A LINEAR MOSFET REGULATOR FOR IMPROVING PERFORMANCE OF THE BOOSTER RAMPING POWER SUPPLIES AT THE APS*

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Abstract

The APS booster ring uses ramping power supplies to power the sextupole, quadrupole, and dipole magnets as the beam energy ramps up linearly to 7 GeV. Due to the circuit topology used, those supplies are unable to follow the linear ramp to the desired accuracy. The best regulation achieved is 0.25% while 0.1% is desired. In addition to the unsatisfying regulation, those supplies are sensitive to AC line perturbation and are not able to reject AC line noises of more than a few tens of hertz. To improve the performance, a linear MOSFET regulation system using paralleled MOSFET devices in series with the power supply is proposed. The system uses a real-time current feedback loop to force the MOSFETs to work in the linear operation mode. By using this linear MOSFET regulator, the voltage drop on MOSFETs, and hence the voltage imposed on magnets, can be regulated very quickly. As a result, the regulation of the magnet current can be improved significantly. So far the simulation results show that with the linear regulator, the current regulation can be improved to better than 0.1%. Because of the high bandwidth of the linear regulator, it can reduce the harmonic content in the output current as well as reject the AC line disturbance. This paper discusses the circuit topology, the regulation method, and the simulation results.

INTRODUCTION

The Advanced Photon Source (APS) booster ring accelerates electron beam energy from 325 MeV to 7 Gev within 250 ms. It operates at a repetition rate of 2 Hz. As the beam accelerates, the magnetic fields of the dipole, quadrupole, and sextupole magnets must change from a certain low value to a certain high value. To meet this requirement, linear current ramps are used to produce the required magnetic fields throughout the ramping cycle [1]. Figure 1 shows the typical magnet current ramp of the booster ramping power supplies. At the beginning of each cycle, the current begins to rise linearly. After 10-15 ms, beam injection occurs [2]. The beam extraction occurs approximately 230 ms after the injection. After the beam extraction, all the magnet currents are ramped down to zero.

The relative current tracking error is defined in terms of ΔI/I error within each cycle, where I is the linear fit to the magnet current and ΔI is the difference between the magnet current and I. An error less than or equal to 0.1% is desired for booster operations. However, the power supplies have not been able to meet this requirement because of design limitations.

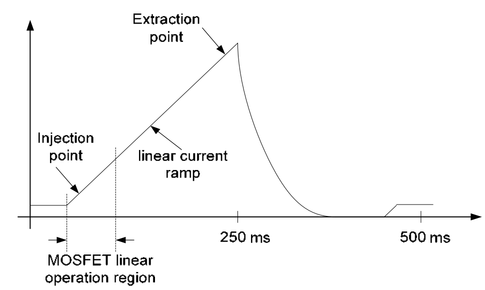

Figure 1: A typical magnet current ramp cycle in the booster.

PREVIOUS CONTROL SYSTEM OVERVIEW

Currently, the booster ramping power supplies are operating in the voltage-controlled mode. As shown in Figure 2, the voltage-mode control system is composed of two loops. The inner loop is a voltage loop. A voltage regulator is used to regulate the output voltage of the power supply. An analog PI controller of the voltage regulator compares the difference between the sensed output voltage, Vo, and the reference voltage, Vo_ref, and then generates the firing angle for the semiconductor switches in the power supply. The outer loop of the control system is a computer-based control regulator that uses an off-line tuning algorithm. Based on the sensed magnet current, it calculates the current tracking error at the end of each ramping cycle and then utilizes a correction algorithm to adjust the reference voltage waveform for the next ramping cycle.

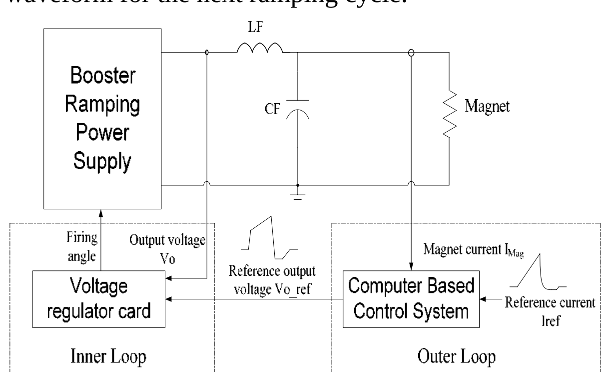

Figure 2: The block diagram of the voltage-mode controlled ramping power supply.

The voltage-mode control system has been in operation for more than ten years. However, the best regulation accuracy achieved is 0.25% - 0.5%, while the design

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specification is 0.1%. This is mainly due to the power circuit that uses a 12-pulse, phase-delayed topology, which has a very limited bandwidth in terms of regulation. In addition, the outer loop of the voltage-mode control system is off-line tuned. There is no real-time current feedback in the system. Because of the imperfections in the AC line and the power supply hardware, the output voltage of the power supplies contains 120-Hz, 240-Hz, and 360-Hz ripples in addition to 720-Hz harmonics. The voltage control loop cannot compensate for them successfully. As a result, current ripples corresponding to those frequencies exist in the magnet current. This further compromises the current tracking accuracy.

