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MASTER

EXPERIMENTAL POWER REACTOR
DC GENERATOR ENERGY STORAGE STUDY

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ABSTRACT

This study covers the use of dc generators for meeting the Experimental Power Reactor Ohmic Heating Energy Storage Requirements. The dc generators satisfy these requirements which are the same as defined in WFPS-TME-038 which covered the use of ac generators and homopolar generators. The costs of the latter two systems have been revised to eliminate first-of-a-kind factors. The cost figures for dc generators indicate a need to develop larger machines in order to take advantage of the economy-of-scale that the large ac machines have. Each of the systems has its own favorable salient features on which to base a system selection.

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1.0 INTRODUCTION

This study was performed to assess the applicability of direct current generators to the energy storage requirements of ohmic heating (OH) systems for large Tokamak fusion power devices. This assessment used the OH requirements for a large Experimental Power Reactor (EPR) as developed in a previous study⁽¹⁾. The basis for the dc generator design was engineering and manufacturing technology as it exists today for these machines. A brief survey was also performed of extensions of today's technology which could significantly improve the performance of dc machines.

The ohmic heating (OH) systems for the Experimental Power Reactor (EPR) designs to date have all used temporary energy storage to assist in providing the OH current change necessary to build up the plasma current in the tokamak. Two alternative approaches have already been evaluated⁽¹⁾. These two alternates were dc homopolar generators and ac generators. Two alternates for ac generators have been evaluated, the round rotor machine as currently used with steam turbines, and the salient pole machine as currently used with water turbines.

LASL has used a 500 kW dc commutated Westinghouse generator in testing the ~ 450 kJ superconducting energy storage coil. This generator has been repeatedly successfully pulsed with currents in excess of six times its 2 kA rating. This indicates that the dc commutated machine may have potential for large energy storage systems with the pulsed nature of the OH circuit.

The previous study of ac generators and dc homopolar generators clearly illustrated that the total OH system circuitry had to be modified to accommodate the characteristics of the energy storage system. It is necessary to develop circuitry appropriate to the dc commutated generator in order to fairly assess its merits with respect to the other types of rotating storage. The circuit has to be developed conjointly with the machine design so that the restrictions and requirements of all components are satisfied.

In order to avoid unnecessary repetition of previous work, the same total energy storage (1 GJ) and the same plasma buildup time (1 s) will be used as in the previous study. This will permit direct comparison with the previous study results for ac generators and homopolar generators.

The complete electrical system was evaluated since the characteristics of the generators lead to other component differences and potentially to different circuit configurations.

The principal emphasis of this study, and that with the homopolar generators and the ac generators, was on the rotating machinery. For the power electronic equipment in the previous study (homopolar and ac machines), past data for large three phase rectifiers were used to provide a size scaling, and all the other equipment was ratioed from these rectifier values. This provided values consistent relative to each other.

Since then the prices of the power electronic equipment have been re-analyzed. This includes the elimination of the first-of-a-kind factors with a consequently large reduction in the estimated prices for the power electronic packages. For comparative purposes tables of revised cost have been included for the homopolar generator and the ac machine.

This study has been directed by the Los Alamos Scientific Laboratory (LASL) under the sponsorship of DOE. The OH coil design and analysis and the determination of the coil requirements was previously performed by LASL and reported separately. Westinghouse provided the design of the OH circuits, the dc machinery design, and estimated the costs for the systems. This work is reported in this document.

Introductory material on OH circuits has been condensed from a previous study⁽¹⁾, and included in Section 2.0 and part of Section 3.0 in order to make this report complete in itself.

2.0 OHMIC HEATING SYSTEM FUNCTIONS

2.1 INTRODUCTION

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).

In addition to the plasma current buildup, there are six 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.

The functions of the OH system are conveniently described in terms of the various operating phases of a complete Tokamak cycle and the function to be performed during each phase.

The next seven sections each describe briefly the OH functions during a particular phase of operation. The final section summarizes the total functions of the ohmic heating circuit.

2.2 PLASMA CURRENT BUILDUP

A fundamental feature of a Tokamak is a large plasma current. For EPR size machines this current is on the order of 5 to 8×10^6 A.

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, ΔI_{OH} . This is called the zero bias circuit. Alternately, 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 $-\Delta I_{OH}/2$.

Figure 2.2-1 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 has 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 - 1000 MJ of stored energy to be transferred out of the coil for EPR, and back into the coil, in a time of one second. If an active power handling device is used, then its peak volt-ampere rating could be as high as ~ 6300 MVA for the 1000 MJ.

By the time the plasma current is fully developed, the plasma resistance has fallen to values characteristic of a superconductor.

2.3 PLASMA INITIATION

The plasma initiation phase actually precedes the plasma current buildup operationally, but it is somewhat easier to describe after the basic current buildup since it complicates the simple current reversal scheme.

At the beginning of an operating cycle the Tokamak vacuum vessel is filled at a very low pressure with gas, usually tritium for deuterium-tritium (D-T) burners. This gas may then be partially ionized by an RF coil or other means

Figure 2.2-1. Simplified OH Reversing Circuit

to ensure that there is a significant ion population in the gas. This makes the initiation of the plasma discharge a little easier and the timing more precise.

As indicated in Figure 2.2-1, 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 circuit and hold it for a period of ~ 10 milliseconds, a relatively high voltage is required. 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. For this study this results in 187.5 volts on the plasma and a similar value of volts per turn on the OH drive coil.

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 lowest cost equipment which will accomplish this.

2.4 FINAL HEATING

Final heating may overlap the plasma current buildup or current maintenance phase or both. The purpose of final heating is to raise the plasma temperature from the level reached by ohmic heating to the level necessary for "ignition". The function of the OH system while this is going on is to continue to increase the plasma current (if full current has not been obtained) and to hold the plasma current in spite of magnetic field effects resulting from the final heating.

2.5 PLASMA CURRENT MAINTENANCE

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 and 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.

2.6 PLASMA CURRENT SHUTDOWN

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 a one second time period for both OH reversals.

2.7 RECOVERY TO INITIAL CONDITIONS

During this phase the residual gas from the spent plasma is pumped out of the vacuum vessel and fresh gas is pumped in. The only function required of the OH system during this phase is to restore the OH drive coil current to the level required for restarting the whole cycle. In the worst case, the ohmic heating circuit would have to remove as much energy from the OH drive coil as it added during the plasma maintenance phase.

2.8 SUMMARY OF SYSTEM FUNCTIONS

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 of phases 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 2.8-1. This same figure also shows the expected plasma current behavior during the cycle.

The OH drive coil current shown in Figure 2.8-1 is based on a judgment that the best approach is to use a dissipative element to provide the plasma initiation voltage and perhaps even additional dissipation during the reversal, so that the reversed coil current is low enough that the additional current added during the plasma maintenance or burn phase brings the final coil current to just that level which will cause the current at the end of the plasma shutdown phase to approximately equal the starting current. Whether or not this can be achieved in practice is not known at this time, nor do we know how to achieve this result at this time because of the calculational uncertainties of the plasma performance. For the present, however, Figure 2.8-1 represents a reasonably probable mode of OH operation in an EPR.

There are two additional functions, pre-ionization of the plasma and pulse cleaning of the vacuum vessel. Since these have not routinely been part of the main OH circuit in the majority of tokamaks, they are not included here as required functions.

Figure 2.8-1. Ohmic Heating Operating Cycle

3.0 OHMIC HEATING CIRCUITS

By grouping together similar functional requirements, the OH system can be reduced to three basic circuit modules (in addition to the OH drive coil). This section addresses the nature of these basic modules, the possible general circuit arrangements of these modules, and specific circuits using dc generators for energy storage.

3.1 BASIC CIRCUIT MODULES

3.1.1 PLASMA INITIATION MODULE

The requirements for the plasma initiation phase are relatively unique and cannot generally be satisfied by the other power modules. A voltage of 187.5 volts per turn 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. The detailed requirements for this plasma initiation pulse (PIP) are dependent on specifics of the design and operation. Currently the experimenters recommend a rise time for the voltage on the order of a millisecond. This voltage needs to be applied to the plasma for a period of the order of 10 to 50 ms.

To keep the required voltage down to the range of 187.5 volts per turn requires a reduced gas density start. This reduction in density is limited by the fact that at very low densities the mean free path for electrons gets long enough for "electron runaway" to occur. In this case, the electrons escape the plasma and impinge on the vacuum vessel wall.

The best estimates at this time call for the 187.5 volts per turn to be induced over a ~ 20 ms period, with a rise time of ~ 2 ms. The OH voltage for this function has an algebraic sign which causes it to oppose the initial flow of current in the OH drive coil. Hence the PIP module extracts energy from the OH

coil. Since the direction of the voltage is fixed by the plasma requirements, the PIP module must remove energy from the rest of the OH circuit during plasma initiation.

The PIP module must handle the peak OH circuit current and simultaneously produce a large reverse voltage. For example, for an EPR with 127 kA OH current at 400 turns, the total PIP peak power may be $\sim 127 \text{ kA} \times 75 \text{ kV} = 9,500 \text{ MW}$. No matter how the coils are 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 the other system.

The energy extracted from the circuit will be of the order of $\sim 250 \text{ MJ}$. This reduces the energy to be stored by the reversing circuit by this amount. Note that the current only drops by $\sim 10\%$ in this process.

The lowest capital cost power supply for removing energy is a resistor. This has been used for plasma initiation in a number of experimental tokamaks. The use of resistors has two drawbacks. The first is that it dissipates the energy it removes, and although the heat might be recovered in the power production cycle of an EPR, the electrical energy is lost. The other drawback is that the resistor(s) must be inserted into the circuit by an interrupting switch to obtain the relatively short voltage rise time needed. In spite of these drawbacks the resistor is still the preferred approach because of its simplicity, easy adjustability, reliability, and low first cost.

