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EPR OHMIC HEATING ENERGY STORAGE

fusion power systems department

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EPR OHMIC HEATING ENERGY STORAGE

Summary

The Ohmic Heating (OH) Systems for all the Experimental Power Reactor (EPR) designs¹⁻⁷ to date have all used temporary energy storage to assist in providing the OH current charge required to build up the plasma current. The energies involved (0.8×10^9 J to 1.9×10^9 J) are so large as to make capacitor storage impractical. Two alternative approaches are homopolar dc generators and ac generators. Either of these can be designed for pulse duty and can be made to function in a manner similar to a capacitor in the OH circuit and are therefore potential temporary energy storage devices for OH systems for large tokamaks. This study compared total OH system costs using homopolar and ac generators to determine their relative merits. The total system costs were not significantly different for either type of machine. The added flexibility and the lower maintenance of the ac machine system make it the more attractive approach.

Introduction

Since ac generators have been built in relatively large size for both steady state machines and short circuit testing machines, the technology is available for combining features of these two types into a large pulsed energy storage machine. A relatively small number of homopolar dc machines have been built, some for low voltage high current in steady state, and some for low voltage high current very short pulse testing. All have generally been relatively small in size. Since the development requirements for the two types of machines are seen as significantly different, it is desirable to determine whether a fully developed version of one machine or the other offers significant advantages in the OH circuits of large tokamaks.

Preliminary investigations indicated that one could not simply make comparisons between the two machines; but that the complete electrical system had to be evaluated since the differing characteristics of the generators should lead to other components in the OH system being different, and perhaps even different overall circuit configurations would be required.

OH System Functions

The major function commonly associated with the Ohmic Heating (OH) system of the Experimental Power Reactor Tokamak (EPR) is that of building the plasma current to the level which provides for plasma stability through the resulting poloidal field, and which provides the base level of heating of the plasma (to ~ 1 keV).

The plasma current buildup is the chief function performed by the rotating machine energy storage devices which were of primary interest in this evaluation. To produce the plasma current buildup, the OH drive coil functions as the primary of a transformer, while the plasma functions as the secondary. The object is to build the plasma current up to some given level and hold it there. Therefore the magnetic field swing in the transformer must all be in one direction.

The change in magnetic field must be accomplished by a unidirectional change in the OH drive coil current. This can be done by starting from zero current and building to a large value, call this ΔI_{OH} . This is called the zero bias circuit. Alternatively, the objective could be achieved by starting with a current ΔI_{OH} and reducing the current to zero. This is called the full bias circuit. Since the plasma only responds through the inductive coupling, the plasma current reflects only the change not the absolute values. The most frequently used approach is the half bias circuit in which the current starts at $\Delta I_{OH}/2$ and goes to $-\Delta I_{OH}/2$. This approach has several advantages; the peak current is half and, therefore, the peak losses can be lower. With the peak current half, the magnetic forces on the turns are lower; and since the current reverses, it affords the opportunity to use a temporary energy storage device which can return the energy when the current reverses.

Figure 1 illustrates a very simple model of the OH circuit during the reversal as well as typical current and voltage waveforms, drawn as if the circuit had no dissipation. The energy storage can be any device or combination of devices which will accept energy from the circuit and return it to the circuit. The energy storage device is shown as a capacitor but it could be a rectifier driven

from the power system, storage batteries, dc generators, ac generators, or another coil with some means of transferring the energy.

This function of the OH circuit frequently receives most of the attention because of its magnitude — 750 to 1500 MJ of stored energy to be transferred out of the coil for EPR, and back into the coil, in a time which is on the order of one to two seconds. If an active power handling device is used, then its peak volt-ampere rating could be as high as ~9500 MVA for 1500 MJ in one second.

In addition to the plasma current buildup, there are five other significant functions which the OH system is typically called upon to perform. Each of these additional functions increases the complexity of the system analysis, strongly influences the design of the circuit, and has a significant influence on the component parameters.

