REVIEW OF THE POWER SUPPLIES FOR ELECTROMAGNET OF THE STORAGE RINGS AND SYNCHROTRONS

A.S. Medvedko
Budker Institute of Nuclear Physics (BINP), SB RAS, Novosibirsk, Russia.

Abstract

The Power Supplies (PS) for system with warm magnets of Storage Rings and Synchrotrons are observed. The review covers an experience of some High Energy Accelerator Centers, including INP as in the field of unipolar PS for bending and quadrupole magnets, as in two/four quadrant operating correcting magnets. SCR and IGBT based PS for current range of some Amps to some kiloAmps are described. The examples of a special type of the PS for Insertion devices - wigglers with elliptically polarized synchrotron radiation are presented. PS of this type produce current of the trapezoidal shape with variable frequency of polarity switching.

1 INTRODUCTION

Magnet system of the Storage Rings and/or Synchrotrons requires big number of different Power Supplies. Some Storage Rings have hundreds of PS channels, some - more than thousand. PSs can be classified into groups: a) Main PS; b) PS for small number or for separate magnets; c) PS for correcting (steering) magnets and d) PS with special functions for Special magnets. Main PS usually consist of one or of small number of the PS with rated power of some hundreds kW up to some MW, typical current range is some kiloAmps. These PS are to be precise devices with accuracy of 10 to 200 *ppm* for Storage Rings and better than 100 - 300 *ppm* for Synchrotrons. The PS for small number or for separate magnets are to be with rated power of some kW up to some hundreds of kW. Their accuracy need to be of the same scale like for the Main PS. Steering magnets usually need the input power less than one kW, accuracy requirements on their output current is approximately ten to fifty times lighter than for the Main PS (0.1% of maximal current looks OK). Usually the steering PS are to be bipolar (two or four quadrant operation). All another are unipolar as a rule, but bipolar when used for (*e+; e-*) booster Storage Rings. Output Voltage of PS is the additional parameter determined by some number of derived, secondary requirements. We need to add that "accuracy" for magnet PS means requirements on both long term stability, and the current ripple level and dynamic parameters (some time). Usually the ripple level requirements are more rigid than that for long term stability. To have high accuracy and high reliability of the PS are the more rigid requirement that PS manufacturers are to follow.

2 MAIN COMPONENTS

We can say that the PS for magnets consist of the next main parts: Power Circuit, precise DCCT and DAC and Low Level electronics. The last includes Interlocks and Computer control, of course. The goal of report is to overview the Power Circuits, Power Components, Power Circuitry and some aspects joined with them. Some time all of these items are named like Power Electronics.

What Power Electronics has/had for the magnet PSs - in the past, now and in the future? Main active components of Power Electronics are:

Motor - Generator	(MG)
Thyristor	(SCR)
Bipolar Transistor	(BT)
Field Effect Transistor	(FET)
Isolated Gate Bipolar Transistor	(IGBT)

The Ignitrons (Exitrons) were active components of converters in the past too.

3 MAIN PS FOR BENDING MAGNETS AND QUADS

3.1 Motor-Generator Systems

These systems are more powerful ones for Storage Ring and/or Synchrotron. Modern machines have separate PS for quad strings to have more flexible operation and to have possibility of manufacturing quads windings with another rated current. Typical designs of PS for this goal are the Motor-Generator assembly and SCR rectifier. Motor-Generator had looked as more preferable devices when industry had no SCR with the kiloAmp rated current.

Motor-Generators are used in both versions - with AC and DC Generator. We can say that Motor - DC Generator assembly is ideal equivalent of transformer and rectifier joined together in one. Due to a huge rotating mass it also serve as a damper of the load pulsing power consumption relative to Mains. This device (DC Generator) being controlled via exciting winding, have a wide dynamic range of output current. It simply reverse current polarity by reversing of the relatively small exciting current. At the 60-th Motor-

DC-Generators were used, for example, at Erevan Synchrotron as DC bias current source of 1300 A, 1.7 MW [1], at VEPP-2 Storage Ring as main PS (up to 7 kA, 800 kW) [2]. Motor-AC-Generators with mercury filled exitron tubes were used during many years at AGS, Broukhaven - up to 70 MVA [3], IHEP synchrotron, Protvino - up to 100 MVA [4], etc.