3.1.2 PLASMA MAINTENANCE MODULE

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 300 volts at 127 kA might suffice for a 1 GJ 400 turn superconducting OH coil, to provide some ability to maneuver current, especially during final heating, an estimate is $\sim 700 \text{ volts}$ at 127 kA or 1750 V at 50 kA.

This Plasma Maintenance Module (PMM) is best provided for with a dual solid state rectifier operated from the power line. The drain on the power line will be of the order of 100 MVA. The dual rectifier is required because the PMM is operating during both the forward and reverse current portions of the OH operating cycle, and in some circuit configurations must follow the transition of current from plus to minus. A single rectifier could be used with a reversing switch.

The PMM also provides the auxiliary function of initially building up the OH coil current from a cold start.

3.1.3 PLASMA BUILDUP MODULE

Assuming that 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.

The simplest device to perform this function is a capacitor which is switched into the circuit across the coil. This forms an LC network with the coil. The current and voltage will vary in a sinusoidal fashion at the resonant frequency of the LC circuit ($f = 1/2 \pi \sqrt{LC}$ neglecting resistance). The voltage and current are approximately $\pi/2$ out of phase, so that the voltage starts out as a sine wave and the current as a cosine wave. After one-half cycle the current will be reversed and the capacitor must be removed from the circuit to prevent continuing oscillation.

For this storage of energy, as in an EPR, dc generators will perform in the circuit just as a capacitor would.

In order for the dc generator to handle both current reversals in one cycle it must reverse its direction of rotation from one current reversal to the other, since voltages of opposite polarities are required. One could reverse the machine field and use a single direction of rotation, but the 10 second interval proposed between the end of the second reversal of one cycle and the beginning of the first reversal for the next cycle makes this difficult and introduces another large pulsing circuit to the system. Therefore, the dc machine will operate from standstill to full speed and back to standstill at each reversal. This has the additional advantage of reducing the duty cycle for brush wear to approximately 10%.

Due to the fact that the dc generator acts just like a capacitor, something special is required to change the LC resonant frequency if the two reversals are different. The field could be changed to accomplish this, but preliminary estimates suggest that the resistive losses during a slow reversal (several times the startup reversal) would be prohibitive. Therefore, some no load switching would be required between reversals. Either modular units would be switched from series to parallel or the number of passes per rotor would be changed by switching.

It is not practical to operate the generator in a PBM that is isolated from ground by a significant voltage. The generator is particularly a problem in this respect since the current must flow through its commutator which must be directly exposed to the ambient atmosphere within the machine.

3.2 MODULE ARRANGEMENTS

Having reduced the ohmic heating circuit to the OH drive coil plus twenty power modules, the possible arrangements can be identified. The details, especially the switching, depend on the specifics of the modules.

There are only eight separate and distinct circuit arrangements of the twenty basic power modules with a single coil. The eight possibilities are shown in block diagram form in Figures 3.2-1A and 3.2-1B. For most of these arrangements there are alternate arrangements which are electrically identical from the circuit point of view but are different with respect to grounding and hence voltages to ground for individual components. These variations are obvious, they occur whenever two or more of the power modules are in series. From the circuit point of view the order of the series elements is meaningless but must be considered when actual circuit elements are identified within each block. No switches are shown in Figure 3.2-1A, B because the switches and their commutating circuits, if any, are dependent upon the content of the modular blocks.

A further variation can be made by splitting one or more blocks into two independent segments when they are used in a series arrangement. This permits better balancing of voltages to ground. This is particularly applicable to the PIM module which may cause transient voltage distributions during switching from the "steady state" voltage distribution. Figure 3.2-2 illustrates how in this series arrangement the voltages of the coil segments will not accumulate; therefore, will not create a voltage equal to the sum of the coil segment voltages. This is accomplished by locating a plasma initiation resistor on each side of a coil segment. Except for variations, the coil segment voltage should be equal but opposite to the drop across the pair of resistors. The arrangement has the advantage of preventing the generator voltage to ground from floating to unacceptable values. Each array of generators can be tied to ground through a resistor.

Circuit Number 1 consists of all the modular power elements in series. There are in fact, a total of six circuit possibilities represented here since the three modules can be arranged in six different orders. These six possibilities are:

CIRCUIT ARRANGEMENT 1.

CIRCUIT ARRANGEMENT 3

CIRCUIT ARRANGEMENT 2

CIRCUIT ARRANGEMENT 4

PIM = Plasma Initiation Module PBM = Plasma Buildup Module PMM = Plasma Maintenance Module

Figure 3.2-1A. Basic OH Circuit Arrangements

CIRCUIT ARRANGEMENT 5

CIRCUIT ARRANGEMENT 7

CIRCUIT ARRANGEMENT 6

CIRCUIT ARRANGEMENT 8

PIM = Plasma Initiation Module PBM = Plasma Buildup Module PMM = Plasma Maintenance Module

Figure 3.2-1B. Basic OH Circuit Arrangements

This spatial curve demonstrates that generator ground points will be at ground since the voltage drops across the resistors will be balanced by the voltage rises across the OH coil segments.

Figure 3.2-2. Generator Ground Voltage With Series Circuits.

- 1a. PIM-PBM-PMM (Illustrated in Figure 3.0-1A)
- 1b. PIM-PMM-PBM
- 1c. PBM-PIM-PMM
- 1d. PBM-PMM-PIM
- 1e. PMM-PIM-PBM
- 1f. PMM-PBM-PIM

Circuit arrangement 2 consists of all the modular power elements in parallel. In this case the order of the modules makes no difference. Circuit arrangements 3, 4, and 5 consist of the possible arrangements utilizing two power modules in series with the third in parallel. Since the choice of the third, parallel module has significant effect on the circuit, each of these is shown as a separate arrangement. Each of those shown represents two possibilities since the two series elements can be placed in either order. Circuit arrangements 6, 7, and 8 are the possible arrangements with two power modules in parallel and the third in series.

One can thus identify at least 20 basic circuit arrangements which could be used for an EPR OH circuit. The eight circuit arrangements illustrated in Figure 3.2-1A, B seem to be the minimum which must be considered as basic variants. An important function of the eight basic circuit arrangements is to function as a check list for reviewing circuit possibilities to reduce the possibility that a good one is overlooked.

Conclusions with respect to these circuits for the EPR OH function cannot really be established without breaking down each module to identify its content, particularly the switching required. The next two sections of this report address this for the dc generator. In each case, they are combined with a switched resistor for the PIM and a conventional dual rectifier for the PMM.

Even at the level of the circuits of Figure 3.2-1A, B, 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 187.5 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::187. 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. This may be accomplished by increasing the voltage of a series switch rather than that of the rectifier or generator of the module, but in any case the paralleling increases the costs. A related but different problem exists in series arrangements. In this case the location of the ground point of the circuit becomes important. For example, if one end of a PIM is at ground and one of the other modules is connected at the other end of the PIM, then the other module must have insulation to ground sufficient for its own voltage plus that of the PIM.

3.3 DC GENERATOR CIRCUITS

The use of a dc generator in the PBM is basically the same as the use of an uncharged capacitor. The plasma initiation needs to be kept short to minimize the system losses, and the plasma buildup time is long, 1000 ms, relative to the plasma initiation time. Hence, if the generator is brought into the circuit during the plasma initiation, at the end of the plasma initiation the voltage on the plasma will drop from 187.5 volts to 1.5 to 3 volts. This is in the order of a factor of 10 too low to sustain the plasma buildup, especially if fresh gas is being added to build the plasma density. Therefore, the dc machine should be switched into the circuit on the order of 30-50 ms before the plasma initiation pulse is started. This requires on the order of 1% additional current in the OH coil to maintain the volt seconds required by the plasma. This creates a potential problem of premature partial breakdown and quenching which may contaminate the gas from the walls. Alternatively, the plasma initiation time can be extended at the expense of increase system losses or a combination of the two can be used. For this study the initiation time was extended to 30 ms. This is the same time used for the homopolar generator in earlier studies.

When a dc generator is used in a series configuration to perform the plasma reversal functions, it is necessary to provide shunt switches across the machine to avoid having the coil current flowing through the machine continuously. This allows the machine to be pulse rated and to be stationary at the beginning of each reversal. Being stationary at the beginning of each reversal allows voltage and rotation to reverse. Circuit 1, Figure 3.3-1, and circuit 7, Figure 3.3-7, have the dc machine in a straightforward series configuration. Since the current must be forced out of the switches and into the machine, commutating circuits are required for both switches.

When a dc generator is used in a parallel configuration, it is necessary to provide series switches to block current and/or voltage when the machine is not required to be active in the circuit. Circuit 2, Figure 3.3-2, Circuit 4, Figure 3.3-4, and Circuit 6, Figure 3.3-6, all have the dc machine in a simple parallel configuration. In these cases, it is not universally necessary to have commutating circuits on both switches. In order to avoid the OH voltage drop to zero it is necessary to pre-initiate the reversal. Circuits 2 and 4 require commutating circuits to force the current out of the machine branch and into the plasma initiation branch.

In circuit 2 the switch in the plasma initiation circuit, S3, is not required to make the circuit function; but, if it were not provided, the resistor would load the circuit with losses during the entire reversal. Circuit 6, Figure 3.3-6, has the machine in a parallel configuration; but the other parallel branch is the PMM, which is a dual rectifier.

The rectifier can be used to commute the generator associated switches with little disturbance to the coil voltage.

Circuits 3, 5, and 8, Figures 3.3-3,5,8, have the machine in series with one other element and in parallel with the third. In circuits 3 and 8 this requires both series and shunt switches. Circuit 5 is a special case in which only series switches are required because the PMM functions as the shunt.

Circuit 1, Figure 3.3-1, has a minimum number of switches and each module has to sustain only its own voltage. Therefore, circuit 1 should be the least expensive system. The most attractive alternate to this is circuit 6, Figure 3.3-6.

