

DESIGN OF THE CONTROL SYSTEM OF PULSED POWER SUPPLIES FOR WHMM INJECTION BUMP MAGNETS

Jiang Zhao, Huajian Zhang, Zhongzu Zhou, IMP/CAS, Lanzhou, China

Abstract

The injection bump system of the synchrotron of the Wuwei Heavy-ion Medical Machine (WHMM) consists of four horizontal bump magnets to merge the injection beam with the circulating beam. In order to control the injection beam with sufficient accuracy, the bump magnets need four pulsed power supplies with high speed, precision, reliability. The power supplies, whose IGBT (Insulated Gate Bipolar Transistor) are working in the linear area, are required to output the maximum current of 2900A. Furthermore, the current pulse is activated by synchronous triggering events, the current pulse frequency is required about 30Hz, and that the pulse current falling edge should be less than 60us. In this paper, a control system for the pulsed power supplies was described in details. The commissioning results showed that the control system owned high reliability and flexible and that beam could be injected effectively into the synchrotron of the WHMM. In addition, one on-line current pulse waveform is shown in the result section.

INTRODUCTION

A facility of heavy-ion medical machine (HIMM) for cancer therapy is under construction at Wuwei city of Gansu province in China. It comprises of an electron cyclotron, a resonance ion source, a cyclotron, a medium energy beam line, a synchrotron, a high-energy beam line, and four therapy terminals. The synchrotron, as a main accelerator, is used for providing deep layer cancer therapy, like cancer of the liver, lung cancer, and so on, with 80 ~430MeV/u C^{6+} ion beam and with 37 cm maximum penetration in water. Beam injection system is the key subsystem for a synchrotron to work and produce the high-quality therapy beam. The pulsed power supplies for magnets of injection system are important components[1] have an effect on the therapy beam quality, and have demanding control requirements compared with common ramping power supplies.

The local bump method is representative of the local orbit correction method, and it has been applied to local orbit feedback systems in some facilities[2]. Similarly, the method could be used for beam injection. Bump magnet makes a local change in the orbit at the injection point of the ring with in tens of microseconds. Some facility adopted switch power supply for injection bump magnet[3]. However, In this facility, four pulsed power supplies for Injection bump magnets, whose IGBT are working in the linear area, are utilized to inject beam to the synchrotron. It is worth mentioning that we developed an FPGA controller combined with an IPC (Industrial Personal Computer equipped with waveform generator card and waveform read card) to control the Injection Bump Power Supplies (IBPSs). The hybrid control system is more reliable and flexible than analog control

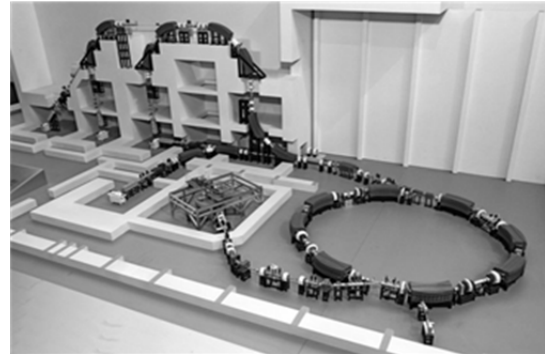


Figure 1: The model of heavy ion machine of medicine. In this paper, the working principle of the IBPSs was introduced in a chief, then the design of the control system of the IBPSs was shown in details.

MAIN CIRCUIT

According to the accelerator physics design, there is quick descent part of a current curve of the IBPSs during the beam injection. Thus, the main circuit design of the IBPSs focused on the implementation of the special requirement. In consideration of performance, cost and operating maintenance of the IBPSs, a reduced topology structure was adopted.

Topology Structure

As the Fig. 2 showed, the IBPSs use the diodes rectifier, B6U1, as the front converter. The converter and the filter circuit composed of L1 and C1 form a DC voltage source. V1 is a high-power IGBT (Insulated Gate Bipolar Translator), which is controlled by the reference voltage signal to generate the ramping current. This topology took advantage of the feature of withstanding high voltage and current to implement fast pulse current. The VM1 and VM3 are a voltmeter. The D1 and D2 mean the output protection diodes helpful to preventing the IGBT from over voltage caused by the voltage oscillation and the open circuit of the load. In an addition, R1 and C2 constitute an output filter circuit, and L2 and R2 represent the load.

