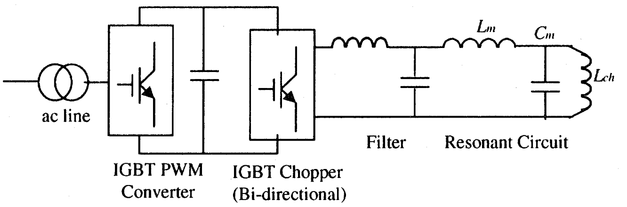

Fig. 5 IGBT PWM converter as ac+dc source for the resonant circuit in series

3 Simulation and Experiment

Parallel and series configurations are evaluated by simulation. JHF design parameters for BM-network [7] are used in the simulation as given in Table 1.

The full performances are shown in Figures 6-8. The current, voltage and stored energy are equivalent in PR and SR configurations (see Figures 6,7). However, the patterns of power drawn by the resonant networks differ significantly in the two configurations as Fig. 8 shows. Since the resonant network works as an approximitely pure resistive load, the active power, amounted to 741 kW in average, is comsumed to make up the dc and ac power losses. In SR configuration, the combined ac+dc voltage forms a two-quadrant converter, supplying unidirectional current and positive and negative voltage. By using IGBT converter (Fig. 5) with a broad bandwidth [7] instead of SCR rectifier, this active power can be produced without reactive power. But it should be noted that the peak power (2.46 MW) delivered by the power source in SR exceeds twice of that (1.12 MW) in PR. Furthermore, in SR the power variation during one magnet cycle is over 100%, while in PR configuration, peak power and power variation are moderate.

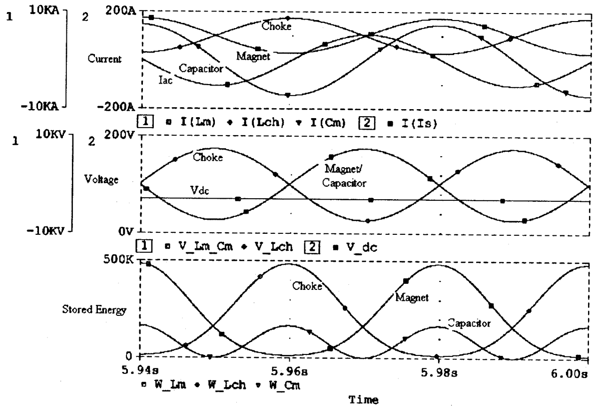

Fig. 6 Current, voltage and stored energy in PR

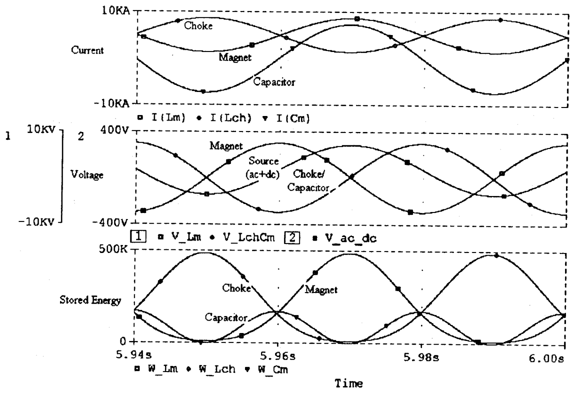

Fig. 7 Current, voltage and stored energy in SR

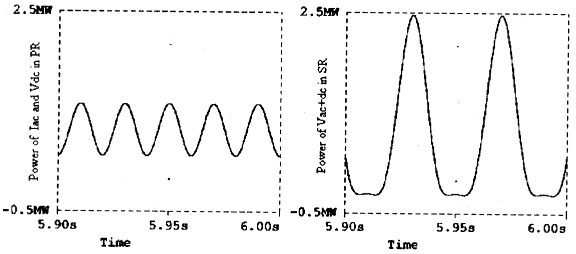

Fig. 8 Power drawn by resonant networks PR (left) and SR (right)

An IGBT PWM inverter and an IGBT PWM converter with chopper have been built at KEK to test the PR and SR configurations, and experiments are under way.

4 Conclusion

IGBT inverter or IGBT converter is replacing the pulsed ac power source to avoid the problems of the high harmonics and achieve better multi-network synchronization. We have presented a design example and simulation for parallel resonant and series resonant configurations. The SR configuration has a number of merits over the conventional PR configuration but higher peak power and large power variation are its major disadvantages.

Table 1 Simulation parameters of the resonant circuits and power sources

Magnet, inductance L_m dc resistance $R_{dc,m}$ number/mesh	12.9 mH 8.5 mΩ 5
Choke, inductance L_{ch} dc resistance $R_{dc,ch}$	12.9 mH 5.23 mΩ
Capacitor C_m	6.28 mF
Resonant circuit resonant frequency f_0 quality factor Q	25 Hz 70
Power source PR configuration SR configuration	I_{ac}=105.6sin($2\pi f_0$) A V_{dc}=69 V V_{ac}=214.9sin($2\pi f_0$) V V_{dc}=69 V ($V_{ac/dc}$= V_{ac}+ V_{dc})
Output, magnet current $I_{m,dc}$ $I_{m,ac}$ magnet voltage $V_{m,peak}$	5025 A 3660 A 7430 V

Acknowledgement

We would like to thank Hitachi Co. Ltd, for co-operation. One of the authors, Fengqing Zhang, thanks JSPS for supporting his research.

References

[1] M.G. White et al., “A 3-BeV High Intensity Proton Synchrotron”, The Princeton-Pennsylvania Accelerator, CERN Symp. 1956 Proc., p525.

[2] J. Ryk, “Gradient Magnet Power Supply for the Fermilab 8-GeV Proton Synchrotron”, Fermilan-Pub-74/85, August (1974).

[3] F.Q. Zhang, T. Adachi, et al., “Phase Synchronization of Multi-Network System for Resonant Excitation of the JHF 3-GeV Booster Magnets”, PAC’99, New York, (1999) 3752.

[4] W. Bothe, “Resonant Excitation of Synchrotron Magnets”, CERN 90-07, July (1990) 271.

[5] K.Bürkmann, et al., “Performance of the White Circuits of the BESSY II Booster Synchrotron ”, EPAC’98, Stockholm, (1998) 2062.

[6] M. Muto, et al., “Highly-Performed Power Supply Using IGBT for Synchrotron Magnets”, PAC’99, New York, (1999) 3770.

[7] “JHF Accelerator Design Study Report”, KEK Report 97-16, JHF-97-10, March (1998).