A BILATERAL POWER SUPPLY WITH ENERGY STORAGE BUFFER FOR THE SUPERCONDUCTIVE COILS OF LARGE PARTICLE ACCELERATORS*

M. Ehsani, Senior Member, IEEE, and R.L. Kustom, Member, IEEE

Abstract: Considerable development and testing on the active control of current in superconducting coils using DC-AC-DC thyristor convertor networks with superconductive magnetic energy storage has been completed. The charging and discharging cycles of the magnet are decoupled from the power grid, and since these networks are asynchronous with the line, operation at any practical frequency for the switching devices is possible. These systems, avoid putting large power bumps on the utility grid during charging and discharging, eliminate phase related noise on other 60 Hz converter systems, and reduce the size of magnet ripple. Operation and design of thyristor networks in closed-loop feedback with variable phase and frequency modes are discussed. Techniques for switching operation at one phase and frequency to another are described. Operating data on a bang-bang controller for 100 A., 4 Hy. load and storage coils is given.

Introduction

Modern high energy particle accelerators are designed with large superconductive coils to generate the magnetic fields required for bending magnets and quadropoles. A typical operating cycle of these magnets consists of the ramp-up or accelerating phase, the flat-top or beam storage phase and the ramp-down phase. The power supplies used for these coils have to satisfy two important requirements during the operating cycle: 1) They must handle the large bidirectional coil powers during ramp-up and ramp-down, 2) They must satisfy stringent coil ripple current and field requirements during beam storage to avoid tune related resonances and loss of dynamic aperture. Coil current regulations of one part in 10,000 or better are usually required.

The conventional power supply configuration for the above application consists of several six-pulse, three-phase SCR converters connected between the utility ac lines and the superconductive coils, Fig. 1(a). Although these have proven to be successful, the use of bilateral supplies with superconductive magnet energy storage between the accelerator magnet and the utility line can provide some significant advantages that might make them an attractive alternative. In particular the system operates independent of the utility system at frequencies which are unrelated to 60 Hz frequency. This operating frequency can be changed to optimize performance during different phases of acceleration and storage. Furthermore, the pulsed powers during coil charge and discharge times are buffered from the utility power system.

This paper describes a class of bilateral circuits for the application to large particle accelerators. The power supply system has been under development at the University of Wisconsin, Argonne National Laboratory and Texas A&M University, over the past several years. [1,3,4,6]

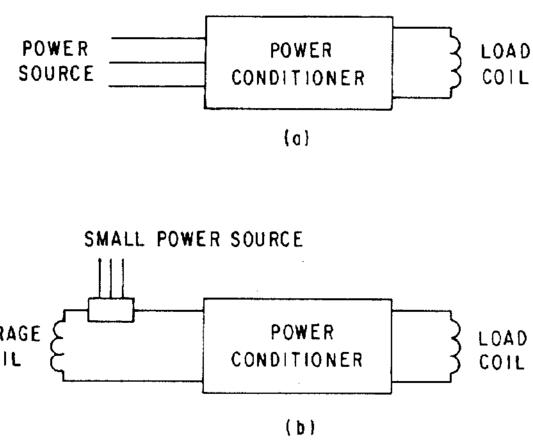

Figure 1. Two power supply arrangements for particle accelerator magnets

Bilateral Superconductive Power Supplies

Bilateral power supply configurations, Fig. 1(b), in which a second superconductive energy storage coil is used as a buffer between the load magnet and the utility line has been suggested by several workers [1,2,3,4,5]. The basic operation of these supplies is as follows. Sufficient energy is initially drawn from a small power source or utility connection, over a long period of time, and stored in the storage coil. Then, the large power fluctuations required in each cycle of the load coil is delivered by the power conditioner-storage coil combination. The utility power system is loaded at a low power level equal to the average losses in the system and, therefore, is completely isolated from the large load coil power fluctuations. Furthermore, the switching power conditioner is not synchronized with the utility line and can operate at the optimal frequencies for maximum power and minimum ripple during the ramp-up and storage phases, respectively.

* Work supported by the U.S. Department of Energy and Center for Energy and Mineral Resources, Texas A&M University.

M. Ehsani is with the Electrical Engineering Department, Texas A&M University, College Station, Texas 77843.

R.L. Kustom is with the Argonne National Laboratory, Argonne, Illinois 60439.

0018-9499/85/1000-3781$01.00© 1985 IEEE

Two examples of bilateral power supplies with energy storage buffers are the single flying capacitor (SFC) [2] and the inductor- converter bridge (ICB) [1]. A study of several of these circuits is presented in [3] and [6]. The remainder of this paper describes the operation and control of the inductor-converter bridge as a bilateral power supply.