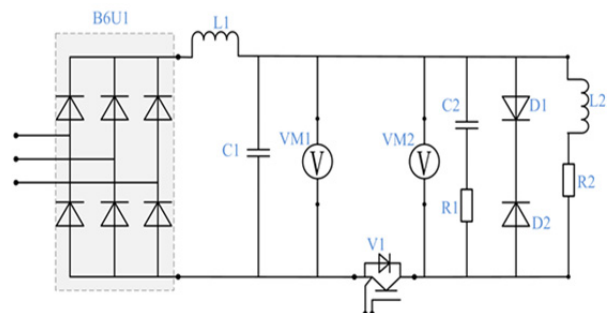


Figure 2: Topology structure of the main circuit.

IGBT Operation Mode

For the IBPSs, there is the requirement that the current falling time from rated value to 0 is at least 30 us, and that the falling process is controllable. Based on this, if these power supplies were implemented through switching power supply, not only the switching frequency is very high, but also the multiple cascaded topology structures must be used to achieve the goal of frequency doubling. And, the cost of such power supplies will grow exponentially. However, in this paper, the linear working way of IGBT is employed to implement fast pulse current. That is to say, the IGBT of the IBPSs works in the linear range.

Regulator and Driver Circuit

The analog regulator of the IBPSs is PID controller, designed by use of the discrete components. The reference signal from IPC is applied to the regulator. To ensure the requirement of the current falling time, the PID parameters should be adjusted carefully by choosing appropriate capacitance and resistance. In fact, the driver circuit of IGBT is also a power amplification electric circuit. The driver board has two main functions: one is the increase of actuating current, the other is detection and exception protection of the IGBT and driver board. In the working process of the driver circuit, the contradiction between quick-response and protection of power supplies always exists. So the design of the driver circuit of IGBT is key in such power supplies.

CONTROL SYSTEM DESIGN

Performance Requirements

As Fig. 1 shows, the synchrotron is the main accelerator in HIMM. Similar to the way of CSRm [4], charged ions may be injected to the synchrotron by means of the multiple multi-turn injection [5]. Only four bump magnets were employed within the injection system of the synchrotron in order to inject C6+ ion beam into the synchrotron. According to the physical design, the performance indicators of the four IBPSs have been listed in Table 1. Especially, because of the faster speed of response, these power supplies were designed as analog power supply [6]. This is distinct from other ramping power supplies in the HIMM.

Table 1: Performance Indicators of IBPSs

Parameters	Value
Tracing error	$\pm 1 \times 10^{-4}$
Waveform cycle(ms)	30
Falling time(ms)	0.03~0.26
Load inductance(uH)	8

The reasons why the control system of the IBPSs is developed separately consist in two parts: 1) satisfy the performance requirement of the IBPSs; 2) need for an interface compatible with the existing digital control system of HIMM. The control system has the physical professionals to feel that there are not any differences

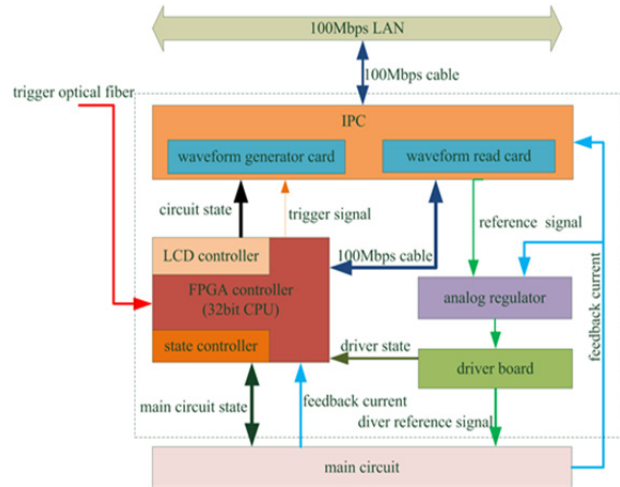


Figure 3: Control system block diagram of IBPSs.

between the IBPSs and other ramping power supplies during operation.

The dashed rectangle of Fig. 3 shows the control system structure of IBPSs. It consists of an IPC (Industrial Personal Computer equipped with waveform generator card and waveform read card), an FPGA controller(including two 32-bit CPU cores, a LCD controller and a state controller), an analog regulator, and a driver board. The control system is winning scheme of combining FPGA controller with IPC. Basically, One objective of IPC is to receive waveform data from the accelerator control system and generate the reference signal for the analog regulator via the waveform generator card. The FPGA controller, which is also used in other ramping power supplies in the HIMM, is mainly utilized to local control of the main circuit state, conversion of the trigger event, and current waveform monitoring. Some examples of local control are the operation of ON or OFF of power supply, state monitor for the main circuit, and so on. In addition, the analog regulator and the driver board are a key to implementing the faster speed of the main circuit response. The trigger optical fiber and the 100Mbps cable is the communication medium between accelerator control system and the IBPSs.