Circuit 6 has two more switches than Circuit 1, but because of the location of the PMM rectifier, it has two less commutating circuits than Circuit 1. In addition, Circuit 6 permits both the dc machine and the PMM rectifier to be midpoint grounded.

3.4 DC COMMUTATED GENERATOR ENERGY STORAGE REQUIREMENTS

3.4.1 BASIC OH CIRCUIT EVALUATION

The basic requirements are taken from the previous energy storage study⁽¹⁾. The maximum energy to be absorbed by the energy storage system is:

$$E_m = 1 \times 10^9 \text{ J.}$$

The reference coil design has a total number of turns of:

$$N_r = 400.$$

The reference coil design has an inductance of:

$$L_r = 0.124 \text{ H.}$$

Neglecting losses in the circuit, the maximum current will be:

$$I_r = 127 \times 10^3 \text{ A}$$

The average value of the reversal voltage for plasma current buildup in one second is:

$$V_r = \frac{L_r I_r}{1/2 \Delta t} = 31.5 \times 10^3 \text{ V.}$$

$$\text{Peak of } \bar{V}_r = \frac{\pi}{2 \sqrt{2}} \times \bar{V}_r = 49.44 \times 10^3 \text{ volts.}$$

All the above quantities can be changed to match the energy storage system except for E_m and the plasma buildup time. Several products are fixed, however, in order to hold E_m and buildup time. These are:

$$N_r I_r = 5 \times 10^7 \text{ A}$$

$$\bar{V}_r I_r = 4 \times 10^9 \text{ VA}$$

3.4.2 GENERATOR EVALUATION

DC commutated generators have voltage limits very much lower than the coils. Therefore, the number of coil segments can be selected without a constraint from coil voltage. This means that $\bar{V}_r I_r = 4 \times 10^9 \text{ VA}$ will be the principal determining quantity in setting the number of coil segments and generators.

An additional criteria from the previous study was that the coil segment current preferred value is $25 \times 10^3 \text{ A}$.

Using the development in Chapter 3 of the previous study report⁽¹⁾:

$$n \times m \left(\frac{\bar{V}_r}{n} \right) \left(\frac{I_r}{m} \right) = \bar{V}_r I_r$$

where n and m are the number of subdivisions of the total OH coil required to accommodate the voltage and current respectively. Now let $\bar{V}_g$ be the average generator voltage over the pulse, and I_g be the peak generator current during the pulse. Then:

$$\left(\frac{\bar{V}_r}{n} \right) = p \bar{V}_g \text{ and } \left(\frac{I_r}{m} \right) = q I_g,$$

where p is the number of generators used in series per coil segment, and q is the number of paralleled generator sets per coil segment. Note that p and q can be integers or the reciprocal of integers if there are multiple coil segments per machine. It follows then:

$$n \times m \times p \bar{V}_g \times q I_g \approx \bar{V}_r I_r,$$

$$\text{or, } (n \times m) \approx \bar{V}_r I_r / p q \bar{V}_g I_g$$

Now the product $(n \times m)$ is the total number of coil segments making up the complete OH coil. It is necessary for $(n \times m)$ to be an integer.

Then the total number of generators required will be:

$$N_G = (n \times m) p q \approx \bar{V}_r I_r / \bar{V}_g I_g$$

Clearly the number of generators must be an integer. The energy required to be stored per generator, E_G , is just the total energy to be stored divided by the number of generators,

$$E_G = \frac{E_m}{N_G} \approx E_m \bar{V}_g I_g / \bar{V}_r I_r$$

3.4.3 FINAL EQUATIONS FOR SEGMENTED GENERATORS AND OH COIL

The total number of turns in the OH coil will be:

$$N_c = N_r I_r / q I_g,$$

and the number of turns per coil segment will be:

$$N_s = N_c / nm \approx N_r p \bar{V}_g / \bar{V}_r.$$

The value of N_s is preferably an integer.

Using the total coil requirements along with the approximate equations just derived yields:

$$\text{No. of Coil Segments} = n \times m \approx 4 \times 10^9 / p q \bar{V}_g I_g$$

$$\text{No. of Generators} = N_G \approx 4 \times 10^9 / \bar{V}_g I_g$$

$$\text{Energy Stored/Generators} = E_G \approx \frac{1}{4} \bar{V}_g I_g$$

$$\text{No. of Parallel Gen./Coil.} = q \approx 25 \times 10^3 / I_g \text{ (preferred)}$$

$$\text{No. of turns per Coil Segment} = N_s \approx 1.25 \times 10^{-2} p \bar{V}_g$$

Keeping in mind the integer constraints, these expressions can be used to perform trade-offs and determine the general configuration of the system. The integer constraints are:

$$(n \times m) = \text{integer (must be an even integer if } q < 1)$$

$$N_g = \text{integer}$$

$$p = \text{integer}$$

$$q = \text{integer or reciprocal of even integer}$$

$$N_s \sim \text{integer} > 1$$

The other item of information needed is the generator voltage profile versus time during the pulse so that the average and peak generator voltages can be related. This requires iteration, since the ratio between peak and average voltage will depend on the ratio between the energy stored per generator, E_g , and the actual maximum energy stored in the generator at full speed. This latter value is size and design dependent. The ratio between peak and average voltage can be altered by varying the field during the pulse. This effect is also design dependent.

3.4.4 GENERATOR h CONSTANT

The required generator h constant (Joules stored per rated watt output) with zero to full speed swing is:

$$h = \frac{E_m}{\bar{V}_r I_r \frac{\pi}{2}} = \frac{1 \times 10^9}{4 \times 10^9 \frac{\pi}{2}} = \frac{1}{2\pi} = 0.159 \text{ s}^{-1}$$

3.5 COIL SEGMENTATION

For the reference ORNL EPR design, with 127 kA in a 400 turn OH drive coil, 187.5 volts per turn requires a total of 75 kV or more. It would be impractical to build a coil in the OH configuration and space which was insulated for 75 kV. The coil can be built in segments; 40 segments of 25 kA each, for example, would require 9.5 kV on each segment. This should be an achievable level. The coil segments can be driven individually by separate segments of the OH system, they can be driven in parallel by an OH system with two times the current, or they can be driven by dividing the OH driving circuit into segments and connecting alternate coil segments and drive circuit segments to form a closed series circuit. Combinations of these techniques are also possible. In actual practice, the number of turns in each segment will vary with the location of the segment in order to balance the system as closely as possible.

DC MACHINE — CIRCUIT 1

O = Switch Open

C = Switch Closed

I = Switch Interrupts

	Pre-Initiation	Initiation	1st Reversal	Burn	2nd Reversal	Recovery
S ₁	C	I	C/O	O	O/C	C
S ₂	O	O	O/C	C	C/O	O
S ₃	I	O	O	O	O	C
S ₄	O	O	O	C	I	O
S ₅						
S ₆						

Figure 3.3-1. DC Machine - Circuit 1

NOTE: S_3 USED TO MINIMIZE LOSSES ONLY

DC MACHINE — CIRCUIT 2

O = Switch Open

C = Switch Closed

I = Switch Interrupts

	Pre-Initiation	Initiation	1st Reversal	Burn	2nd Reversal	Recovery
S_1	I	O	O	O	O	C
S_2	O	O	O	C	I	O
S_3	O	C	I	O	O	O
S_4	C	I	C/O	O	O/C	O
S_5	O	O	O/C	O	C/O	O
S_6						

Figure 3.3-2. DC Machine - Circuit 2

NOTE: S_3 USED TO MINIMIZE LOSSES ONLY

DC MACHINE — CIRCUIT 3

C = Switch Closed

O = Switch Open

I = Switch Interrupts

	Pre-Initiation	Initiation	1st Reversal	Burn	2nd Reversal	Recovery
S_1	I	O	O	O	O	C
S_2	O	O	O	C	I	O
S_3	O	C	I	O	O	O
S_4	C	I	C/O	O	O/C	I
S_5	O	O	O/C	I	C/O	O
S_6						

Figure 3.3-3. DC Machine - Circuit 3

DC MACHINE — CIRCUIT 4

C = Switch Closed

O = Switch Open

I = Switch Interrupts

		Pre-Initiation	Initiation	1st Reversal	Burn	2nd Reversal	Recovery
S ₁	C/O	O	C	O	O	C	
S ₂	O	O	O	C	O	O	
S ₃	I	C	I	O	O	C	
S ₄	O	O	O	C	I	O	
S ₅	C	I	C/O	O	O/C	O	
S ₆	O	O	O/C	I	C/O	O	

Figure 3.3-4. DC Machine - Circuit 4

DC MACHINE — CIRCUIT 5

C = Switch Closed

O = Switch Open

I = Switch Interrupts

		Pre-Initiation	Initiation	1st Reversal	Burn	2nd Reversal	Recovery
S ₁	I	O	O	O	O	C	
S ₂	O	O	O	C	I	O	
S ₃	C	C	C/O	O	O/C	O	
S ₄	O	O	O/C	I	C/O	O	
S ₅	C	I	C/O	O	O/C	C	
S ₆	O	O	O/C	C	C/O	O	

Figure 3.3-5. DC Machine - Circuit 5

DC MACHINE — CIRCUIT 6

C = Switch Closed

O = Switch Open

I = Switch Interrupts

	Pre-Initiation	Initiation	1st Reversal	Burn	2nd Reversal	Recovery
S_1	I	O	O	O	O	C
S_2	O	O	O	C	I	O
S_3	C	C	C/O	O	O/C	O
S_4	O	O	O/C	I	C/O	O
S_5	C	I	C/O	O	O/C	C
S_6	O	O	O/C	C	C/O	O

Figure 3.3-6. DC Machine - Circuit 6

DC MACHINE -- CIRCUIT 7

C = Switch Closed

O = Switch Open

I = Switch Interrupts

	Pre-Initiation	Initiation	1st Reversal	Burn	2nd Reversal	Recovery
S ₁	C	I	C/O	O	O/C	C
S ₂	O	O	O/C	C	C/O	O
S ₃	I	O	O	O	O	C
S ₄	O	O	O	C	I	O
S ₅	O	C	O	O	O	O
S ₆						

Figure 3.3-7. DC Machine - Circuit 7

I = Switch Interrupts

		Pre-Initiation	Initiation	1st Reversal	Burn	2nd Reversal	Recovery
S ₁	I	0	0	0	0	C	
S ₂	0	0	0	C	I	0	
S ₃	C	I	C/O	0	O/C	I	
S ₄	0	0	O/C	I	C/O	0	
S ₅	0	C	I	0	0	0	
S ₆							

Figure 3.3-8. DC Machine - Circuit 8

4.0 FINAL CIRCUIT SELECTION

4.1 GROUND RULES

In the course of the previous study⁽¹⁾ a number of ground rules were developed to ensure that the final circuits were practical, workable designs. These have been modified to account for the different properties of the dc machines.