In this paper, a MOSFET linear regulation system is presented to improve the current regulation accuracy of the booster ramping power supplies to 0.1%. In the proposed system, paralleled MOSFET devices are inserted in series with the load magnet. The voltage drop of MOSFETs is regulated to fine tune the voltage across the magnets. Because of the high bandwidth of the MOSFET linear regulator, it is capable of reducing the output noises caused by the AC line perturbations and by the main power circuits. As a result, the magnet current regulation is improved. Simulation results verified that the proposed system can achieve 0.1% current regulation accuracy during the ramp cycle.

THE OPERATION PRINCIPLE OF THE PROPOSED MOSFET LINEAR REGULATION SYSTEM

As shown in Figure 3, the proposed linear MOSFET regulation system is composed of paralleled MOSFET devices, a linear MOSFET regulator, and gate drive and protection circuits for the MOSFET devices. The sum of the drain currents of paralleled MOSFETs is equal to the magnet current.

In the proposed system, paralleled MOSFET devices are inserted between the output of the power supply and the magnet. The output voltage of the power supply is equal to the voltage imposed on the magnet plus the voltage drop on the MOSFETs. The key point of the proposed linear MOSFET regulation system is that these MOSFETs operate in linear mode instead of saturated mode. When a MOSFET operates in the linear region, the voltage drop (Vds), of the MOSFET is determined by the gate voltage (Vgs), and the MOSFET drain current (Id). By adjusting the gate voltage, the voltage drop of the MOSFET can be regulated quickly.

In the proposed control system, the control of the power supply itself is the same as before, but the output voltage of the power supply is higher than the required magnet voltage. The MOSFET regulator regulates the difference between the power supply output and the magnet voltage to produce the desired current. Furthermore, any voltage disturbances or voltage ripple in the power supply output voltage will be sensed and compensated for by regulating the voltage drop on the MOSFETs.

As shown in Figure 3, the linear MOSFET regulator is composed of two loops. The outer loop is a current feedback loop. Its inputs are the sensed magnet current and the reference current. The output of the current loop is the voltage reference for the inner loop. The inner loop is a voltage loop. Its inputs are the sensed magnet voltage and the voltage reference. The output of the voltage loop is the gate voltage for each MOSFET. Both of these loops use PI controllers as their control units.

In the proposed linear MOSFET regulation system, a real-time current-feedback loop is utilized to force the MOSFETs to work in the linear operation mode. As a result, the voltage drop on the MOSFETs, and hence the voltage imposed on magnets, can be regulated very quickly. The regulation of the magnet current will be greatly improved, and the harmonic currents will be significantly reduced as well.

DESIGN CONSIDERATION FOR MOSFET OPERATING IN LINEAR MODE

Assuming the drain current is the same, when a MOSFET works in linear mode, its power loss is much higher than working in saturation mode because a MOSFET's voltage drop is much higher in linear mode. In the proposed system, if MOSFETs had to work in the linear mode during the whole ramp cycle, many MOSFETs would be needed in parallel to prevent them from overheating. Fortunately this is not the case. The MOSFETs only need to work in linear mode to regulate the voltage for the first 35-45 ms of the ramp.

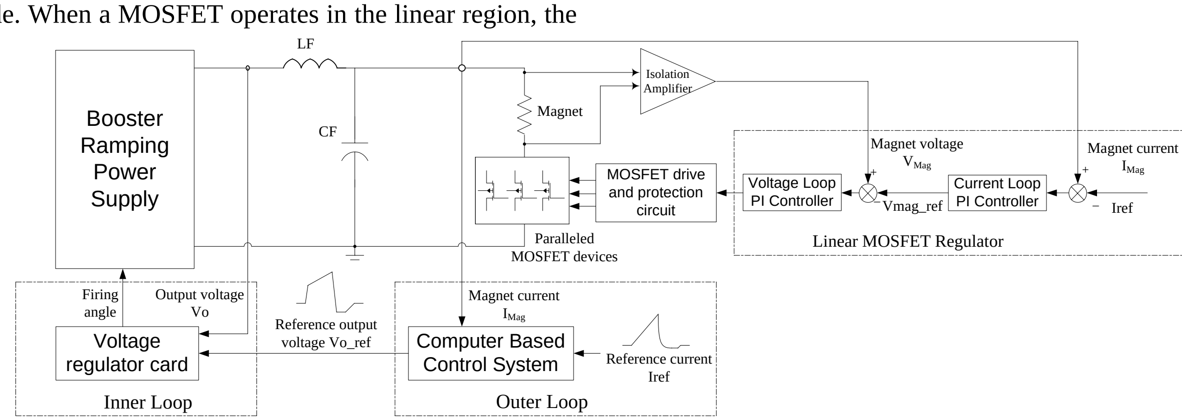

Figure 3: Block diagram of the proposed MOSFET linear regulation system for the ramping power supply.