One of disadvantages of the Motor-DC Generator assembly is wide frequency spectrum of ripples of it's output voltage. Lowest ripple frequency is the Motor rotating frequency that usually equal to 4 Hz to16 Hz, it's level in voltage can be up to some percentages; highest frequencies are determined by switching brushes and collector bars and can be up to some kHz. This create a problem in damping them. Another one - this assembly produce low frequency ground vibrations that can excite beam oscillation. Some, now traditional, methods of ripple damping were applied for these systems. It is interesting to point out works of my colleagues from BINP [5,6] who had developed the "two loops" current stabilizers for some different Motor-DC-Generator devices for the VEPP-3 and VEPP-4 Storage Rings. They had developed the "Active Filter Loop" of both types (feed-forward and feedback) for ripple damping and got better than 100 ppm peak-to-peak ripple level in current through all current and frequency ranges. The slow current stabilizing loop operates via exciting winding of the DC Generator with using of a DCCT or a resistive shunt for current measurements. Some of these PSs are used at BINP up to now. Most of referred systems are replaced by newly developed with thyristor rectifiers.

New life of Motor-Generator in the PS system for Storage Ring had described by Jean-Francois Bouteille of ESRF, Grenoble [7, 8] some years ago. In his work on increasing of a reliability of ESRF PS system operation he had pointed out that up to 250 voltage drops (up to 5% in level) during one year are occurred with input feeders due to thunderstorms and another weather reasons. He had described the buffer power plant. Plant includes some sub units (up to 10 sub units with 1 MVA each) consisting of Diesel, Clutch, Alternator with rotating mass Energy Storage and Transformer. The advantages of this buffering are described at the reports too.

3.2 SCR converters

Historically due to step-by-step increasing of rated Current/Voltage of Thyristor (SCR) the SCR phase-controlled Converters had actively replaced all another types of DC PS for magnets. It is not a problem now to have SCR of up to 25 class with 2.5 kA mean (4 kA rms.) on-state current (Surge current up to 30 kA). Some different configuration kinds of Converter for magnets are moved approximately into two directions: Six-pulse and Twelve-pulse circuits. Twelve-pulse devices are usually done as assembly of two Six-pulse bridge rectifiers with Delta and Wye connection of input transformer secondary windings.

One of the examples of Twelve-pulse circuitry design is realized at the APS Booster Synchrotron for current up to 900 A and voltage up to 1000V [9]. Fig. 1 presents this circuit. Two of these PS are connected in series (Master-Slave Mode) to get the specified current ramp during particle accelerating. PS works with voltage and current feedback loops. This PS includes a passive LC filter (partially damped) with resonant frequency 20 to 30 Hz. By the way, PS have two DCCT: one - for current stabilizing feedback loop, another - for measurements.

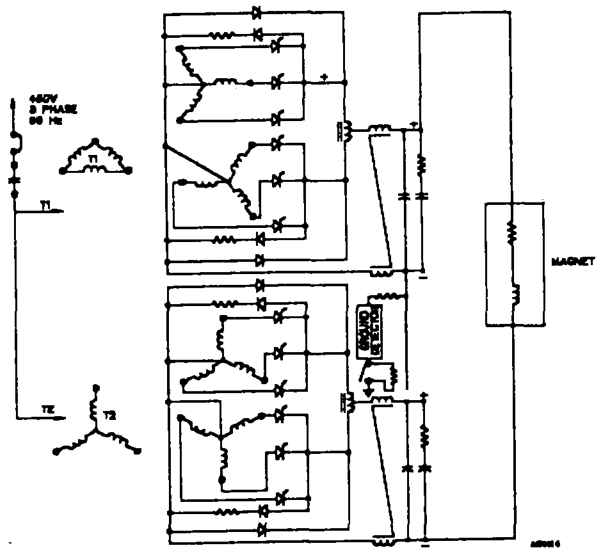

Fig. 1 Simplified schematic of Quadrupole Power Supply (ANL, Argonne)