MACHINE GROUNDING

Large rotating machinery cannot readily be isolated from ground and operated at large voltages above ground. This is especially true of a dc generator because its commutator promotes corona. Therefore, the dc generator shall be end or center grounded.

RECTIFIER GROUNDING

Rectifiers fed from the line to provide the Plasma Maintenance Module function can be operated off ground. Up to ~ 500 volts off ground will cause little or no penalty since the only change is isolation of the gate control circuits, and these should be isolated in any case for transient protection. From 500 to ~ 15,000 volts off ground, the costs will increase moderately to insulate the devices themselves. These rectifiers should be well below this 15,000 V to ground.

TRANSIENT VOLTAGE SUPPRESSION

When the plasma initiation resistors are switched into the circuit, the voltage distribution around the circuit undergoes a major readjustment. All parts of the circuit have capacitance to ground. During the voltage readjustments from switching, the charging of the stray capacitances to ground strongly influence the local voltages; and, if the stray capacitances are significantly unbalanced with respect to the normal ground point, voltage flashover may occur. This is particularly true for large coil drive circuits in which the grounding

is either high resistance or high impedance to minimize coil damage in the event of ground faults. With high impedance grounds the "ground" point of the circuit can be forced far from ground potential by the combination of switching transients and unbalanced stray capacitance. Capacitance to ground can be added with sufficient magnitude that the stray capacitances become unimportant. This should be minimized to control cost and maintain the circuit response characteristics. Therefore the following requirement shall be applied:

- 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. An exception to the symmetry will be for the plasma maintenance module since its voltage is less than one percent of the plasma initiation voltage. Supplying two symmetrical PIM's instead of one would only increase the cost with no compensating advantage.

CURRENT BALANCING OF COIL SEGMENTS

An OH coil is not a simple solenoid because of the requirement to minimize the OH flux in the plasma region. As a result, the end turns may have 6 to 8 times the diameter of the central turns. It will be difficult, perhaps impossible, to balance simultaneously and exactly the lead effects, the self-inductances, the resistance, and the mutual coupling to other circuits.

It will be necessary to force a current balance between paralleled segments of the coil for at least the plasma maintenance (burn phase) and recovery periods. Therefore, the following requirement and recommendation are applicable:

- 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.

RECTIFIER TYPE

Knowledge of the performance of large tokamak plasmas is not sufficiently advanced to clearly establish whether six pulse rectifiers are an acceptable drive for an OH circuit, or how much filtering might be required. For the purpose of this study we will assume that 6 pulse rectification is acceptable from the standpoint of the plasma. The line driven rectifiers for plasma maintenance can readily be made 12 pulse and will be shown that way.

4.2 CIRCUIT REQUIREMENTS

The preliminary basis for the development of the generator and circuit designs was based on the estimate that the machines would have to absorb 1 GJ from the OH coil over half a second and release the energy back to the coil in the following half second. In the reference design, with 400 turns and 0.124 H, this implies ~ 127 kA initial current.

The best final estimates, based on calculations by the Los Alamos Scientific Laboratory (LASL) and the University of Texas, result in 1 GJ initially stored in the coil (less energy is stored in the machines), and a peak current of 127 kA in the 400 turn coil. The plasma initiation voltage for the dc machine circuit is 187.5 volts/turn from the same calculations. The peak reversal voltage for the dc generator circuit was calculated to be 49.4 kV.

Due to the uncertainties involved in the design of superconducting OH coils, LASL has recommended that the current per conductor in the OH coil be limited to 25 kA. This clearly requires that the OH coil be segmented to operate at reasonable voltage levels. If the OH coil is segmented into an even number of segments, then pairs can be selected, one from the top half of the coil and one from the bottom half such that their characteristics match and they can be driven in parallel with fixed compensation. This permits 50 kA circuits. The separate 50 kA circuits will require active compensation to operate at the same currents since they cannot be exactly matched, particularly in mutual coupling to the plasma and the other poloidal fields.

4.3 DC MACHINE CIRCUITS

Two reference dc machines will be paralleled to handle 50 kA (See Section 5.0), therefore, two pairs of coil segments will be associated with each machine circuit. Since the voltage per machine is approximately 1260 V, four series machines will be used in each machine circuit. More than this is not practical since no machine can be operated at more than 2600 volts above ground with conventional machine design.

From the data of Section 4.2, the number of total ampere-turns required is:

$$400 \text{ T} \times 127,000 \text{ A} = 5.08 \times 10^7 \text{ AT},$$

and the number of volt amperes required for reversal is:

$$39.63 \times 10^3 \text{ V} \times 127 \times 10^3 \text{ A} = 5.0292 \times 10^9 \text{ VA}$$

At 25 kA in the coil conductor this would require 2,032 turns with a peak reversal voltage of 201 kV. The stored energy per machine requires 160 machines. Since they are to be used in eight-machine arrays, 20 circuits of 50 kA are required. The number of coil segments has to be a multiple of 20. Two coil segments at 25 kA are required for each machine circuit to match the 50 kA per array of machines. Therefore, the number of coil segments has to be 40. The number of turns per coil segment will be

$$\frac{5.08 \times 10^7 \text{ AT}}{40 \times 25 \times 10^3 \text{ A}} = 51 \text{ T},$$

and the voltage per coil segment for reversal will be:

$$\frac{5.0292 \times 10^9 \text{ VA}}{40 \times 25 \times 10^3 \text{ A}} = 5.0 \times 10^3 \text{ V}.$$

Since there are 51 T per coil segment, the plasma initiation voltage required is:

$$51 \text{ T} \times 187.5 \text{ V/T} = 9,560 \text{ V}.$$

The plasma maintenance function will require about 1 V/T or 51 V per coil segment.

With these values combined with the ground rules defined in Section 4.1, the first circuit choice for the dc generator energy storage is as shown in Figure 4.3-1.

An alternate dc generator circuit was developed based on series operation as shown in Figure 3.2-3. The required components will be a duplication of those for the reference circuit. A fundamental of this circuit will be to have the same series current in all pairs of OH coil segments. For this, circuit current in the generator ground resistor will be an indication of unequal coil currents. These can be due to variations in the coil inductance, variations of resistance of the plasma initiation resistors, and generator differences. The resistors can be trimmed to offset the inductive and/or resistive variations. Adjusting the generator fields may also be used to minimize the ground current. It is difficult to assess the effect of the mutual inductance since it will not necessarily be the same for all coil segments. Even so the above adjustments may be used to reduce this effect.

The alternate dc generator circuit is shown in Figure 4.3-2. It offers a better method of having the same current in all coil segments. The ground currents will be a fraction of the coil currents and, therefore, will be a better indication of any current difference between coils. For the recommended circuit a shorted turn or shorted coil segment will not produce ground current and, therefore, have no effect on the generator voltage to ground. The same situation in the alternate circuit will produce a ground current which will raise the generator voltage to ground. This may not be all bad since a generator would feed a shorted coil through the ground resistors which would limit the current. The recommended circuit with a shorted coil would not have the generator current limited by the ground resistor.

The cost of the two dc generator circuits is the same. The importance of the differences will depend on the circuit parameters which will have to be evaluated. The recommended circuit was selected primarily because the twenty subcircuits are isolated from each other. Isolation is a fundamental circuit principal which is used to minimize interactions.

For completeness the circuits for the homopolar generators and for the ac machines are shown in Figures 4.3-3 and 4.3-4, respectively.

Typical, one of twenty circuits. Each set of eight dc generators serves two parallel coil segments. The total number of generators is 80, of coil segments is 40. Each resistor, R, has a resistance of ~ 0.096 ohms to produce ~ 4.8 KV for a total initiation voltage of ~ 9.6 KV across 51 turns. Maximum voltage to ground is 4.8 KV.

Figure 4.3-1. DC Generator OH Circuit

Typical, one of twenty circuits. Each end of a pair of coil segments is in series with a circuit, so 20 circuits and 20 pairs of coil segments are in series. The total number of generators is 80, of coil segments is 40. Each resistor, R, has a resistance of 0.096 ohms to produce 4.8 KV for a total initiation voltage of 9.6 KV across 51 turns. Maximum voltage to ground is 4.8 KV.

Figure 4.3-2. Alternate DC Generator OH circuit.

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, 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 4.3-3. Homopolar 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 4.3-4. Round Rotor AC Generator OH Circuit.

5.0 DC MACHINE ENERGY STORAGE

5.1 OPERATION

This investigation of the suitability of the conventional direct current machine for energy pulsing was based on the concept of the machine acting as a capacitor to resonate the energy between the machine and the ohmic heating coil. The choices of machine characteristics were made to best suit the particular ohmic coil considered in the previous study⁽¹⁾.