Waveform Data Forwarding

Waveform data packaged by using self-defined communication protocol are received [7], extracted and saved as TXT file by an application installed on IPC. These waveform data are simultaneously forwarded to the FPGA controller. The application was carried out by C# language to achieve such function. The TXT file on the IPC provides the card of waveform generation data points to generate a reference signal. Reliability and variety network development kit are the beauty of IPC platform, which transmits control data and is compatible with complex networks.

Waveform generation card A waveform generator card and a waveform read card based on FPGA and PCI bus were developed and equipped on the IPC. The core of the waveform generation card is a 14-bit DAC with 1MB data

depth of storage and a synchronous sample rate of 1Ksps \sim 50Msps. And the output voltage range is $\pm 0.1V$ 、 $\pm 1V$ 、 $\pm 10V$. In view of waveform length and accuracy need of the IBPSs, on-line waveform data rate is configured to 1Msps, and the $\pm 10V$ output voltage is chose in terms of the DCCT current sensor of the IBPSs.

Loading of reference waveform data The trigger signal is a rising edge signal of 3.3 V from FPGA controller. It indicates the drive program mounted in the IPC to load the reference waveform data from a TXT file. At the moment of loading, a reference signal for the analog regulator arises on the BNC (Bayonet Nut Connector) of the waveform generation card. The drive program was developed by C language in Microsoft Visual C++ environment and could launch itself whenever the IPC is turned on. Other hardware parameter of the card is set through the interface of the drive program. For instance, trigger mode, output voltage range, data depth of storage, data rate, and so on.

Current waveform monitoring

Pulse width protection Because of the smaller resistance of the load and the IGBT working in the linear area, the peak loss of the IGBT in the IBPS is very high, at most 90KW. In order to protect the IGBT, all we must do is to confine the pulse width of a current waveform to the safe range. A piece of module for current pulse width protection was developed in the FPGA controller by using the VHDL (Hardware Description Language). There are two key parameters in the module. One is a float value, called current testing point, and the other is an integer value (the unit is half microsecond) named current pulse width time. The module will shut down the power supplies when the output current is greater than the current testing point and keeps the time more than the current pulse width. The on-line value of the two parameters is set at 100.0 A and 200 us..

Set-points check As Table 1 showed, the current rising and falling time of the IBPSs would be very short. The shorter the time is, the larger the induced voltage on the inductive load is. To avoid the greater induced voltage from damaging the main circuit, the waveform data with the too short rising or falling time should be detected and removed from the IPC and FPGA controller. What's more, rate of change between two adjacent set-points is checked in the IPC and FPGA controller. If the current value between two adjacent set-points is larger than 100.0, the waveform data are invalid, and then the timestamp of invalid data is recorded in a .txt file. Whatever the accelerator control system, there is a chance of waveform data errors during the process of calculation and transmission, so the feature of the set-point check is essential.

Conversion of Trigger Event

A rising edge of 3.3V is required and used for triggering the waveform reference signal. The control system of HIMM has provided a trigger event, a 32-bit serial and transmitted via optical fiber to power supply. A piece of

conversion module, which is a signal interface converting the trigger event into the rising edge of 3.3V, is designed by VHDL. Only the trigger event matching the code[8] saved previously in the FPGA controller could be transformed into a rising edge of 3.3V. As far as the IBPSs to be concerned, the cycle of the trigger event is about 30 ms. Other key feature of the module is the accurate delay adjustment of the rising edge of 3.3V. The delay resolution is 20 ns. And a 32-bit integer, which is downloaded into the FPGA controller together with the waveform data, is employed to set the delay required by beam injection of the synchrotron system.

RESULTS

Current Test Waveform

A piece of the current testing waveform of an IBPS was illustrated in Fig 4. The channel 1 represents reference signal from IPC, and the channel 2 means current waveform derived from current DCCT whose ratio is 400A/V. And channel 3 indicates the load voltage. The top current is 2800A. And the falling time from 2800A to 0A is 60 us. This is a very key parameter for beam injection. As can be seen, the parameter is better than the needed.

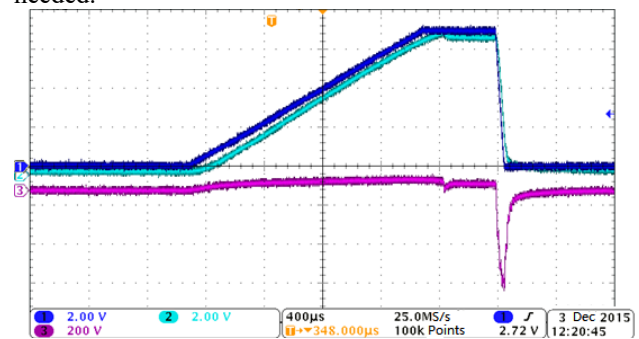


Figure 4: Current test waveform of an IBPS.