After that, the current tracking error becomes small naturally as the current ramps up, and the beam gains enough energy so it is not as sensitive to the noise in the magnet currents. Therefore, the MOSFET devices only need to work in the linear mode between the start point and 20-30 ms after the injection point (shown in Figure 1). Outside this region, all the MOSFETs are fully turned on.

When paralleled MOSFET devices are running in the linear operation mode, the current sharing between MOSFETs is not the same as that in saturated mode. The V-I characteristic is no longer a resistive one. It is rather similar to the BJT operation; under the same gate voltage, the drain current of each MOSFET may be different due to the different characteristics of MOSFETs. It can be a serious problem for parallel-operated MOSFETs if current sharing is not under control. To overcome this problem, a simplified current-sharing control circuit is added into the system (shown in Figure 4). The sensed current is amplified and fed back to the gate drive circuit. By controlling the gate voltage, the drain current through each MOSFET is forced to be balanced.

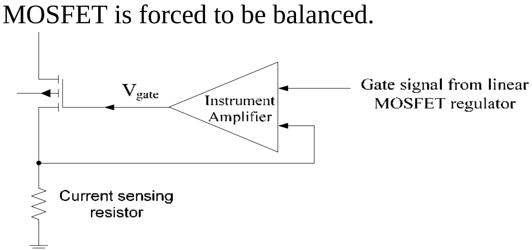

Figure 4: The schematic of the simplified MOSFET current sharing circuit.

SIMULATION RESULTS OF THE PROPOSED LINEAR MOSFET REGULATION SYSTEM

Simulation results are used to demonstrate the performance of the proposed linear MOSFET regulation system. The parameters of the sextupole magnets and power supply are used in the simulation. The parameters are: $L = 12\ mH$, R = 0.8 Ω. The beam injection point is at 15 ms. To illustrate the performance of the proposed control system under harmonic noises, a small 360-Hz noise is injected into the output of the ramping power supply.

Figure 5 and Figure 6 show the waveform of the voltage drop on the MOSFETs and the current tracking i/I curve respectively, when the MOSFETs work in linear mode, where i is the magnetic current. It is demonstrated that under the control of a linear MOSFET regulator, the voltage drop on a MOSFET is adjusted quickly, so that the current tracking tolerance (0.1%) is met before the injection point. Figure 5 also shows that the 360-Hz noises are sensed and compensated by the voltage drop on the MOSFET. As a result, the current waveform is free of 360-Hz harmonics.

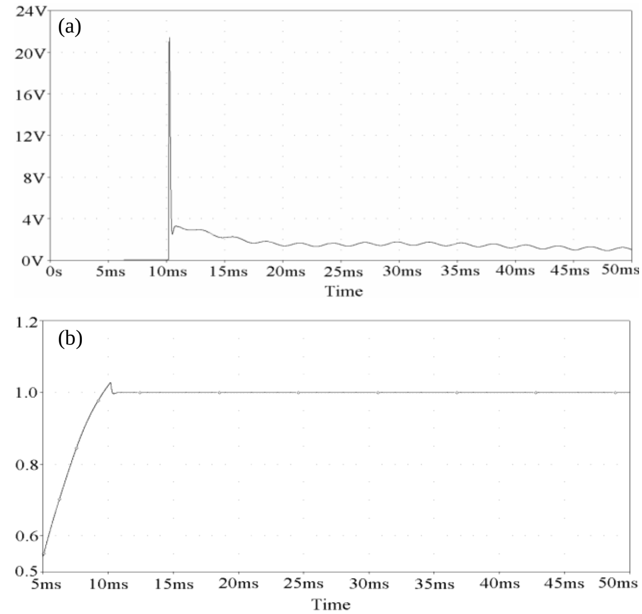

Figure 5 (a): Voltage drop on MOSFET devices during the MOSFET linear operation region during the MOSFET linear operation region, (b): around the injection point.

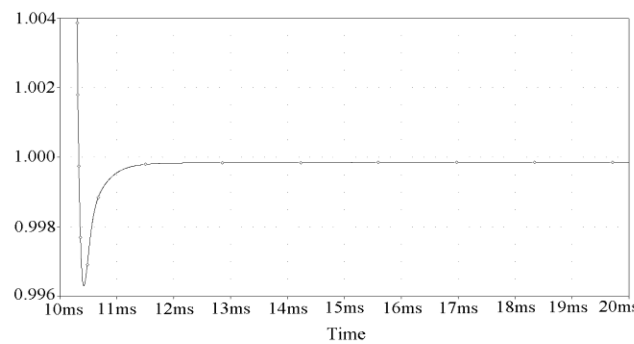

Figure 6: Current tracking i/I curve of magnet load.

CONCLUSION

In this paper, a linear MOSFET regulation system is proposed to improve the current regulation of the APS booster ring ramping power supplies. In the proposed system, the MOSFET devices work in linear mode. The voltage drop on the MOSFETs is regulated rapidly to compensate for the derivation of power supply output voltage. Simulation results show the effectiveness of the proposed system. The current tracking accuracy is improved to 0.1%. A spare sextupole power supply is being used to verify the simulation results in a real circuit.

REFERENCES

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