NEW ENERGY REPLACEMENT METHOD FOR RESONANT POWER SUPPLIES

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Abstract

The Resonant Power Supply is an economically and technically advanced solution for Rapid Cycling Accelerators. Several papers dealt with the design and operation of these power supplies, however, the energy replacement methods were not discussed in the past. This paper analysis different energy-replacement methods and presents a new method. This method uses a 24-pulse converter to regulate the magnet current during flat-top and injection periods and replaces the energy loss by charging the accelerator capacitor bank during the flat-top, reset and injection periods, charge is injected in the circuit during the acceleration period, when it replaces the energy loss. This paper compares the new method with the existing ones. The analyses proved the feasibility of the proposed method. The operation of the proposed method was verified by a model experiment, which showed that the new circuit can be controlled accurately and operates with smaller disturbances to the power line than the existing systems.

Introduction

The Resonant Power Supply is proposed for the control of magnet current in a Rapid Cycling Accelerator. The main advantage of this method is the reduction of the AC electric network pulse loading by oscillating the stored energy between the magnets and capacitor banks. The electric network supplies only the energy losses. Several papers dealt with the system operation and design [1,2], but energy-replacement methods were not analyzed in the past. The purpose of this paper is to present a systematic analyses of the possible energy-replacement methods and identify the most advantages one.

System Losses

The main operational requirement is that the magnet current has to be maintained constant during the flat-top and injection periods. This calls for a highly controllable magnet power supply which generates a negligible amount of harmonics. Recent studies, show that a thyristor controlled, 24-pulse converter meets this requirement. The expected current harmonic content is less then 1/100000 and the current can be controlled in every 700 μs. The steady-state operation requires that the current at the end and at the beginning of the cycle be the same. This can be achieved by replacing the energy losses. The sources of energy losses are the :

* magnet and choke resistance.
* thyristors, both in converters and switches.
* AC system (transformer, bus etc.).

The system equations indicate that this is a system with two degrees of freedom, therefore, the system control requires two independent sources. One of them is the magnet power supply, which keeps the magnet current constant and replaces about 40 % of the losses. The second source is a make-up power supply, which injects energy into the system. The system topology shows that for energy injection the following alternative locations are available :

a). A power supply is connected in series with :

* the choke.
* the thyristor switch.
* the capacitor bank 1, 2, or both.
* the magnet and choke.

b) A power supply is connected in parallel with one of the capacitor banks. Figure 1 shows the possible locations.

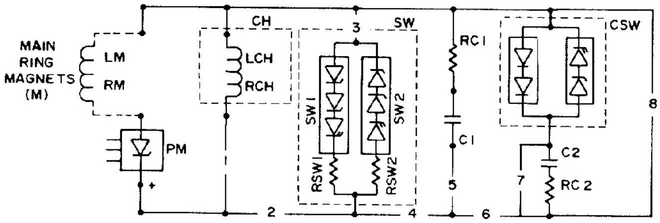

Fig. 1 Possible location of make-up energy sources.

Analyses of different options

A cursory investigation of the possible injection locations permits the elimination of the insertion of a power supply in the thyristor switch circuit (location 3) or in the common lead of the magnet and choke (location 2), because the power supply operation would affect both the choke and magnet current.

1. Power supply in series with the choke.

Both the magnet and the choke have a converter connected in series as shown in Fig. 2.

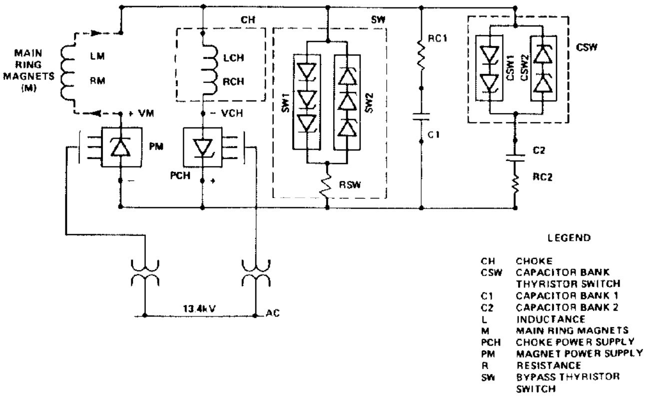

Fig.2 Make-up power supply connected in series with the choke (location 1).