The Inductor – Converter Bridge (ICB)

Figure 2 shows the schematic diagram of an ICB circuit. The load magnet, L_L, and the storage magnet, L_s, are each connected to a full wave three-phase converter. The converter SCRs are commutated by a set of y-connected capacitors on the ac lines which connect the storage and load side converters. The switching sequence on the storage converter is SS1-SS5, SS1-SS6, SS2-SS6, SS2-SS4, SS3-SS4, SS3-SS5, SS1-SS5, etc. The same switching sequence and frequency is used on the load converter. However, a leading switching timing of the load converter, relative to the storage converter, will cause a net energy transfer from storage to load coil, and vice versa. The switching frequency of the converter is usually so high that only an infinitesimal fraction of the system energy is stored in the capacitors at any time. Therefore, the capacitive energy requirement of the system is very low relative to the amount of inductive energy.

Although this paper is based on the three-phase ICB, other ICBs with 1,3,5,7, etc. number of phases have been described in references [3,4,5].

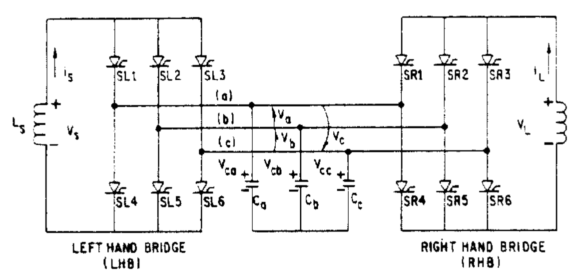

Figure 2. Circuit diagram for the three-phase ICB

ICB Operation During Current Ramp – Up

It has been shown in [3] that the average load coil voltage is given by

$$V_L = (18 I_s / \Pi^2 \omega C) \sin\phi, \qquad (1)$$

where I_s is the storage coil current, ω is the angular frequency of each converter, C is the capacitance per phase and ϕ is the phase angle by which the load converter leads the storage converter. Current ramp-up is supplied by the maximum V_L. Equation (1) shows that maximum V_L, for a given I_s, is achieved when the operating phase, ϕ, is 90° and the converter operating frequency, ω, is at the minimum. The minimum operating frequency is determined by the maximum allowable voltage on the capacitors [3,4].

Similar operation is used during the ramp-down period but with ϕ equal to -90°. Equation (1) shows that at $\phi = -90°$; a negative average voltage will be applied to the load. For lower rate of current ramping the control parameters, ω and ϕ, can be adjusted accordingly.

An example of load current ramp-up and flat-top operations in a 11 kW experimental ICB, which was developed at Argonne National Laboratory, is shown in Fig. 3.

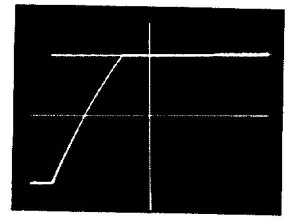

Figure 3. Coil current ramp-up and flat-top in the experimental ICB

Active ICB Operation During Current Flat – Top

A straight forward method of ICB operation during the current flat-top is with zero operating phase (ϕ=0°). In this mode of operation both the storage and the load coils will see the voltage wave form shown at the bottom of Fig. 4. Although no net energy is delivered to the load magnet, the instantaneous voltage will cause coil ripple currents. The magnitude of the nth harmonic current is

$$I_n = V_n / 6n\omega L_L, \qquad (2)$$

where V_n is the magnitude of the nth harmonic of the coil voltage, ω is the converter angular frequency and L_L is the coil inductance. Since the magnitude of the coil and capacitor harmonic voltages are proportional to the peak capacitor voltages, they are also proportional to the converter period [3,4]. Therefore, the coil harmonic voltages are inversely proportional to the converter frequency. From the above discussion the dependence of the nth harmonic ripple current on the converter frequency can be expressed as:

$$I_n = K / n\omega^2 L_L \qquad (3)$$

where, K is the constant of proportionality.

Equation (3) shows that the coil ripple current reduction can be strongly influenced by the converter operating frequency, ω. Therefore, the ICB is operated at the highest switching frequency permitted by the SCRs, during the flat-top current period. The coil energy losses during long beam storage experiments are periodically replenished by shifting to ϕ=90° or some other angle, for short periods of time.

Active ICB operation during current flat-top simplifies circuit and control complexity. However, switching at the highest ICB frequency increases losses over lower operating frequencies and further improvement may be possible by a freewheeling method described below. Furthermore, the coil ripple currents caused by this method could be more than the freewheeling case. The ripple current is one consideration in chosing the number of phases (pulse number) in the ICB design.