Looking at Figure 1, the simple current reversal begins with zero voltage on the coil, hence zero voltage on the plasma (the electromotive force applied to the plasma circuit by the OH circuit is approximately the same as the volts per turn applied to the OH drive coil). To achieve the objective, i.e., transform a weakly ionized high resistance gas into a low resistance plasma type discharge, it is necessary to quickly provide a relatively high voltage to the plasma circuit

Figure 1. Simplified OH Reversing Circuit

and hold it for a period of 10 to 50 milliseconds. This period may be longer or shorter depending upon the initiation voltage and the voltage available to continue the plasma current buildup after the initiating voltage is removed. The initiation voltage has been of the order of 10 to 20 volts per meter of plasma length. For the EPR designs this results in 400 to 800 volts on the plasma and a similar value of volts per turn on the OH drive coil. The volts per turn on the OH coil can be substantially reduced by contributions from the other poloidal coils.

The most common approach to achieving the plasma initiation voltage is to insert resistance into the coil circuit. Since the voltage required is one which initially opposes the current, a resistor is the cheapest piece of equipment which will accomplish this. Alternates are power supplies and pre-charged storage devices such as capacitors.

More sophisticated alternatives make use of separate initiation coils, high power R-F heating, or differential driving of other poloidal field coils. None of these was proposed for the ORNL EPR design selected as the basis for this study, none has been used on an operating tokamak, and no complete systems analysis has yet been reported for any of them. Therefore, for the purpose of this study we chose to follow the known approach of using resistors for initiation.

The plasma current provided by the OH circuit heats the plasma to ~ 1 keV. Final heating to deuterium-tritium ignition conditions is performed by other means such as neutral beam injection. This final heating is provided separately from the OH circuit and influence the OH only by requiring current changes to maintain plasma stability.

Once the plasma is initiated, the current built up, and the final heating completed, the plasma typically needs less than a volt to maintain a constant current. For EPR, a low voltage full OH current source is needed for this purpose for essentially continuous operation (see section on recovery). The actual plasma current maintenance period, usually called the burn cycle or burn period, is expected to last on the order of a minute. The function of the OH circuit is to provide the low level plasma drive necessary to overcome the small resistive loss the thus maintain

the level of the plasma current. It is important to note that during this phase, the OH current is steadily increasing even though the plasma current is constant.

The plasma shutdown is the least understood of the operational phases, largely because this phase has not really been important to tokamak devices to date. The function of the OH circuit in this phase is to again reverse the OH drive coil current but now over a period which may not be the same as the one to two seconds for the plasma current buildup. For the present it appears reasonable to use identical time periods for both OH reversals.

The final function of the OH circuit is to restore the initial conditions during the recovery period.

The functions of an EPR OH circuit can be neatly categorized and described as separate and distinct phases as has been done above. In the real system, however, the different phases must blend together, in some cases overlap each other, and, most important, the energy gains and losses must be balanced for the complete cycle to repeat.

The exact details of the OH currents and voltages will depend upon the specific requirements involved, circuit arrangements used, and components selected. The general concept of the OH current and voltage over the operating cycle is illustrated in Figure 2. This same figure also shows the expected plasma current behavior during the cycle.

Basic Circuit Modules

The first basic OH circuit module is the Plasma Initiation Module (PIM). The requirements for the plasma initiation phase are relatively unique and cannot generally be satisfied by the other power modules. A voltage of the order of 400^+ volts per turn (10^+ volts per meter of plasma length) is required to cause the initial ionization of the tritium gas and cause sufficient ampere seconds of current to flow to reach the point at which temperature induced ionization will sustain the ion density. Currently the experimenters recommend a rise time for the voltage on the order of a millisecond.

Figure 2. Ohmic Heating Operating Cycle

To keep the voltage down to the range of 10 volts/meter requires a reduced gas density start. This reduction in density cannot be carried too far, since at very low densities the mean free path for electrons gets long enough for "electron runaway" to occur in which the electrons escape the plasma and impinge on the vacuum vessel wall.

The PIM must handle the peak OH circuit current and simultaneously produce a large reverse voltage. For example, for an EPR with 175 kA OH current at 400 turns, the PIM peak power may be $\sim 175 \text{ kA} \times 160 \text{ kV} = 28,000 \text{ MW}$. No matter how the coil is divided up, the total driving power requirement remains the same. Part of the drive voltage may be provided by other poloidal coil systems and the power requirements for the OH circuit reduced at the expense of increasing the power requirements in another system.