5.2 APPLICATION

The requirements of this reference coil are:

TABLE 5.2-1
OH COIL CHARACTERISTICS

TOTAL STORED ENERGY	$1 \times 10^9 \text{ J}$
TOTAL NUMBER OF TURNS	400
INDUCTANCE	0.124 H
MAXIMUM CURRENT	$127 \times 10^3 \text{ A}$
INITIATION VOLTAGE	$75 \times 10^3 \text{ A}$
CURRENT REVERSAL TIME	1 S
AVERAGE REVERSAL VOLTAGE	$31.5 \times 10^3 \text{ V}$
PEAK REVERSAL VOLTAGE (FULL SWING)	$49.47 \times 10^3 \text{ V}$
PREFERRED COIL CONDUCTOR CURRENT	$25 \times 10^3 \text{ A}$

It was planned that the mode of operation would be for the dc machine to speed up from standstill to full speed in a half second interval and then slow to stand still in the following half second. It would remain at standstill for the next 50 seconds before repeating the acceleration and deceleration period

again. This mode results in minimum losses, brush wear and required maintenance. The 62 second pulsing cycle is shown in Figure 5.2-1. It should be noted that the plasma initiation voltage is not supplied by the dc machine. The machine functions as the capacitor in the plasma build-up module.

Unfortunately several inherent characteristics of large dc machines prevent their operation at the voltages required for the total coil, nor can a single commutator supply 127,000 amperes. These inherent characteristics would require some sectionalizing of the ohmic coil.

The cycle shown in Figure 5.2-1 has many features favorable for large dc machines. Commutation is the most difficult at high current with high speed and flash-overs are most likely at conditions having high voltages, high currents and weak fields. In this application, the high currents and high voltages do not coincide and saturation can be held to a high level during reversals.

Because the current and voltages follow sine-cosine forms, the energy per generator will be $0.16 \times V_g I_g$ where V_g and I_g represent peak voltages and peak currents respectively.

5.3 MACHINE DESCRIPTION-GENERAL

Large direct current machines have been in use on large blooming and slabbing steel mills since 1905 when they began to replace the huge steam engines that were universal. Since that time thousands of very large dc commutating machines have been in successful service over the world in countless applications where speed control and energy swings were needed.

The large reversing mill drive motor service most nearly resembles the needs of this case. Such motors have large diameter rotors 10, 12, or 15 feet in diameter and cores may reach 100 inches in length. The large piece of steel (hot ingot) enters the rolls and the motor current increases to about 180% of rated current during acceleration and the speed then drops to zero when the ingot clears the rolls. The stored energy is returned to a flywheel MG set and the motor then accelerates in the opposite direction for the ingot to return through the rolls

Figure 5.2-1. Idealized Adaptation of 62 Second Pulsing Cycle for Machine Sizing

to be further reduced. The motors may reverse rotation from base speed to base speed in one second as they pump energy back and forth. The operators usually raise the circuit breaker setting from the specified 275% load to over 300% load and usually operate with peak currents on their motors for each ingot to a value of 300% current rating.

Because of the long abuse of these large machines they are well understood by design engineers and limitations have been well established. It is recognized that such long experience results in conservative designs. In this study we used the upper limits in applying design factors for favorable costs, but none that should result in poor operation, failure or even undue maintenance.

The large dc machine for energy storage will differ some from those reversing mill motors described above, but will have quite similar components. See Figure 5.3-1.

The stationary frame or yoke carrying the main and commutating poles may be from a rolled steel slab or made up of laminated sheets depending on the manufacturers practices.

The stationary main poles support the main excitation field coils and the compensating bars in their pole faces. These poles are made up of riveted laminations as are the commutating poles located between the main poles.

The single air gap between the main pole faces and the armature core will be approximately 0.200 inches wide.

The rotor core will be built of 0.025 inch thick steel lamination segments and will use dovetails or through bolts to mount on the armature spider. Three-eighths inch wide radial ducts will permit the ventilating air to cool the core and coils as it passes from the spider bore to the air gap.

The rotor coils will be held in their slots with glass wedges and the coil extensions will be held against coil supports with glass polyester non-magnetic

FIGURE 5.3-1

banding. Special bracing will be provided to prevent coil endturn movement during acceleration and deceleration. The armature cross-connections will be located at the rear of the machine for ease of bracing and accessibility.

The commutator will be overhung from the armature spider and will have "Vee" end rings with provision for expansion longitudinally with temperature changes during loading and unloading.

The necks (risers) will be of special material and be specially braced to avoid fatigue failures from the cyclic operation.

The spider will transmit no torque to the shaft and is designed to suit. The shaft must support the rotor, but since it transmits no torque it will have no extensions or coupling.

The pedestal bearings are insulated and designed for journal lubrication to suit starting from standstill twice every 62 seconds.

5.4 DESIGN CONSIDERATIONS

5.4.1 OPERATION

Normal direct current machines are designed for momentary loads of 200% and 275% on reversing mills. Due to the cyclic load values on this application it will be designed for its peak load to be 400% of "normal" rated.

5.4.2 COMMUTATION

Because commutation is the primary factor in causing commutator bar burning and brush wear the maximum reactance voltage of commutation during the cycle will be held to limits normally found at peak overloads in service i.e. < 20 volts per bar. This will insure reasonable maintenance. The clearance between the commutating zone and the adjacent main pole tip in the neutral zone between main poles will be in excess of 1.5 inches.

5.4.3 FLASH-OVERS

One of the most destructive failures that can occur on a large dc machine is for an arc to form across the commutator surface between brush arms. It may melt large holes in the commutator surface and into the brush holders.

The normal starting point of such an arc formation is between bars that are connected to a coil under the greatest flux density in the air gap. This peak is caused by a badly distorted main pole flux. Under such conditions a small arc would jump across the mica space between the bars, shorting the bars, raising the next bar to a potential that the arc progresses due to voltage and ionized air. The original flux distortion is caused by the fact that the rotor rotates and its armature reaction averages to a fixed straight line through zero under the middle of the pole to a maximum value at the centerline between poles, while its compensating winding lies in stationary slots in the main pole faces producing a stepped increase in ampere turns rather than a straight line to match the armature reaction. Tests have shown that even with perfect commutation flashovers can form at voltages between bars of 43.7 volts on a motor with 0.040 inches thick mica between bars and at much lower values under operation as a generator. The flux distortions are easily calculated and thus maximum volts per bars are also subject to accurate calculations.

5.4.4 CREEPAGES

The commutator copper surface on direct current machines must be bare for good brush contact. Normally, not only the bars are bare, but the risers and the joints between the risers and the armature coil leads are also bare. The steel rear vee ring is insulated from the bars with mica and other materials for about 3 inches, but it is also bare beyond that distance. Carbon dust continually wearing off the carbon brushes is carried by the air currents back into the area behind the risers and below the front coil extensions. The areas are large and possible creepage paths from the rear end of the bars to "ground" and to the other potential are infinite. Unless the paths are very long and the machine voltage "reasonable," flashovers also occur in this confined space. Fluidized bed coatings on these paths can provide added protection, but even on motors with reduced numbers of poles operating voltages seldom exceed 1600 volts.

5.4.5 HEATING

In a dc machine of this rating the principal losses will be from I^2R in the armature and compensating and commutating windings. The core, stray load, brush I^2R and friction and windage losses are relatively small and deserve no special attention. The excitation losses depend primarily on the saturation of the rotor teeth and the pole face teeth. Thus, a "copper rich" machine with wide slots will have the lowest losses even with increased excitation losses.

5.4.6 COMMUTATOR

The commutator, the heart of the dc machine, must be precisely designed, built and maintained. It will have over 1200 wedge shaped bars on this application with "vee" notches in the end of the bars. Each bar must be separated from the adjacent one with mica plates about 0.060 inches thick. The bars are held only on their ends by insulated steel rings inserted in the "vee" notches. The bars will be approximately 21 inches long and have a width of about 0.250 inches at the top.

For acceptable commutation and brush wear while under all conditions of temperature variation (perhaps 55° C rise with load) and at all speeds its concentricity within 0.002 inches, its truth should be within 0.0001 inches bar-to-bar and the indexing and skew of the bars should not exceed 0.020 inches.

The commutator explains the relatively high cost of direct current machines.

5.5 MACHINE SELECTION

When limits are set on just a few of the factors listed above, the design required is already essentially fixed and there are few options open to the engineer.

5.5.1 AIR GAP FLUX DENSITY

The normal large dc machine operates at an air gap flux density between 60,000 lines per square inch to a Tesla. This provides normal saturation, but also allows some field adjustment by the operator, if needed.

5.5.2 VOLTAGE BETWEEN ADJACENT COMMUTATOR BARS

To avoid flashovers from spike voltages between bars a conservative calculated maximum voltage between bars for a generator would be about 30 to 35 volts.

5.5.3 SPEED, CORE LENGTH, AND ROTOR DIAMETER RELATION

For the given choices if we solve the following equations simultaneously it can be shown that the product of speed, core length and rotor diameter is a constant.

$$\beta_g = \frac{E \times P \times 60 \times 10^8}{2 \times B \times N \times \pi \times D \times L \times C_p}$$

$$\text{Volts/Bar} = \frac{E \times P \times d}{B \times C_p} = 30$$

where:

$$\beta_g = \text{Air gap density} = 60,000 \text{ lines/in}^2$$

$$E = \text{Induced voltage}$$

$$B = \text{Number of commutator bars}$$

$$N = \text{RPM}$$

$$D = \text{Rotor diameter}$$

$$L = \text{Rotor core length}$$

$$C_p = \text{Ratio of effective main pole flux width to pole pitch} = 0.684$$

$$d = \text{Distortion factor due to imperfect compensation} = 1.01$$

$$\epsilon = \text{Stored energy}$$

Solving the equations:

$$N \times L = \frac{4.728 \times 10^5}{D}$$

5.5.4 ROTOR WK^2

For each diameter rotor being considered it is possible to express the WK^2 of the rotor by a formula involving only the core length for the construction considered:

$$D = 120" \quad WK^2 = (398.5 + 19.3 L) 10^3$$

$$D = 144" \quad WK^2 = (804.6 + 33.3 L) 10^3$$

5.5.5 ROTOR ENERGY

Stored energy may be expressed in terms of RPM and WK^2

$$KW \text{ Sec} = 2.31 \times WK^2 \times N^2 \times 10^{-7}$$

5.5.6 ROTOR LENGTH WITH SET DIAMETER

For 120 inch diameter rotors:

$$\epsilon = 2.31 (398.5 + 19.3 L) 10^3 \times N^2 \times 10^{-7}$$

$$\text{from 5.5.3} \quad N = \frac{3940}{L} \quad \text{and solving the equations, then:}$$

$$L = \frac{6.92 \times 10^4 + \sqrt{47.9 \times 10^8 + 0.0572 \times 10^8 \times \epsilon}}{2 \epsilon}$$

5.5.7 ROTOR LENGTH WITH SET ENERGY

If we assume that the stored energy required is $\epsilon = 5 \times 10^6$ Joules per generator, then:

$$L = 25.2 \quad \text{and} \quad N = 156.4$$

If other constraints are not considered, curves may be drawn for that rotor diameter showing D^2L , speed, inertia stored energy versus core length. See Figure 5.5.6-1.