The magnet power supply is a 24-pulse unit. The choke power supply is a 12-pulse high voltage converter. The magnet power supply maintains the flat-top and injection current constant, which requires a small 20-30 V. The choke power supply is a high-voltage (1-3 kV) unit which operates as an inverter during flat-top and as a rectifier during injection. The control of this power-supply voltage regulates the choke current in such a way that the current at the end of the cycle is the same as at the beginning. The current and voltage waves were calculated by computer. The results shows that the choke power supply reduces the choke current during flat top and increases it during injection.Thus, the energy loss is replaced.

The currents change slowly, which eliminates the generation of system oscillation through transmission-line effects. The synchronization of the power supplies, connected in series, is not critical because of the slow change of current. Actually, the power supplies may be operated even during the injection and reset period. The disadvantage of this method is the pulse loading of the AC system.

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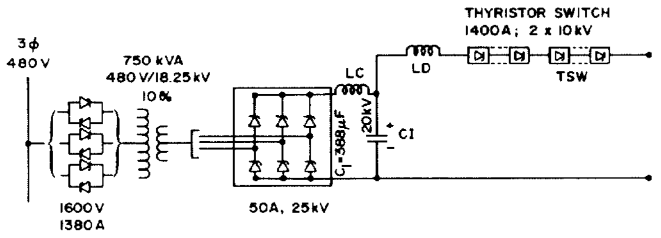

Fig. 3. Energy injection circuit.

2. Current injection in the choke circuit.

The make-up energy is injected into the choke circuit during the reset period. The choke converter is replaced by an impulse generator, shown in Fig. 3. (location 1) The capacitor C is charged by constant current during the whole period and discharged by the thyristor switch during the reset period. The capacitor discharge injects current into the choke circuit and replaces the losses. The system operation was simulated by a small scale-model. The tests demonstrated the successful energy replacement, both when the energy was injected at the end of the cycle or at the currents cross-over point.

This method eliminates AC system pulse loading. However, the system can be controlled only at the end of each cycle. A sudden current change may cause oscillation and the injection circuits have to be well synchronized.

Preag [1] proposed the use of one large injection circuit, which would inject energy through the secondary choke windings. The drawback of this circuit is its large size. A large accelerator has 15-20 MW losses.

3. Power Supply in series with Capacitor Banks.

Once again the magnet current is regulated by the magnet power supply. The make-up energy is supplied by a power-supply connected in series with Capacitor Bank 1 (location 5). This power supply pre-charges the bank during the flat top period and the energy, stored in Capacitor Bank 1, is transferred into the system during the reset period. When the by-pass switch opens, the power supply is shunted by a thyristor switch which by-passes the supply as the capacitor-bank current reverses. A diode is used to divert the capacitor current from the power supply. The circuit diagram is shown in Fig. 6.

The advantage of this system is the reduction of AC-system pulse loading and automatic synchronization with the by-pass switch. However, the additional thyristor switch and diode increase the cost of the system. Capacitor Bank 1 is relatively small, which requires 2-3 times higher pre-charged voltage than the operating voltage. Because of the significant cost increase and technical problems, this method has been eliminated.