The second basic OH circuit module is the Plasma Maintenance Module (PMM). The requirements for the plasma maintenance phase and of the recovery phase of OH operation are quite similar. A power supply is required to add or remove energy from the OH coil at or near full current at a relatively slow rate. Although less than 200 volts at 175 kA might suffice for a 1 to 2 GJ 400 turn superconducting OH coil, to provide some ability to maneuver current, especially during final heating, we have used ~ 500 volts at 175 kA bidirectional current.

The third basic unit is the Plasma Buildup Module (PBM), of which the rotating energy storage machines are a part. Assuming the EPR OH circuit will be the half-biased type, i.e., the OH current will have approximately equal positive and negative swings, then the plasma buildup phase will require reversing the OH current. The plasma shutdown phase also requires reversing the current. Each of these then requires removing the energy from the coil, temporarily storing it, and returning it to the coil. The Plasma Buildup Module (PBM) should be able to handle both of these functions.

There are eight fundamental possible arrangements of these circuit modules to be considered. Each of these has many variants, depending in part on the internal makeup of each module.

Even at the level of the module block diagrams one can draw some preliminary conclusions. For an EPR with a superconducting OH coil, the PMM will have to provide one-half to a few volts per turn. The PBM on the other hand, with a one second plasma buildup time needs to provide on the order of 100 volts per turn. The PIM must deliver ~400 volts per turn. The minimum insulation levels for each module will be in approximately the same ratio's as the required volts per turn, i.e., 1::100::400. When any two of the power modules are paralleled, the voltage standoff rating of the module which is inherently the lower voltage must be raised to match the highest voltage of the other module. Hence, in general, paralleling of modules is less attractive than a series arrangement.

Design Ground Rules

In the course of this study a number of ground rules were developed to ensure that the final circuits are practical, workable designs. These have been reduced to the following considerations:

- The ac generators shall be center grounded.
- The dc generators shall be end or center grounded depending on design.
- Machine grounds shall be resistance or impedance connections to ground to limit ground fault currents to protect both generators and coils.
- The PMM rectifiers should be grounded as a preferred practice; if not grounded the rectifiers should be less than 15 kV off ground.
- All circuits shall be symmetrical with respect to ground to the extent achievable to control transients during switching. Capacitance to ground may then be added for final trimming.
- Current balance between parallel coil segments shall be directly controlled during the plasma maintenance period and during the recovery period.
- Current balance between parallel coil segments should be directly controlled during the plasma buildup and plasma shutdown periods.
- Initial OH stored energy is 1000 MJ.
- Initiation voltage is 187.5 V/turn (reduced by effect of other poloidal coils).

- OH coil conductor (superconductor) current limited to 25 kA.
- All rectifiers will be 6 pulse 3 phase.

Final Circuit Selection

Two circuits were chosen for use with each type of machine which gave the best cost approach for each. These circuits, with the associated ratings are illustrated in Figure 3 through Figure 6. The homopolar machines were required to operate over the full speed range in order to be able to reverse the voltage, while the ac machines operated over speed ranges set by the inertia which normal design practice would yield.

Figure 3 is a relatively straightforward homopolar OH circuit. The homopolar voltage was achieved by using a wound rotor machine. The size per machine was selected by optimizing voltage and stored energy. Figure 4 eliminates the resistor switch with an inductor. Since about 22% of the circuit energy was left in the inductor and dissipated in the shunt switch, the generator voltage had to be raised and the OH coil increased for comparable performance.

Figure 5 illustrates the circuit for the round rotor ac generator. The circuit of Figure 6 is for the salient pole ac machines. Two machines rather than four could be used, but approximate design data was available for the size selected. Note that the higher inertia of the salient pole machines gave two advantages. The peak (rated) voltage was lower and simultaneously the resistor voltage required was reduced because of the higher starting voltage.

Cost Comparisons

The principal emphasis of this study was on the rotating machinery. Conceptual designs were developed sufficient to identify weights of materials and other information required for preparing price estimates for the rotating machines. These were then all analyzed by the same price estimators to arrive at representative values. For the power electronics equipment, past data for large three phase rectifiers were utilized to provide a size scaling, and all the other equipment was ratioed from the rectifier values. This provided price levels which were believed to be consistent relative to each other.