Figure 5.5.6-1. DC Machine Characteristics, 120 Inch Diameter - 20 Pole.

It should be noted that the electrical capabilities of the various combinations have not been established, but general value of maximum speed has been shown.

Similar curves may be drawn for each diameter under consideration. See Figure 5.5.6-2 for $D = 100$ inches and Figure 5.5.6-3 for $D = 144$ inches.

5.5.8 DISCUSSION OF MACHINE CHARACTERISTIC CURVES

The curves have considered the core length and speed combinations to suit the mechanical stored energy, but have not considered the electrical energy that must be furnished to match the inertial energy.

The other restraints described above in 5.4 now become important.

Past practice has shown that large dc machines are well balanced electrically and magnetically if the pole pitch is approximately 18.9 inches, and a neutral zone for commutation between the pole tips of about 6.3 inch is provided; thus, the use of 16, 20 and 24 poles result respectively for 100, 120 and 144 inch rotor diameters. The number of poles fixes the parallel circuits in the rotor and the number of brush arms on the commutator. Of course, other diameter-pole combinations are possible and were considered.

Thus, if an optimum armature winding were developed for the surface area in a pole pitch for the 120 inch machine it would still be the same optimum combination for all three diameters. However, since the number of parallels is the same as the number of poles and because the number of brush arms is also the same, the total current available would be proportional to the number of poles. The voltage induced for the same speed would be the same in all three cases since the number of conductors per pole pitch would not change.

Because the pole pitch space increases if the number of poles for a given diameter is reduced, the number of conductors per circuit increases resulting in increased induced voltage across the circuits. Thus, high voltage dc machines (above about 1000 volts) often have fewer poles and reduced currents.

Figure 5.5.6-2. DC Machine Characteristics, 100 Inch Diameter - 16 Poles.

Figure 5.5.6-3. DC Machine Characteristics, 144 Inch Diameter - 24 Poles.

Many such machines have been built in Europe with voltages up to 1800 volts. These are very heavy machines with deep cores and yokes and massive poles.

Because of the high currents needed on these units and the risks of creepage flashes with higher voltages, the values of 1,250 volts peak and 25,000 amperes peak were chosen. This provides electrical stored energy of $25,000 \times 1,250 \times 0.16 = 5 \times 10^6$ Joules per generator. This rating matches the capability of the 120 inch diameter, 25.2 inch long core at 156.4 RPM unit shown in Figure 5.5.6-1. A complete design study verifies the correctness of the choice. This rating requires 200 machines to meet the requirement of 1×10^9 Joules stored energy.

The smaller 100 inch diameter machine with only 16 poles and circuits is suitable for 20,000 amperes and 1,250 volts or 4×10^6 Joules with a 24 inch long core and 198 RPM. This requires a total of 250 units.

The larger 144 inch diameter unit with 24 poles would be suitable for 30,000 amperes and 1,250 volts or 6×10^6 Joules at 125 RPM and 26.5 inch long core. This would require 167 units.

5.6 OPTIONS

5.6.1 LARGE POLE PITCH

Design for larger pole pitches (by reducing the number of poles) to permit higher voltages. This would result in reduced speeds to meet the stored energy requirements since WK^2 values would be increased.

Creepage problems would be increased.

5.6.2 HIGHER AIR GAP FLUX DENSITIES

Operate at higher air gap flux densities. The number of conductors (and commutator bars) is fixed by the volts per bar limit and the increased flux would permit a slight reduction in core length with a higher speed, but with the same voltage and current as before.

5.6.3 INCREASING THE NUMBER OF COMMUTATOR BARS

Avoid volts per bar problems by increasing the number of bars.

This can be done by using duplex windings and providing twice as many parallel circuits in the rotor winding. The doubling of the number of conductors results in loss of copper space due to the conductor insulation added by the additional conductors. The additional number of commutator bars is costly. The sharing of current between the two winding sometimes results in problems.

5.6.4 USE OF A "PUNGA" WINDING

Avoid volts per bar restraints by the use of a "Punga" winding. This cuts the volts per bar in half by furnishing double the number of commutator bars and connecting every other bar to the rear of each coil by connections through the spider. This requires transposed conductors in the rotor slots. The cost is prohibitive.

5.6.5 "COPPER RICH" MACHINE

Design a "copper rich" machine by very high saturation in the rotor and stator teeth to hold losses to a minimum. This is desirable.

5.7 AUXILIARIES

5.7.1 EXCITATION

The excitation needs per generator will not exceed 32 kW. While some adjustment should be provided, the field current will be constant during current reversals. Sufficient control should be provided to remove the excitation during the burn period to conserve energy.

5.7.2 VENTILATION

The low velocity of this dc machine will not provide adequate cooling to prevent accumulating temperatures as the cycles repeat indefinitely. It is proposed that top mounted fans be provided to force limited air through the machines to permit stable temperatures. Air would be taken from the "room" or

into ducts for discharge outside. For this analysis it was assumed that the dc machines would be "out-doors" and front and rear endbells were shown. See Figure 5.3.1.

5.7.3 LUBRICATION

The bearings provided will be self lubricating and no external cooling would be necessary. However, since the machine will be at standstill for relatively "long" periods between pulses it is believed a "drip" type auxiliary system should be provided to insure that oil is on the journals at all times. This has been included.

5.8 DC MACHINE DESIGN SUMMARY

TABLE 5.8.1

NUMBER OF UNITS	160 (80 w/dual rotors)*
PULSING MVA	31.2
"K" AMPERES	25
"K" VOLTS	1.25
POLES	20
MAXIMUM RPM	156.4
WK ²	$0.88 \times 10^6 \text{ # ft}^2$
ENERGY	$5 \times 10^6 \text{ Joules}$
ROTOR DIAMETER	120 inches
ROTOR LENGTH	25.5
BRUSHES/ARM	10
BRUSH SIZE	2 (1/2 x 1-3/4)
WEIGHT	141,000 lbs.
OUTLINE DIMENSIONS	126 inches x 190 inches
LOSSES DURING PULSE AS % JOULES TRANSFERRED	
COST PER SINGLE UNIT	\$448,000

*Note that the dc machines actually store only ~ 0.8 GJ out of the 1 GJ originally in the coil due to the energy consumption of the initiation circuit.

6.0 ENERGY STORAGE COSTS

6.1 EQUIPMENT PRICE ESTIMATES

The ideal method of estimating prices is: 1) carry out a design effort sufficient to prepare detail drawings, develop complete parts breakdowns, and identify manufacturing methods; 2) prepare price estimates on all parts and materials; 3) identify all machine and labor operations and estimate the price for these; 4) total parts, materials, machine, and labor prices; 5) add overheads and profit margins. The effort required to use this ideal approach could not be included within the scope of this study. Alternate means were necessary to estimate the equipment prices. Fortunately there are many similarities between the equipment required for an EPR OH circuit using dc generators for energy storage and EPR OH circuits using other energy storage systems. Consequently, if the comparable elements are estimated on a common basis, a fair comparison is achievable without detailed pricing on a fine basis.

The principal interest is in the relative cost of the energy storage system using dc generators as compared to systems using either homopolar generators or ac generators. Since reporting on the latter two systems, we have re-analyzed the prices for the power electronic equipment⁽¹⁾. This evaluation resulted in the elimination of the first-of-a-kind factors with a resultant large reduction in estimated costs for the power electronic packages. For fair comparison, one homopolar generator energy storage system and one ac generator energy storage system have been recalculated and the revised costs included in this report.

The plasma maintenance modules supply the burn power. These utility power line driven rectifiers have a low output voltage at high current. This reduced voltage lowers the voltage rating of the rectifier devices but not the required number of devices. The component price variation with voltage rating is small. Consequently, these low voltage rectifiers cost more than high voltage

rectifiers of the same power rating. Back to back rectifiers are required because of the output current reversal. For the dc generator circuit there will be one plasma maintenance rectifier per circuit as indicated in Section 4.1.

The basic elements of an SCR switch, exclusive of commutating circuits, are the same as those for a rectifier even though the configuration is topologically different. The number of SCR devices required is significantly different from that required for a rectifier when both are compared on the basis of the dc currents and voltages. From the voltage standpoint, the voltage stand-off rating of a three phase bridge rectifier is twice the ac peak line to line voltage or ~ 2.1 times the dc open circuit voltage. The ratio between rated SCR device voltage and the maximum operating voltage can be reduced from the 2.5 used for a line driven rectifier to 1.7 or less since all these switches transfer current to a parallel circuit element which then controls the peak voltage. This is different from a circuit breaker application. The average dc current for a device used in a 3 phase rectifier is about $2/3$ the dc rating of the same device so that two parallel devices are required in a switch to carry the same current as three "parallel" devices carry in a rectifier. Using these factors, the cost of the large SCR switches can be calculated from the price of the "equivalent" rectifiers. This ensures that comparable pricing is used for switches and rectifiers.