The Twelve-pulse configuration can solve most of problems joined with ripple requirements when the input AC greed have equal amplitudes of each phase and small distortion level. Some AC greed asymmetry lead to generation at the converter output of subharmonics with frequencies up to the 50 (60) Hz. This situation can eliminate the advantages of Twelve-pulse circuit relative to Six-pulse one. To have a reliable situation in current ripple damping the Active Filter inserting into circuit is more popular step of designing PS for the Storage Rings. The reports [10, 11, 12] presents some old and new realization of PS with Active Filter made with using of the transformer, installed in series with magnets. Fig. 2 show the Russian PS IST2 (up to 2.5 kA, up to 460 kW) realizing this principle.

Original solution of "Active Filter" topology was described by M. Fathizadeh for APS Storage Ring dipole magnet [13]. This PS have output current max. value close to 500 A and voltage up to 1700 V. It have Twelve-pulse SCR phase-controlled rectifier and, in series, Switch Mode PS as the Active Filter (Fig. 3). Active Filter is included into voltage on load controlled loop, slow current stabilization use the DCCT and 17-bit DAC for control.

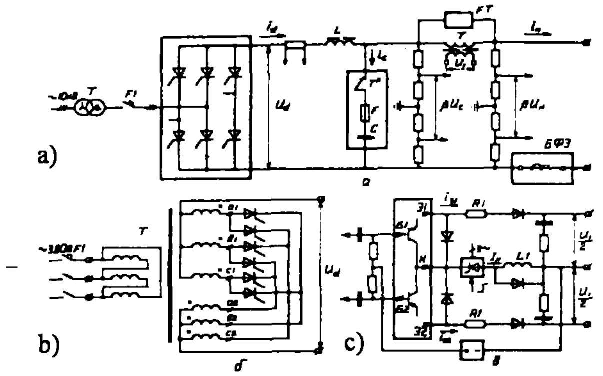

Fig. 2. IST2 precision PS Family a) base version; b) rectifying ring version; c) Power Amplifier (BINP, Novosibirsk; Electrofizika, St.-Peterburg; TEZ, Tallin)

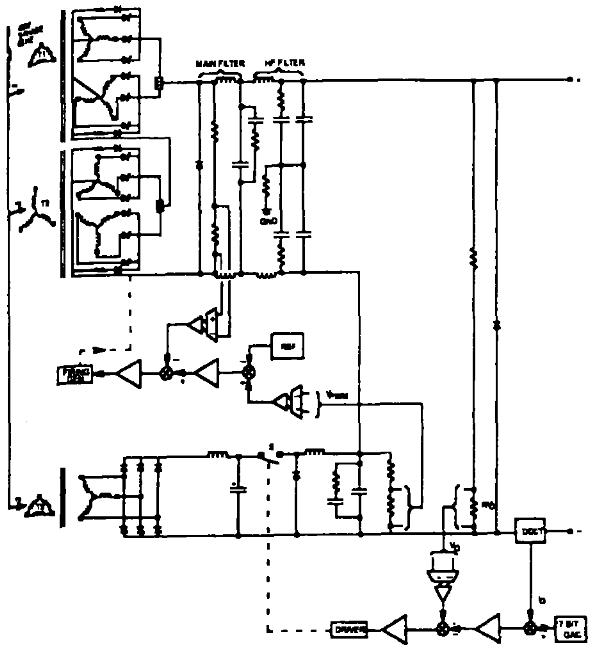

Fig. 3 Block diagram for storage ring power supply using SCR phase-controlled and Switch Mode power supply (SLAC, Stanford)

Watanabe at [14] presents feed-forward ripple damping configuration with using a computer-feedback loop with self-learning control both of voltage and current. The goal is to have fast time response and low ripple level simultaneously. Work is in a progress.