Typical, one of three circuits. Each pair of Homopolar Generators serves eight coils in parallel. The total number of generators is six, of coil segments is 24. Each resistor, R_r has a resistance of $\sim 0.16 \Omega$ to produce ~ 8 kV for a total initiating voltage of ~ 16 kV across 85 turns. Maximum voltage to ground is 8 kV.

Figure 3. DC Generator OH Circuit

Typical, one of three independent circuits. Each pair of Homopolar Generators serves eight OH coil segments in parallel. The total number of generators is six, coil segments 24. Each resistor, R , is $\sim 0.045 \Omega$, and the associated inductance is $\sim 0.026 \text{H}$. Maximum voltage to ground is 9 kV.

Figure 4. Alternate DC Generator OH Circuit

Typical, one of two independent circuits. Each generator feeds two parallel circuits with a total of eight coil segments. Each resistor, R , has a resistance of $\sim 0.37 \Omega$ to produce 18.5 kV for a total initiating voltage including generator output of ~ 48 kV across 254 turns. Maximum voltage to ground is 24 kV.

Figure 5. Round Rotor AC Generator OH Circuit

Typical, one of four independent circuits. Each generator feeds one circuit with a total of eight coil segments. Each resistor, R , has a resistance of $\sim 0.34 \Omega$ to produce ~ 17 kV for a total initiating voltage including generator output of ~ 48 kV across 254 turns. Maximum voltage to ground is 24 kV.

Figure 6. Salient Pole AC Generator OH Circuit

Tables 1 through 4 give the resulting values of estimated prices for each of the four circuits of Figures 4-1 through 4-4. These estimates show no significant difference between the alternatives from the cost standpoint.

We have recently re-analyzed the prices for power electronic equipment. In this evaluation we were more successful in eliminating the first of a kind factors with a consequent large reduction in the estimated price of the power electronics packages. All four cost estimates, using the best price estimating data now available to use fall between 71 and 75 x 10⁶ dollars, including the rotating machines as originally estimated. The original conclusion, that there is no significant long term cost differential, still holds.

Conclusions

Based on the studies performed, the ac generator is an attractive choice for OH energy storage, it's total system cost is comparable with that of the homopolar. It provides a much more flexible operating system since it allows the OH voltage to be continuously tailored to satisfy the plasma system requirements. The variation in OH current during the burn cycle was not considered in this study but is readily accommodated in the ac system. The homopolar system costs will increase significantly if the variation is large. The ac machine is essentially fully developed, whereas the homopolar current collection system remains as a difficult development problem.

Based on the original price estimates, the development of large mechanical switches capable of 10⁵ to 10⁶ operations reliably with steady state current ratings of 50 to 100 kA is an attractive alternative. However, based on using the more recent price estimates, the attractiveness of the all solid-state option has increased. It should be noted that the switches used in the proposed OH circuits should be capable of operating much closer to rated voltage limits than is normal for ac system switches because the switching voltages can be closely controlled.

TABLE 1
EPR OH CIRCUIT - HOMOPOLAR ENERGY STORAGE COST 1
See Figure 3

Quantity	Item	Rating	Quantity x Rating	Unit Cost	Total Cost
6	Homopolar Generators	850 MVA 200 kA, 4.25 kV	5100 MVA	3.06×10^6	18.4×10^6
6	Generator Switches 2 Comm. Circ/Sw	850 MVA 200 kA, 4.25 kV	5100 MVA	9.12×10^6	54.7×10^6
12	Line Rectifiers	4.25 MVA 50 kA, 85 V	102 MVA	0.840×10^6	10.1×10^6
24	Resistor Switches, 1/2 Diode, 1 Comm. Circ/Sw	400 MVA 50 kA, 8 kV	9600 MVA	3.78×10^6	90.8×10^6
24	Resistors	20 MJ/pulse 50 kA, 8 kV	480 MJ/pulse	0.0934×10^6	2.2×10^6
	TOTAL				176.2×10^6

Costs are in 1977 dollars based on fully developed manufacturing capability.