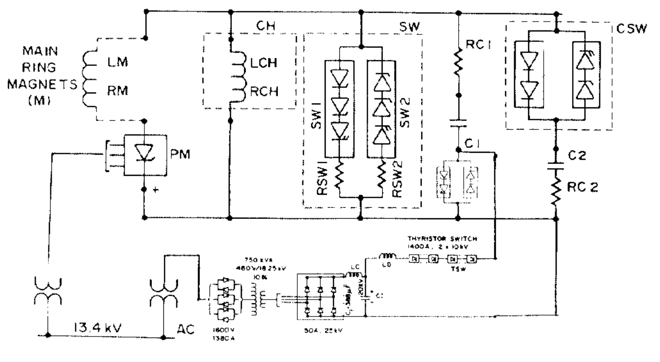

Fig.4 Power Supply in series with the Capacitor Bank 1.

Although Capacitor Bank 2 (location 6) is larger and already has a suitable diode and thyristor switch, it can not be used in the described mode. This is because it operates only during the acceleration period and Capacitor Bank 2 can be charged only during the preceding, short injection period. This generates severe AC pulse loading. Charging of Capacitor Bank 2 during the flat top is not possible because of the by-pass switch polarity.

The insertion of a Power supply in the common lead of the two capacitor banks (location 4) is not feasible because the banks operate at different time periods.

4. Power supply in parallel with the capacitor bank.

4.1 Energy injection into Capacitor Bank 1.

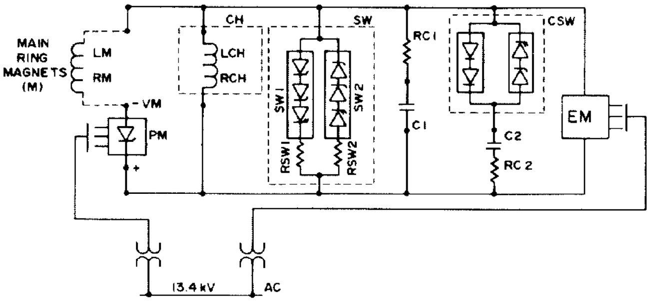

Fig. 5. Energy injection into Capacitor Bank 1.

Capacitor Bank 1 is short circuited periodically by the by-pass switch. This prevents pre-charge of the bank, but energy can be injected during the reset or injection period. The circuit arrangement is shown in Fig. 5 (location 7).

The injection circuit is the same as in Fig 4. The capacitor in the injection circuit is charged by constant current during the whole period and discharged during the reset time. When the injection circuit thyristor switch is fired, a transient starts. This divides the charge of the injection capacitor between Capacitor Bank 1 and the injection capacitor. The result is the effective parallel connection of the two banks, which affects the swing frequency. The capacitor bank has to be discharged at the beginning of the reset period to avoid frequency change during the reset. This assures that the two banks operate in parallel. However, the charge division produces transients which may cause disturbances.

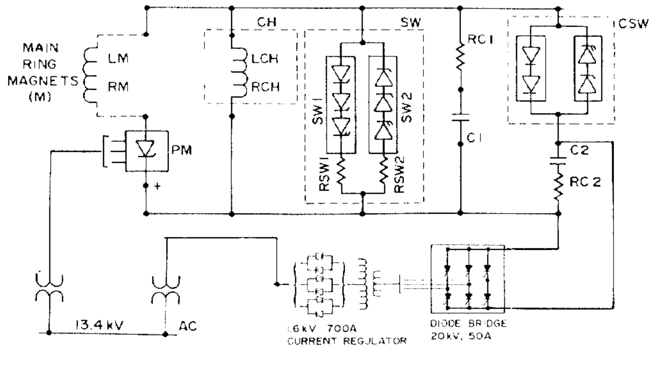

Fig. 6. Capacitor Bank 2 is pre-charged.

The discharge of the banks at the crossover point of the choke and magnet current, when Capacitor Bank 1 voltage is maximum, reduces the transients. This occurs because the voltage difference between the injection capacitor and Capacitor Bank 1 is smaller. But the parallel connection of the injection capacitor at the middle of the reset period decreases the swing frequency and increases the reset time.