The cost of commutating circuits has been taken as $1/3$ the cost of a one way SCR dc switch based on the limited available data. Where switches are two way, we have assumed that snubber circuits, buswork, etc. are common.

In developing cost, comparable ratings must be used for the systems. In the case of the dc generators its total ratings will be the same as that of the dc homopolar generators. Therefore, the total MVA of the dc generators will match that of the homopolar machines. This reduces the number of required dc generators from the 200 indicated by approximate calculations to 160 single armature generators or 80 double armature generators.

6.2 SYSTEM PRICE ESTIMATES

Table 6.2-1 contains the cost breakdown for a dc generator energy storage circuit for the reference EPR ohmic heating system. Table 6.2-2 is the revised cost breakdown for the homopolar energy storage circuit. Table 6.2-3 is the revised cost breakdown for the ac generator (round rotor) energy storage circuit. Table 6.2-4 compares the total cost of these systems.

For the homopolar circuit the revised cost is still about 5×10^6 dollars more than that of the ac generator circuit, even though the total cost are each approximately 100×10^6 dollars less than previously reported. For each system the costs other than the generators were almost equal. The revised costs reduced both of these by the same portion so that the total cost differential did not change.

These tables reveal various facts about the different systems. The homopolar system and the dc generator system have the same subsystems, each of which has the same total subsystem rating. The homopolar system has six circuits against 20 for the dc generators. The subsystems in each circuit for the homopolar system have higher ratings and, therefore, an economy of scale cost advantage which is $\$7.4 \times 10^6$. This excludes generator cost.

The dc generators have two factors which significantly increase their cost over that of the machines of the other systems. First, the rating of the biggest dc generator is considerably less than that of either an ac machine or a homopolar generator. Consequently, the dc generator has an economy of scale cost disadvantage. For comparison, the dc generator is rated at 62.8 MVA while a homopolar can handle 850 MVA or 13.5 times as much power. This is why 80 dc generators are required as against 6 homopolar generators. The other factor affecting the generator cost is the expensive commutator. The commutator is built up of bars of hard copper insulated by mica segments. The mica segments and copper bars are clamped between V-clamps and insulated therefrom with mica. The surface requires precise machining for good commutation.

The dc generator system requires 40 resistor switches as compared to 24 for the homopolar system. This increase in segmentation will increase the cost for these switches by almost 10 percent.

Resistors have a long established technology. The rating for the dc generator system is the same as for the homopolar generator system. The cost will be the same even if the segmentation is different.

The generator switches increase from six for the homopolar system to 40 for the dc generator system. The reduced economy of scale will increase the switch cost for the dc generator system by over 25 percent.

6.3 ALTERNATE DC GENERATOR

An alternate would be to take advantage of manufacturing economies of a standard production generator. The generator selected for the evaluation is the largest made by General Motors - type EMD D79GB shunt motor - industrial dc generator. It has a nominal rating of 750 volts and 750 amperes continuously, 1150 amperes intermittent. It has a 920 volt capability at no load. This drops to 850 volts at 750 amperes. Since it is not common to pulse rate machines for one second pulses, it was assumed the generator would handle a peak of five times rated current or 3750 amperes peak for one second. This is 476 amperes RMS for two pulses in 62 seconds which is well below the 750 amperes dc rating.

The evaluation of an energy storage system using the standard production dc generator is based on the following.

- General Motors No. EMD D79GB shunt motor
- Assume the machines can be arranged in arrays which will use the same equipment as the dc generator system in Table 6.2-1.
- Assume the generator can handle a one-second peak pulse of five times rated current - 3750 amperes. Peak volts will be 920 volts.

TABLE 6.2-1

EPR OH CIRCUIT - D C GENERATOR ENERGY STORAGE COST

See Figure 4.3-1&2

Quantity	Item	Rating	Quantity x Rating	Unit Cost	Total Cost
80	D C Generators 2 Bearing-double armature	62.8 MVA (25kA, 1260 V) x 2	5030MVA	$\$0.830 \times 10^6$	$\$ 66.4 \times 10^6$
40	Generator Switches	125.7MVA 50kA, 2520 V	5030MVA	$\$0.619 \times 10^6$	$\$ 24.8 \times 10^6$
20	Line Rectifiers	2.55MVA 50kA, 51 V	51MVA	$\$0.258 \times 10^6$	$\$ 5.2 \times 10^6$
40	Resistor Switches, 1/2 Diode 1 Comm. Circ./Sw	240MVA 50kA, 4800 V	9600MVA	$\$0.809 \times 10^6$	$\$ 32.4 \times 10^6$
40	Resistors	12MJ/pulse 50kA, 4800 V	480 MJ/pulse	$\$0.056 \times 10^6$	$\$ 2.2 \times 10^6$
	TOTAL				$\$131.0 \times 10^6$

Cost are in 1977 dollars based on fully developed manufacturing capability.
 The 1978 generator cost were adjusted to 1977 dollars by assuming an 8 percent
 77/78 escalation.

TABLE 6.2-2

EPR CH CIRCUIT - HOMOPOLAR ENERGY STORAGE COST 1

See Figure 4.3-3

Quantity	Item	Rating	Quantity x Rating	Unit Cost	Total Cost
6	Homopolar Generators	850MVA 200kA, 4.25kV	5030MVA	3.06 x 10 ⁶	18.4 x 10 ⁶
6	Generator Switches 2 Comm. Circ/Sw	350MVA 200kA, 4.25kV	5030MVA	3.17 x 10 ⁶	19.0 x 10 ⁶
24	Line Rectifiers	2.125MVA 50kA, 42.5 V	51MVA	0.257 x 10 ⁶	6.2 x 10 ⁶
24	Resistor Switches, 1/2 Diode, 1 Comm. Circ/Sw	400MVA 50kA, 8kV	9600MVA	1.24 x 10 ⁶	29.8 x 10 ⁶
24	Resistors	20 MJ/pulse 50kA, 8kV	480 MJ/pulse	0.0934 x 10 ⁶	2.2 x 10 ⁶
	TOTAL				<u>\$75.6 x 10⁶</u>

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

TABLE 6.2-3

EPR OH CIRCUIT - A C GENERATOR ENERGY STORAGE COST 1

See Figure 4.3-4

Quantity	Item	Rating	Unit Cost	Total Cost
2	A C Generators (Round Rotor)	1979MVA 2 x 40.8kA, 14kV	6.48×10^6	13.0×10^6
4	Generator Rectifier	950MVA 50kA, 19kV	5.74×10^6	23.0×10^6
8	Generator Rectifier Switches	475MVA 50kA, 9.5kV	1.37×10^6	11.0×10^6
2	Generator Drives	2MVA 18.6kVdc, 107A	0.40×10^6	0.8×10^6
4	Line Rectifiers with Transformers	12.75MVA 50kA, 255V	0.34×10^6	1.4×10^6
8	Resistor Switches, 1/2 Diode 1 Comm. Circ./Sw	925MVA 50kA, 18.5kV	2.51×10^6	20.1×10^6
8	Resistors	27.8MJ/pulse 50kA, 18.5kV	0.13×10^6	1.1×10^6
	TOTAL			$\$70.4 \times 10^6$

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

- Cost - \$23,300 in 1977 dollars (each) including blower for forced ventilation.
- A flywheel will be added to each machine which will match the mechanical storage capacity to the electrical energy. Assume the flywheel adds 20 percent to the machine cost. Cost - \$27,960 per generator with flywheel in 1977 dollars.
- Number of generators = $\frac{5030 \times 10^6 \text{ VA}}{920 \text{ V} \times 3750 \text{ A}}$

= 1458 generators
- System cost

1458 generators	$\$40.8 \times 10^6$
Associated equipment	$\$64.6 \times 10^6$
Total	$\$105.4 \times 10^6$

The cost indicates there can be a saving by using standard production generators when compared to the dc generators per Table 6.2-1. The quantity (1458) of generators is likely to have higher installation and maintenance costs. This was not an in depth evaluation. The current pulse rating will require verification. The associated equipment is based on having 20 circuits - the same as for Figure 6.2-1. This also will require verification.

TABLE 6.2-4

COST COMPARISONS OF ENERGY STORAGE SYSTEMS
FOR EPR-OH CIRCUIT

	AC GENERATOR ENERGY STORAGE COST 1 (REVISED COST)	HOMOPOLAR ENERGY STORAGE COST 1 (REVISED COST)	DC GENERATOR SYSTEM
COST OF ENERGY STORAGE MACHINES	$\$13.0 \times 10^6$	$\$18.4 \times 10^6$	$\$66.4 \times 10^6$
COST OF ASSOCIATED EQUIPMENT	\$57.4	$\$57.2 \times 10^6$	$\$64.6 \times 10^6$
TOTAL	$\$70.4 \times 10^6$	$\$75.6 \times 10^6$	$\$131.0 \times 10^6$

Costs in 1977 dollars are based on machine characteristics to best suit the particular ohmic heating coil considered in the previous study WFPS-TME-038, November 1976.

7.0 POTENTIAL FOR COST REDUCTION

The objective of this study was to evaluate the potential of dc machines as currently manufactured for application to OH energy storage systems. Having obtained the results reported in Section 6.0, it became clear that we should evaluate the potential of dc machines beyond current design practice.

7.1 FACTORS LIMITING ELECTRICAL SIZE

The principal limitation on electrical size is the limit on peak volts per bar (differential voltage between bars) on the commutator. The limit is established by flashover or arcing over the commutator. Design practice provides margin between peak bar to bar voltage and the flashover limit. The flashover limit is an approximate empirical value set by past (bad) experience.