To the end of this part of review it is interesting to present the results of M. Kumada et al. from HIMAC [15] in their investigation on the ripple damping problem. Authors of report had looked on the PS and magnet of the ring as on integrated system where magnet string is presented as a 6-terminal ladder circuit with common and normal (differential) mode lines of signal propagation. The result of authors activity is presented at the histogram, Fig. 4 in comparing of their and some another laboratories results.

Main recommendations of report are: to install Static (Passive) Filter and Active Filter of Common and Normal (differential) modes; to reduce the common mode impedance; to implement of a ground neutral line to power supply and magnet string; to install bypass (damping) resistors; to use PLL based timing system and to install the Static VAR Compensator to reduce the variation of the AC line voltage by the reactive compensation.

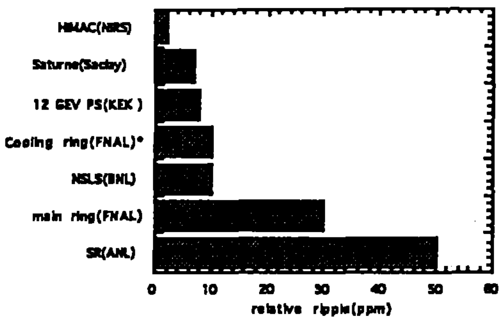

Fig. 4. A comparison of the ripple performance (NIRS, Chiba)

3.3 Switch Mode explosion (IGBT and MOSFET Revolution)

Switch Mode PS circuitry principles are well known during many years, but only the IGBT and FET/MOSFET devices had made real revolution with PS. They had appeared in hands of PS manufacturers for professional applications approximately ten years ago and looks now like an ideal (or close to ideal) switches, pushed the Switch Mode PS technology to the next, highest level, ***«State-of-art»*** level. Typical IGBT modules can work with 1200 V OFF-state voltage and rated current up to 400 A for ON-state. Modules have anti-parallel Diode with adequate parameters for shunting IGBT at the reverse direction. Power FET have approximately 100 V with 400 A rated current and less than 0.003 Ohm resistance for ON-state. Switching ON/OFF time less than 100 nanosec minimize the dynamic losses inside the Modules. So, now it is widely presented the IGBT and FET based Switch Mode devices in some different applications that allow us to solve most of problems with less price, less volume and mass, but with better main parameters than earlier. In addition, the Power Schottky Diodes with rated current of some hundreds Ampere are in our active too. Number of developed Switch Mode PSs is growing so fast, that the examples presented below can show the tendency only. As a bright example of these elements application it is necessary to repeat about Active Filter mentioned above (Fig. 3).

Very attractive PS architecture had presented by joined team of LBL, SLAC and LLNL for PEP-II PS system [16]. It was built: 21 PS Systems for large strings; more than 250 Medium PSs and 900 to 1000 PS channels for correction and trim coils. Single channel architecture consist of: Voltage regulated/Voltage controlled PS - as it's power train, driven by current regulating loop with high stability (<2 ppm/°C) error amplifier. Current measurements: two identical integrated type DCCT (Magnetic Comparator and electronics on the same package). One DCCT for current control through the current regulation loop and the other one as independent diagnostic readback. Long term stability close to 50 ppm, ripple level less than 100 ppm. Power part of Large Magnet String PS is presented at Fig. 5.

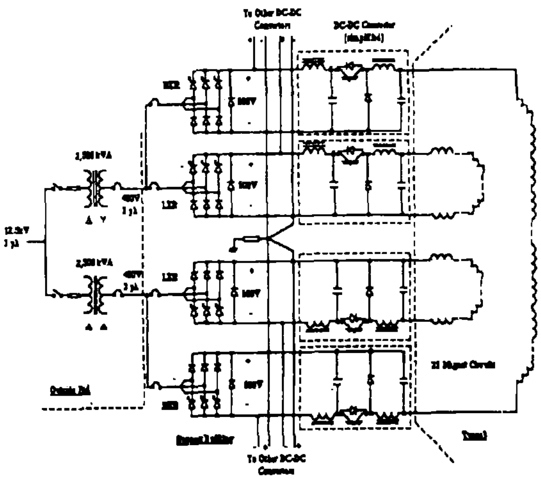

Fig. 5. String magnet Power Supplies. Simplified power circuit (SLAC, Stanford)

It include Bulk DC PS (Six pulse, half-controlled, SCR) driving several DC-to-DC Chopper-Converter. Each channel has rated current up to 890 A, output voltage up to 690 V. The 200 kW DC-to-DC converter is presented at Fig. 6.