TABLE 1. Comparison of Energy Replacement Methods

Name	*1.Cont*	*1.pulse*	*5 pp*	*7*	*8*
Economics	good (3)	medium (4)	worst (5)	medium (4)	very good (1)
Controll-ability	continuous (1)	Good but only at the end of each cycle (2)	(2)	(3)	(2)
Proven Technology	yes (1)	Thyristor switch is not tested (3)	(5)	(3)	yes (2)
Synchroniza-tion Need	none (1)	needed (3)	little (2)	worst (5)	none (1)
Transients	none (1)	little (2)	medium (3)	(4)	little (3)
AC-System Pulse Loading	worst (5)	none (1)	medium (3)	(2)	little (2)
Reliability	(2)	(3)	(4)	(5)	(1)
Oscillation Generation	none (1)	current step (2)	(5)	voltage step (4)	(3)
Total	**15**	**20**	**29**	**30**	**14**

Experimental studies show that, the charge-division-generated transients disturb the magnet current. The magnitude of the disturbance depends on the by-pass switch impedance. Current change is unacceptable during the acceleration period, however, it has no effect on the beam during the reset period. Therefore, energy should be replaced during the reset.

This method eliminates the AC system pulse loading and permits control of the system at the end of each cycle. The charge division generated transients may produce disturbances and system oscillation.

4.2 Energy make-up through Capacitor Bank 2.

Capacitor Bank 2 operates only during the reset period, which permits the pre-charge of the bank with a power supply during the rest of the cycle. The circuit is shown in Fig 6 (location 8). The energy replacement circuit is a regulated three phase diode rectifier, which charges the Capacitor Bank 2 with constant current. The firing of Capacitor Bank 2 Thyristor Switch, at the beginning of the reset period, transfers energy from the pre-charged Capacitor Bank 2 into the system. The energy transfer starts with a transient, which divides Capacitor Bank 2 charge between the two banks and equalizes the bank voltage.

The effect of the transients during reset is negligible, but may produce oscillation in a system with several units connected in series. This system eliminates AC-system pulse loading. It does not need an extra thyristor switch. Synchronization is automatic with the operation of the capacitor bank switch. The three-phase diode rectifier is simple, reliable equipment. The only disadvantage is the transients generated by the charge equalization.

Comparison of Different Systems.

The presented analyses identified eight possible locations for energy replacement as shown in Fig. 1. The study indicated that locations 2,3,4,6 are technically not feasible. The energy replacement can be achieved by two basically different methods :

a) Continuous replacement by a power supply.
b) Sudden energy injection, when a capacitor is charged slowly and discharged suddenly in a selected time.

At location 8 only the impulse type system can be used. At location 5 and 8 only the continuous system is feasible. At location 1 both methods can be used.

The remaining feasible locations were investigated and the advantages, were compared.with disadvantages. The results of the comparison are presented in Table 1. Using engineering judgment, a number from 1 to 5 is assigned to each evaluation criterion to permit numerical comparison.

Table 1 Indicates that the most advantages energy replacement is # 3 when Capacitor Bank 2 is charged continuously and discharged during the reset period. This system used standard, well proven economic circuits. It does not need extra switching devices or synchronization.

Conclusion

The results of the study are :

* The system requires two independent control sources :
  -Magnet power supply.
  -Make-up power supply.
* The Make-up Power Supply can be inserted in eight (8) different locations.
* Both continuous and pulse type energy replacement is proposed.
* The most feasible technique is the pre-charge of Capacitor Bank 2.

References.

[1] W. F. Praeg, "Dual Frequency Ring Magnet Power Supply with Flat-Bottom," IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, Aug. 1983.

[2] G. Karady, H.A. Thiessen, E.J. Schneider, "Resonant Power Supplies for a Rapid-Cycling Accelerator", IEEE Trans. on Nuclear Science, Oct. 1988, Vol 35, No. 5, pp 1992-1098.