On-line Current Waveform Under Beam Injection

The IBPSs as the key component in HIMM has run successfully in the field. The aim of beam injection has been achieved. An on-line current waveform of an IBPS was shown in Fig 5. The blue curve(the channel 1) is the reference signal from the physicist, and the red curve (the channel 2) is showing the on-line current waveform at the

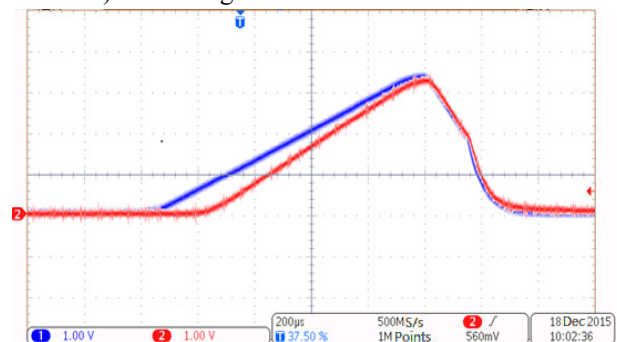


Figure 5: On-line current waveform of an IBPS.

moment of beam injection. It is observed that the process of current falling is divided into two parts. One is the linear decline section; the other is the curve decline section. Only two parts coincide exactly with the reference signal could ensure that the beam is injected successfully into the synchrotron.

CONCLUSIONS

The control system of the IBPSs combined the FPGA controller and IPC equipped with waveform generator card and waveform read card was designed as an interface between the main circuit of IGBT working in linear area and the existing digital accelerator control system. It is sufficiently flexible and reliable. And the reprogramming of FPGA along with the reliability and variety network development kit for IPC brought the system some outstanding advantages. The commissioning results testified that the desired performance indicators of the IBPSs were achieved, and the beam is injected into the synchrotron highly effectively. In the future, an integrated update will be executed for the control system of the IBPSs on the premise of optimizing performance.

REFERENCES

- [1] I. Sakai, A. Takagi, Y. Mori, S. Machida, M. Yoshii, T. Toyama, M. Shirakata, Y. Shoji, H. Sato, K. Kitagawa, Positive-ion multi-turn injection with bi-waveform fast orbit-bump magnets[J]. 1996.
- [2] N. Nakamura, H. Takaki, H. Sakai, M. Satoh, K. Harada, Y. Kamiya. New orbit correction method uniting global and local orbit corrections[J]. Nuclear Instruments and Methods in Physics Research A. 2006, 556 421-432.
- [3] S.B. Dewan, W. Eng, R.F. Lambiase, J. Sandberg, B. Holmes, K. Rust, J. Zeng, "1.12 MVA Peak Two Quadrant Pulse Switch Mode Power Supply for SNS Injection Bump Magnet", In Proc. 8th European Particle Accelerator Conference (EPAC02), Paris France, June 2002, pp. 2460-2462.
- [4] J.W. Xia, W.L. Zhan, B.W. Wei, Y.J. Yuan, M.T. Song, et al. "The heavy ion cooler-storage-ring project (HIRFL-CSR) at Lanzhou[J]", Nuclear Instruments and Methods in Physics Research A. 2002 488: 11-25.
- [5] Peng Li, Y.J. Yuan, J.C. Yang, J.W. Xia, W. Zhang, R.S. Mao, D.Y. Yin, W.P. Chdl. "The status and improvement of the HIRFL-CSR operation software[J]", Nuclear Instruments and Methods in Physics Research A. 2013, 697: 17-22.
- [6] Walter F. Praeg, "A Pulsed Power Supply for Injection Bump Magnets[J]", Industrial Electronics & Control Instrumentation IEEE Transactions on. 1979, IECI-26(1): 301-308.
- [7] Wang Rongkun, Chen youxin, Yuzhen Huang, Daqing Gao, "A new digital pulse power supply in heavy ion research facility in Lanzhou[J]", Nuclear Instruments and Methods in Physics Research A. 2013, 727: 46-50.
- [8] Jiang Zhao, Daqing Gao, Youxin Chen, Ruishi Mao, Peng Li, *et al.* "Implementation of an FPGA controller for correction power supplies in heavy ion synchrotron[J]", Nuclear Instruments and Methods in Physics Research Section A. 2015, 777: 167-171