There are two principal causes of flashover. Some amount of sparking normally occurs as the trailing edge of the brush leaves the commutator bar. In a well designed machine this is small and quickly extinguishes. However, these tiny arcs leave behind a zone of air containing a relatively large number of ions (oxygen, nitrogen, copper, carbon). If the voltage between bars after the brush clears the gap is sufficient to accelerate the ions and buildup the ionization then flashover occurs. The second mechanism results from deposition on the bar to bar insulation of conductive dust from the brushes and to a minor extent from the commutator surface. This leads to a phenomenon called surface tracking. Tracking is a mixture of conduction through particles on the surface and tiny arcs between particles. This ultimately results in complete electrical breakdown across the insulator surface and flashover of the commutator.

The volts per bar limit not only constrains machine voltage, but also machine current. The commutation (switching) of current from bar to bar develops voltages due to di/dt in the windings. The residual current (which causes the small sparking at the trailing edge of the brush) produces voltage due to the

interruption of the arc. These voltages increase with increasing current. Thus the volts per bar limit tends to set volt ampere limits on the machine design.

The winding inductance including the end turn effects contribute to current limits, since the winding inductance produces the commutating and spark interruption voltages.

The total voltage which can be generated appears to be limited by two factors. The total voltage appears across a group of commutator bars. The conductive dust tracking breakdown can be produced by the total voltage acting across the insulating gaps in series. If one of a series of insulating gaps begins to conduct, the voltage stress on the other gaps increases, leading to breakdown across the whole group. The second factor is that the total voltage cannot be increased by simply increasing the number of commutator bars. This, one would expect, would lead to a longer total tracking path (more insulators in series) and be within the volts per bar limit. The limitations of shipping place an upper limit on the diameter of the commutator, hence on the number of bars.

7.2 POSSIBLE DESIGN ALTERNATES

The most promising design alternate is a means for raising the volts per bar limit. To accomplish this, the insulation directly between bars is eliminated. Air is forced to flow radially outward between bars. This air flow sweeps away the ions formed by sparking and thus inhibits breakdown due to this cause. The air flow also sweeps away the conductive dust to a filter system. This cleanup plus the absence of an insulator surface on which to deposit inhibits tracking breakdown. Design of the commutator bar supports may have to be modified to maintain long leakage paths.

A test was run in Europe utilizing a version of the ventilated commutator discussed above⁽⁹⁾. Operation was achieved at ~ 10 times the normal volts per bar level. Operation at 10 times normal voltage was not completely satisfactory due to roughness and out-of-round condition of the commutator. The test machine operated at low current only so that commutation problems may not have been fully evident. An offset in the center of the commutator bar was provided to

increase commutation time. If in fact a factor of 10 can be achieved, then a given rotor diameter and commutator size machine could produce several times the volt amperes by increasing the armature core length to the limit permitted by commutation reactance. Each machine would thus be substantially larger in electrical size, and a significantly smaller number of machines would be required for a given service.

A more advanced design would reduce the winding inductance by essentially placing the rotor windings in the air gap. This would also provide room for some increase in copper cross section to either increase capacity or reduce losses. Since the air gap would be several inches instead of 0.2 inches, superconducting field coils would be required to provide the additional ampere turns. The field problems around the brushes would be substantially less than for homopolar machines with superconducting field windings because of the different field orientation.

Finally, larger machines could be manufactured to be assembled in the field to avoid limitations imposed by shipping. Final machining in the field would require development of a special machine tool, along the lines of the one Westinghouse uses for on-site truing of turbine-generator journals.

8.0 CONCLUSIONS

8.1 SYSTEM COST

The OH system cost, Tables 6.2-1 through 6.2-4, are strongly dependent on an economy of scale factor. The dc generator system requires 80 machines and costs 73 percent more than the homopolar generator system which has six machines. It in turn cost ten percent more than the ac system which has only two machines. The major cost of the latter two systems comes from the power supplies and the switches. The dc generator costs are 51 percent of its total system cost. None of the costs includes any development since the object has been to determine the potential of each energy storage system.

The essential conclusion is that the energy storage systems with just a few machines have the least cost and that the cost of switching dominates these costs.

8.2 FLEXIBILITY

The dc generator can carry current in either direction so it is capable of handling the current reversal. It handles the voltage reversal automatically by rotating in the opposite direction. An option for voltage reversal is to reverse the field. For this there must be adequate time to accomplish the reversal. By contrast the ac machines have their power fed through a rectifier bridge which carry only unidirectional current. A second bridge of opposite current polarity is required in order to handle a current reversal.

There is flexibility between the voltage and equivalent capacitance of a dc machine. The stored energy will be a function of the machine speed. For a given peak energy (speed) a change in the field will produce a proportional voltage change which will be offset by a change in the equivalent capacitance.

8.3 RELIABILITY

The reliability of the dc machines is expected to be similar to that of today's dc machines. The losses of the conceptual design are within acceptable limits and deserve no special attention. The commutators of dc machines are subject to flashovers, a situation which is difficult to assess. However, the peak voltage occurs at zero current which minimizes the possibility of flashovers. From past experiences with brushes, it is anticipated that dc generators will not achieve the reliability of ac machines plus rectifiers.

8.4 MAINTAINABILITY

Since dc machines have a large number of brushes, the amount and frequency of maintenance will be high when compared to ac machines with their rectifiers.

8.5 DEVELOPMENT

The dc machine as contemplated in this report has been verified in the industry and no additional development is required for the requirements selected for it.

However, it may be possible by new developments to obtain higher peak ratings per machine if the phenomenon of flash-over and commutation are studied in greater depth. These new investigations would involve the commutator and commutation phenomena primarily. Following successful development testings a prototype large machine would be required to completely verify the design and manufacturing principles.

8.6 CONCLUSIONS

The dc machines can meet the EPR OH electrical requirements as defined for this study. If they are designed by today's standard approach, their total system cost will be significantly more than either of the other systems - 86 percent more than that with ac machines and 73 percent more than that with homopolar machines.

The relative circuit simplicity and reduction in total component count in the circuits would make dc machines attractive if the size and cost limitations can

be overcome. We believe that the size limitations can be overcome at the cost of development of new design methods, particularly the vented commutator. This will result in cost reductions due to economy of scale, and further reductions since the commutator size and cost will be reduced even further. A design study will be required to ascertain the maximum potential for cost reduction.

9.0 RECOMMENDATIONS FOR DC GENERATOR DEVELOPMENT

9.1 COST CONSIDERATIONS

The 80 dc machines of 62.8 MVA cost five times that of the ac machines. It is apparent that these costs must be reduced to be competitive. It should not be necessary to match that of the ac machines. The cost of the commutator will prevent this. If the dc generator cost can be reduced by a factor of 3 or more, the system cost will be close enough to make a selection on merit. The development of dc machines of comparable ratings should make them competitive because of economy-of-scale.

9.2 ENERGY STORAGE SYSTEM CONSIDERATIONS

- An OH circuit with dc machines is simpler to control and has fewer components than a circuit with ac machines.
- The total circuit cost with fully developed large machines is probably about the same for ac, dc, and homopolar. Consequently, the choice of machines can be made on grounds other than cost.
- DC machines are used in industry. Therefore, the development and manufacturing of new dc machines for fusion power should have further applications. It may be possible to share development cost and manufacturing facilities with other users.
- Large dc machines would have a better current-voltage match to superconducting OH coils than homopolars.
- DC machines (and homopolars) allow greater flexibility in substituting mechanical switches (if developed) than a system with ac machines.

- DC machines are readily available in small sizes for coil and switch development work.
- Once the dc machine field is set the generator will act as a fixed capacitance, whereas the ac machine capacitance is subject to the capability of the control circuit to continually phase shift the converter correctly while both the voltage and frequency are changing. The fixed capacitance will improve the testing repeatability of this parameter, thereby allowing better evaluation of other variables.

9.3 RECOMMENDED DC MACHINE DESIGN

To increase the peak power rating of a dc machine will require a design with increase voltage and/or current capabilities. Recommendations to accomplish this are:

- Operate the commutator in either a CO_2 or an SF_6 atmosphere which will withstand higher voltages.
- Blow clean air (or other gas) on the commutator so as to prevent brush carbon collection which will short out adjacent bars, thereby causing a flashover.
- Design commutator so clean air (or other gas) can be blown between bars. The spacing and creepage should allow higher operating volts per bar. The air flow should prevent collection of carbon dust and the resultant flashovers.
- Locate the armature coils in the air-gap in order to both reduce the generator inductance and to improve the cooling of the conductors.

9.4 ALTERNATE DC MACHINE DESIGNS

An alternate would be to use a new design concept such as a superconducting heteropolar motor which is a Westinghouse proprietary design. Capabilities of 250 to 500 MVA have been projected for this machine. Another new concept is the Segmented Magnet (Segmag) motor. In this the armature coils are segmented; that is, they are not connected in the armature, but they are tied together in series-parallel combinations by way of the brushes. See reference (3) for details.

9.5 RECOMMENDED DC GENERATOR DEVELOPMENT OBJECTIVE

The ultimate objective is to develop large dc generators capable of competing with the largest ac machines for OH energy storage. A 250 MVA generator would be an appropriate goal. Possible peak rating for this are:

KV	5.0	10.0
KA	50.0	25.0

The 5 to 10 KV rating is four to eight times the 1260 volts of the 31 MVA generators. The object of the 5 KV at 50 KA (or 10 KV at 25 KA) is to take advantage of the benefits of scaling and design innovations to achieve an economically competitive machine with the advantages of the dc system. It is recommended that in initial prototype be built with about half of this rating. The object of the prototype will be to perfect the design innovations necessary for increasing dc generator ratings. It is further recommended that the knowledge gained from the first prototype be used for developing and building a second unit with a rating of the order of 250 MVA or larger if the testing program justifies a larger unit. The first step in this process would consist of small scale experiments to verify the design principle and conceptual design and costing of an advanced large dc machine.

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