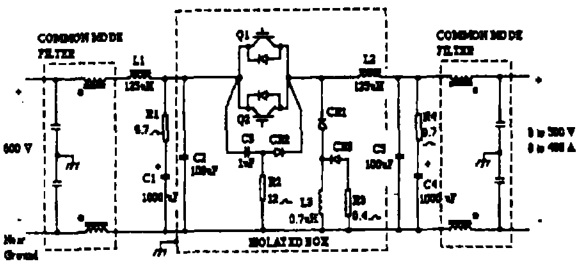

Fig. 6. . 200 kW DC-to-DC converter power circuit (SLAC, Stanford)

Two 600 A, 1200 V IGBTs are alternately gated at 10 kHz to have effective 20 kHz internal frequency. The work [17] of APS presents slightly another experience of Switch Mode DC-to-DC chopper unipolar PS. They had developed and commissioned up to 680 PSs with stability +/- 60 ppm, current up to 460 A.

Work [18] from CERN had presented a Switch Mode device with 10 V, 2 kA output and with efficiency 80% (Fig. 7). This is full H-bridge based on the MOSFET switches with using the using Pulse-Width Modulation (PWM). It is necessary to outline the typical for low voltage Switch Mode circuitry topology to obtain high output current with using of diode rectifiers with relatively small rated current. It use summing of the rectifiers output current with the help of transformers that's primary windings are connected in series. As the next step one of the last CERN reports on PS [19] shows «Present development directions» on Switch Mode PS development. The 12.5 kA, 10 V DC-to-DC power converter prototype is developed with using the Switch Mode (20 to 50 kHz) technology in collaboration of CERN with industry. It is recommended to have high current Modules with output power less than 30 to 50 kW and placed in parallel or in series. An analysis of different Switch Mode topologies and a lot of arguments and recommendations in favor of Modular PWM Soft-Switching Converters are presenter. The report of KEK B-Factory [20] had showed that 20 kW unipolar and 300 W bipolar Switch Mode units can be used as base devices for PS system of B-factory Storage Ring.

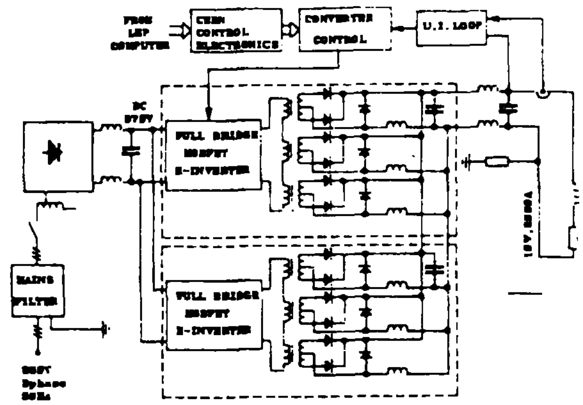

Fig. 7. Switch Mode power converter with using Pulse-Width Modulation (CERN, Geneva)

4 CORRECTING MAGNETS POWERING

As we had mentioned upper, correcting magnets usually need power less than one kW, PS usually are to be bipolar (two or four quadrant operation). At INP, for example, we had made Switch Mode PS for correcting (steering) magnets of the VEPP-4 more than 20 years ago [21]. It was bipolar transistor half-bridge DC-to-DC converter with 12.5 kHz clock frequency of PWM and galvanically isolated drivers of output circuits. Some modifications of this device with up to ±10 A, ±20 V output are under operation up to now, total number of them is more than one thousand.