ICB Freewheeling Operation During Current Flat – Top

The beam storage time in the accelerator requires a constant magnetic field and current which is as ripple free as possible. In superconductive magnets with sufficiently large inductances, current may be sustained within the acceptable bounds if the load converter simply operates in freewheeling mode during beam storage time. In this mode of operation, all the SCRs of one load converter branch; e.g., SL3 – SL6, are in conduction. Similar freewheeling conduction pattern, SS3 – SS6, is imposed on the storage side simultaneously. The voltage across the coil will consist of the sum of SCR conduction voltages in one branch plus the resistive drops in the cables and connectors.

Entering and leaving the freewheeling mode of operation can be briefly described as follows: prior to entering freewheeling, the ICB is brought to zero angle operation by a phase shift [3,4]. The instantaneous capacitor voltages and the storage and load coil voltages for this case are shown in Fig. 4. Note that at the end of SS2-SS6 conduction interval v_{C1}, v_{C2} and v_{C3} are charged to maximum positive voltage, zero and maximum negative voltage, respectively. Now if SCR's S3-S6 are fired on both converters, SCR S2 will commutate off through the commutation loop consisting of S2, S3, C_3 and C_2 on each converter. The above capacitor voltages will remain ideally unchanged for the duration of freewheeling. To enter normal converter switching operation, SCRs S3 - S4 are fired on each converter. Proper capacitor voltages exist to commutate S6 off in the commutation loop consisting of S4, S6, C_3 and C_1, on each converter. Once normal converter operation is resumed, a phase shift to a new operating phase, ϕ, can be implemented for further charging or discharging the load coil.

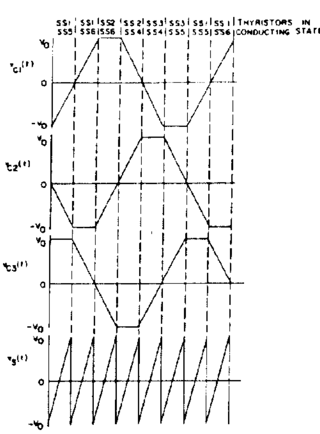

Figure 4. Voltage waveforms of the three-phase ICB at zero operating angle

For very long periods of beam storage the capacitor voltages, during freewheeling, will decay through leakage. This capacitor decay can be compensated for by local voltage supplies, connected to C_1 and C_3, such that their low rate of charging does not interfere with the normal ICB operation. Alternatively, special storage converter switching methods are possible to recharge the ICB capacitors before resuming normal operation [4].

The flat-top duration can be so long that the small parasitic voltage on the coil will cause unacceptable current and field decay. In these cases the magnet has to be periodically replenished for the lost energy by alternate operations in freewheeling and $\phi = 90°$ modes [4].

Conclusions

The bilateral power supply with energy storage buffer is an attractive alternative to the conventional accelerator coil power supply with direct connections to the utility power systems. This paper described the inductor-converter bridge (ICB) circuit which is one such bilateral supply. It was shown that the ICB isolates the utility power system from the large power swings, required by the accelerator coils. Furthermore, the coil ripple currents can be more easily reduced because the ICB converters are not locked to the 60 Hz line and can operate at higher frequencies or at zero frequency (freewheeling). The superconductive storage coil needed for the ICB can share the cryogenic facilities of the accelerator coils and can be designed to minimize the coil costs for the energy storage required.

The utility power required for the operation of an accelerator with ICB supply is at a more constant level of average system losses. This power can be supplied from a smaller utility substation or even a local power generator. This advantage will eliminate the dependence of large accelerators on large electrical load centers.

The details of operation and control of ICB systems are presented in [3] and [4]. Further work on ICB and other bilateral superconductive power supplies is underway at Argonne National Laboratory and Texas A&M University.

References

[1] H. A. Peterson, N. Mohan, W.C. Young and R.W. Boom, "Superconductive Inductor Converter Units for Pulsed Power Loads", *Proceedings of International Conference on Energy Storage, Compression and Switching*, Asti-Torino, Italy, Nov. 1974.

[2] E. P. Dick and H. Dustman, "Inductive Energy Transfer Using a Capacitor", *Proceedings of International Conference on Energy Storage, Compression and Switching*, Asti-Torino, Italy, Nov. 1974.

[3] R. L. Kustom, *Thyristor Networks for the Transfer of Energy Between Superconducting Coils*, University of Wisconsin Press, 1980.

[4] M. Ehsani and R. L. Kustom, *Development, Analysis and Control of the Inductor-Converter Bridge*, Argonne National Laboratory Report, ANL/FPP/TM-144, 1981.

[5] M. Ehsani, R. L. Kustom, and R. W. Boom, "A One-Phase Dual Converter for Two Quadrant Power Control of Superconducting Magnets", *IEEE Transactions on Magnetics*, Vol. MAG-21, No. 2, March 1985.

[6] M. Ehsani and R. L. Kustom, *Converter Circuits for Superconductive Magnetic Energy Storage*, Texas A&M University Press, to be published, Sept. 1985.