TABLE 2
EPR OH CIRCUIT - HOMOPOLAR ENERGY STORAGE COST 2
See Figure 4

Quantity	Item	Rating	Quantity x Rating	Unit Cost	Total Cost
6	Homopolar Generators	1046 MVA 5.23 kV, 200 kA	6276 MVA	3.06×10^6	18.4×10^6
12	Line Rectifiers	4.25 MVA 50 kA, 85 V	102 MVA	0.840×10^6	10.1×10^6
6	Shunt Switches, 2-way, 2 Comm. Circ./Sw	2475 MVA 9.0 kV, 275 kA	16200 MVA	21.44×10^6	128.6×10^6
6	Inductors	52 MJ 200 kA	312 MJ	0.52×10^6	3.1×10^6
6	Resistors	105 MJ/pulse 200 kA, 9 kV	630 MJ/pulse	1.66×10^6	10.0×10^6
					<hr/> $*170.2 \times 10^6$

*This circuit requires the OH coil to be 13% larger; this cost is not included here.

Costs are in 1977 dollars based on fully developed manufacturing capability.

TABLE 3
EPR OH CIRCUIT - AC GENERATOR ENERGY STORAGE COST 1
See Figure 5

Quantity	Item	Rating	Quantity x Rating	Unit Cost	Total Cost
2	AC Generators (Round Rotor)	1979 MVA 2 x 40.8 kA, 14 kV	3958 MVA	6.48×10^6	13.0×10^6
4	Generator Rectifier	950 MVA 50 kA, 19 kV	3800 MVA	14.64×10^6	58.6×10^6
8	Generator Rectifier Switches	475 MVA 50 kA, 9.5 kV	3800 MVA	4.14×10^6	33.2×10^6
2	Generator Drives	2 MVA 18.6 kV dc, 107A	4 MVA	0.409×10^6	0.8×10^6
4	Line Rectifiers with Transformers	12.75 MVA 50 kA, 255 V	102 MVA	1.13×10^6	4.5×10^6
8	Resistor Switches, 1/2 Diode, 1 Comm. Circ/Sw	925 MVA 50 kA, 18.5 kV	7400 MVA	7.40×10^6	59.2×10^6
8	Resistors	27.8 MJ/pulse 50 kA, 18.5 kV	222 MJ/pulse	0.13×10^6	1.0×10^6
	TOTAL				170.3×10^6

Costs are in 1977 dollars based on fully developed manufacturing capability.

TABLE 4
EPR OH CIRCUIT - AC GENERATOR ENERGY STORAGE COST 2
See Figure 6

Quantity	Item	Rating	Quantity x Rating	Unit Cost	Total Cost
4	AC Generators (Salient Pole)	919 MVA 13 kV, 40.8 kA	3675 MVA	4.85×10^6	19.4×10^6
4	Generator Rectifiers	875 MVA 50 kA, 17.5 kV	3500 MVA	13.71×10^6	54.8×10^6
8	Generator Rectifier Switches	437.5 MVA 50 kA, 8.75 kV	3500 MVA	3.88×10^6	31.0×10^6
4	Generator Drives	1.5 MVA 18.6 kV dc, 80 A	6 MVA	0.396×10^6	1.6×10^6
4	Line Rectifiers with Transformers	12.75 MVA 50 kA, 255 V	102 MVA	1.13×10^6	4.5×10^6
8	Resistor Switches, 1/2 Diode 1 Comm. Circ/Sw	850 MVA 50 kA, 17 kV	6800 MVA	6.91×10^6	55.3×10^6
8	Resistors	25.5 MJ/pulse 50 kA, 17 kV	204 MJ/pulse	0.12×10^6	0.9×10^6
	TOTAL				167.5×10^6

Costs are in 1977 dollars based on fully developed manufacturing capability.

The cost of initiation is a significant portion of the OH system cost. There is a potential for reducing this by performing the initiation in another circuit. For example, by modifying the vertical field coils and circuits to provide the flexibility for differential turn currents and providing the initiation as a pulse. This requires a full electrical and coil system analysis to determine the net savings possible.

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