Modern Switch Mode for the Correcting magnet we can see, for example at [22, 23, 24]. These devices are developed for the four quadrant operation with using of full H-bridge and DC-to-DC PWM technology with the clock frequency 25 to 30 kHz. They have different output parameters up to ±150 A ±50 V (Fig.8); ±12 A ±50 V (Fig. 9) and ±15 A ±150 V (Fig.10). All reports present the circuitry with one Bulk PS for some channels, that looks like optimal configuration.

One of serious problems of the Switch Mode technology is the switching noise and PS influence on another electronics equipment. Most of referred reports presents some circuits and recommendations to get acceptable compatibility of new Switch Mode devices.

The Common Mode and Differential Mode HF filters at the output of most of the PS are presented, of course.

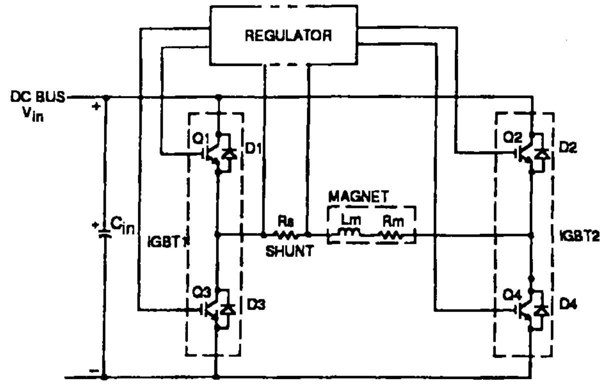

Fig. 8 Simplified circuit of four quadrant Full - Bridge power converter (ANL, Argonne)

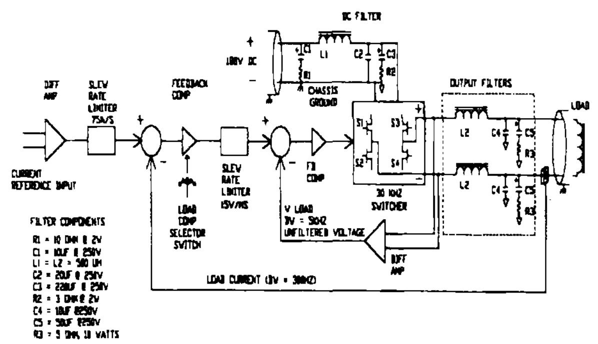

Fig. 9 Four quadrant DC-to-DC regulator configuration (FNAL, Batavia)

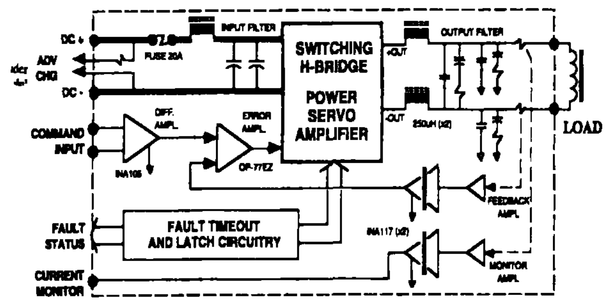

Fig. 10 Corrector PS power Module (SLAC, Stanford, LBL, Berkeley)

At the last (Fig. 10) version we can see returning to resistive shunts but with Optically Isolated differential amplifiers.

5. POWER SUPPLIES FOR THE ELLIPTICAL MULTIPOLE WIGGLERS

New insertion device for electron storage rings - Elliptical Multipole Wiggler (EMW) - became popular now between synchrotron radiation users. To create rotating magnetic field one coordinate of magnetic field (usually vertical) is formed with permanent magnets, horizontal - with AC current of trapezoidal shape. This task forced us to develop two PS systems [25] with current range of 200 to 1200 A with trapezoidal current - in - time shape and variable frequency. (Fig. 11)

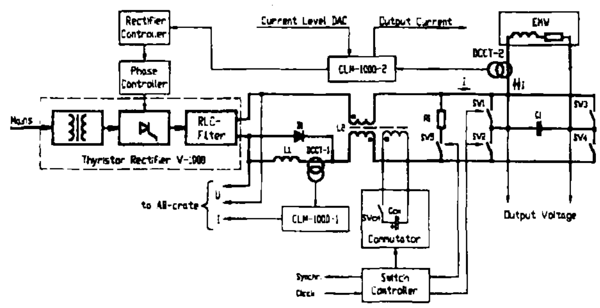

Fig. 11 Block diagram for the Elliptical Multipole Wiggler power supply. (INP, Novosibirsk)

One PS has 100 Hz, another - 10 Hz of maximal frequency. Load has 5.5 mOhm resistance with time constant up to 90 msec, so forced switching and flat top level current stabilizing were necessary. It have six-pulse converter with LC and SCR H-bridge that is driving to switch-ON/OFF by Switch Controller and commutator. Resulting polarity reversing time not exceed 1.5 msec for one PS and 6 msec for another. Both polarities current difference better than 0.1% were obtained.

6. SHUNT REGULATORS

As a final, I would like to point out that special class of PSs - passive Shunt Regulators had got new possibilities too. New generations of them based on MOSFET and Power Bipolar Transistors allow us to do Shunt Regulators with analogous mode of output transistor operation [26, 27]. One of topology is presented at Fig. 12. It is a 20 A, 400 W Module using eight losser stages. Each have it's local current stabilizing loop and indicator fuse. In case of burned fuse load current redistributes automatically between another stages. Power part of Shunt Regulator is arranged closely near shunted magnet.

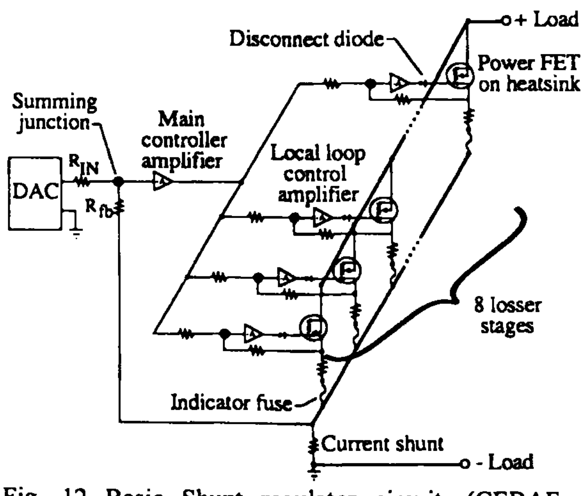

Fig. 12 Basic Shunt regulator circuit. (CEBAF, Newport News)

7. CONCLUSION

Only power part configuration of different type PS for magnets was reviewed. Unfortunately, we did not observed long term accuracy of PS and computer control rules. Interlock and internal measurements and tests were also out of view. The same we need to say about some special aspects, like quench protection design, of PS for superconducting magnets.

The reliability and maintainability of PS for magnets and for another purposes are also very important, interesting and useful field of analysis and discussion because magnet PS System is one of more huge, more expensive and complicated Systems of modern Synchrotrons and Storage Rings.

8. REFERENCES

1). K.M. Kozlov, K.K. Vlasov et al "Erevan synchrotron magnet field stabilizing system" Proc. of the First All Union Particle Accelerator Conference (1968), p.207

2). M.M. Karliner, B.V. Levichev, A.S. Medvedko "DC current stabilizer for the storage ring electromagnet" " Proc. of the First All Union Particle Accelerator Conference (1968), p. 279

3). J.N. Sandberg, R. Casella et al "The AGS Main Magnet Power Supply Upgrade" US PAC-95, Vol.3 p.1964

4). E.V.Kornakov, N.A. Monoszon, et al «The details of supplying circuit of the IHEP proton synchrotron electromagnet» Proc. of the First All Union Particle Accelerator Conference (1968), p.174

5). B. A. Baklakov, V.F. Veremeenko et al "Power Supply system for the electromagnet and quadrupole lenses of the VEPP-3 Storage Ring"" Proc. of the III All Union Particle Accelerator Conference (1972), p. 39

6). B. A. Baklakov, V.F. Veremeenko et al "Powering of the Storage Ring VEPP-4 electromagnetic system" Proc. of the VI All Union Particle Accelerator Conference (1978), p. 185

7). J-Francois Bouteile "A High Quality Power Supply at the ESRF" Proc. of the EPAC-94, Vol.3 p. 2335

8). .Jean-Francois Bouteile "A High Quality Power Supply (HQPS) at the ESRF" Proc. of the EPAC-96, p. 2334

9). J. A. Carwardine, S. V. Milton, and D.G. McGhee "Performance of the Ramping Power Supplies for the APS Booster Synchrotron" Proc. of the US PAC'95,Vol.3, p. 1967.

10). . A. V. Vasilievsky, A. A. Buz'ko et al «Power Supply systems of the UNK injection channel» Proc. of the XIV All Union Particle Accelerator Conference (1994), p.54

11). B.A. Alekseev, V. A. Zaenko et al "Second generation of the stabilized Power Supplies of IST - type for the High Energy Accelerators" Proc. of the X All Union Particle Accelerator Conference (1986), p. 306.

12). Rudolf Richter, Roberto Visintini "Performance of the ELETTRA Storage Ring Main Power Supplies" Proc. of the EPAC-94, Vol. 3 p.2327

13). M. Fathizadeh "Analysis and Design of a High-Current, High-Voltage Accurate Power Supply for the APS Storage Ring" Proc. of the US PAC-93, Vol.2 p. 1288

14). S. Watanabe et al. «Study of a magnet Power Supply for a MUSES booster synchrotron» Proc. of the EPAC-96, vol.3, p. 2340.

15). M. Kumada et al. «The HIMAC Very Low Ripple Synchrotron» Proc. of the EPAC 94, Vol.3 p.2338

16). L.T. Jackson, A.H. Saab and D. W. Shimer "PEP-II Magnet Power Conversion Systems" Proc. of the US PAC-95, Vol.3, p. 1961

17). D. D. McGhee "Circuit Description of Unipolar DC-to-DC Converter for APS Storage Ring Quadrupoles and Sextupoles" Proc. of the US PAC-93, Vol. 2 p. 1271

18). H. W. Isch, A. Dupaquier et al. «Switch Mode power converters; Present and future» Proc. of the US PAC-89, Vol.2 p. 1151

19). F. Bordry, A. Et al. «High Current, Low Voltage Power Converters for LHC, present development Directions» Proc. of the EPAC-96, Vol. 3 p.2314

20). Tadashi Kubo, Masato Yoshida «Magnet Power supply system for KEK B-Factory» Report # 5P9 at the US PAC-97, to be published

21). E.I. Zagorodnikov, A.S. Medvedko «Power Amplifier with Pulse - Width Modulation» Pribori i Tekhnika Experimenta, 1978, #6, p. 94

22). Y.G. Kang «Design and Development of a Bipolar Power Supply for APS Storage Ring Correctors» Proc. of the US PAC-93, Vol. 2 p. 1268

23). G.E. Leyh et al «A Multi-Channel Corrector Magnet Controller» Proc. of the US PAC-95, Vol.3, p. 1976

24). L.Bartelson et al. «Four quadrant DC-to-DC switching supply for the Fermilab main injector» Report # 5P7 at the US PAC-97, to be published

25). A. Medvedko et al «The Power Supply System for Elliptical Multipole Wigglers» Report # 5P3 at the US PAC-97, to be published

26). J. Martin et al. «A 20 Ampere shunt regulator for controlling individual magnets in a seriesed string» Proc. of the US PAC-95, Vol. 3, p. 1973

27). S.H. Nam et al. «A high current shunt regulator for quadrupole magnets in PLS 2 GeV storage ring» Report # 5P13 at the US PAC-97, to be published

References are not pretend to outline some priorities of referred authors. The goal was to show some typical or more interesting kinds of PSs and to present some of INP developed systems.