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# Impact of Uniform Electrode Current Distribution on ETF

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Work performed for  
**U.S. DEPARTMENT OF ENERGY**  
**Fossil Energy**  
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Prepared for  
Twentieth Aerospace Science Meeting sponsored by  
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Abstract

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A basic reason for the complexity and sheer volume of electrode consolidation hardware in the MHD ETF Powertrain system is the channel electrode current distribution, which is non-uniform. If the channel design is altered to provide uniform electrode current distribution, the amount of hardware required decreases considerably, but at the possible expense of degraded channel performance. This paper explains the design impacts on the ETF electrode consolidation network associated with uniform channel electrode current distribution, and presents the alternate consolidation designs which occur. They are compared to the baseline (non-uniform current) design with respect to performance, and hardware requirements. A rational basis is presented for comparing the requirements for the different designs and the savings that result from uniform current distribution. Performance and cost impacts upon the combined cycle plant are discussed.

Introduction

Due to the combined Faraday and Hall fields within the channel, every anode and cathode voltage is different from its neighbor. This unique voltage must be accommodated and maintained by the consolidation network if power is to be extracted from the gas in an optimal fashion. In a Faraday generator, the individual electrodes must be isolated from one another and see a separate load. Their currents must also be controlled, so that local disturbances within the generator are limited in their power dissipation and do not upset its stability.

When the Faraday generator is diagonally connected, current from the upstream cathodes are routed to the downstream anodes that are at the same voltage via a connection that crosses the channel diagonally. This is equivalent to putting the Faraday sources in series. If the generator current profile is not axially uniform (constant load factor generator, for example), the diagonal connection cannot be a simple cathode-to-anode tie, since the upstream cathode current is usually greater than the downstream anode current. To make the diagonally-connected generator to perform as a Faraday machine, a summing junction must be provided in the diagonal connection to remove or make up the difference in current.

Non-uniform generator current profile is a feature of the open-cycle linear MHD generators defined by previous studies for utility application, including the MHD-ETF (Reference 1). The ETF consolidation network (fig. 1), described in detail by the CDER (Reference 2), is a complicated

system because it must accommodate this non-uniform current profile. Using the consolidation methods developed by AERL, groups of eight electrodes each are consolidated together for current control and then diagonally connected. At each diagonal tie point (serving the eight-electrode groups) a current injection/bleed element is introduced to provide the necessary current variation. Additional stages of consolidation are then used to distribute makeup/bleed current to each of these tie points.

If the channel design, however, was changed to provide uniform electrode current distribution over the entire generator length so that all electrode currents were equal, a considerable savings could be realized in the consolidation network. This is because the diagonal connections from cathode-to-anode would no longer need the summing junctions since all currents are the same. Furthermore, Demirjian and Quijano (Reference 3) have shown that electrode current control can be accomplished by controlling only the diagonal currents, using transformer coupling mechanisms similar to those formerly used to consolidate the adjacent electrode segments. The hardware required is equivalent to only a single level of consolidation. By employing uniform electrode current distribution, it is possible to eliminate several levels of consolidation from every cathode to anode connection in the diagonal traverse and to minimize the segmentation required.

MHD Channel Comparisons

In order to assess the performance impact of incorporating uniform current distribution as an ETF design feature, a channel design and performance analysis was carried out (Reference 4), and followed with a combined cycle MHD/bottoming plant simulation. Three cases were considered for comparison:

CASE I - The reference case, namely the ETF channel described by the CDER. This channel is a 12 meter, variable load factor Faraday machine whose peak Hall field is limited to 2500 volts/meter. Its design (including selection of channel length) is optimized to yield maximum net electrical power from the ETF combined cycle plant.

CASE II - This channel design is an attempt to provide uniform current distribution without exceeding the limits imposed on the reference design. The electrode current is held constant until the peak Hall field limit, 2500 volts/meter, is reached. Then it is allowed to decline so that this limit is not exceeded.

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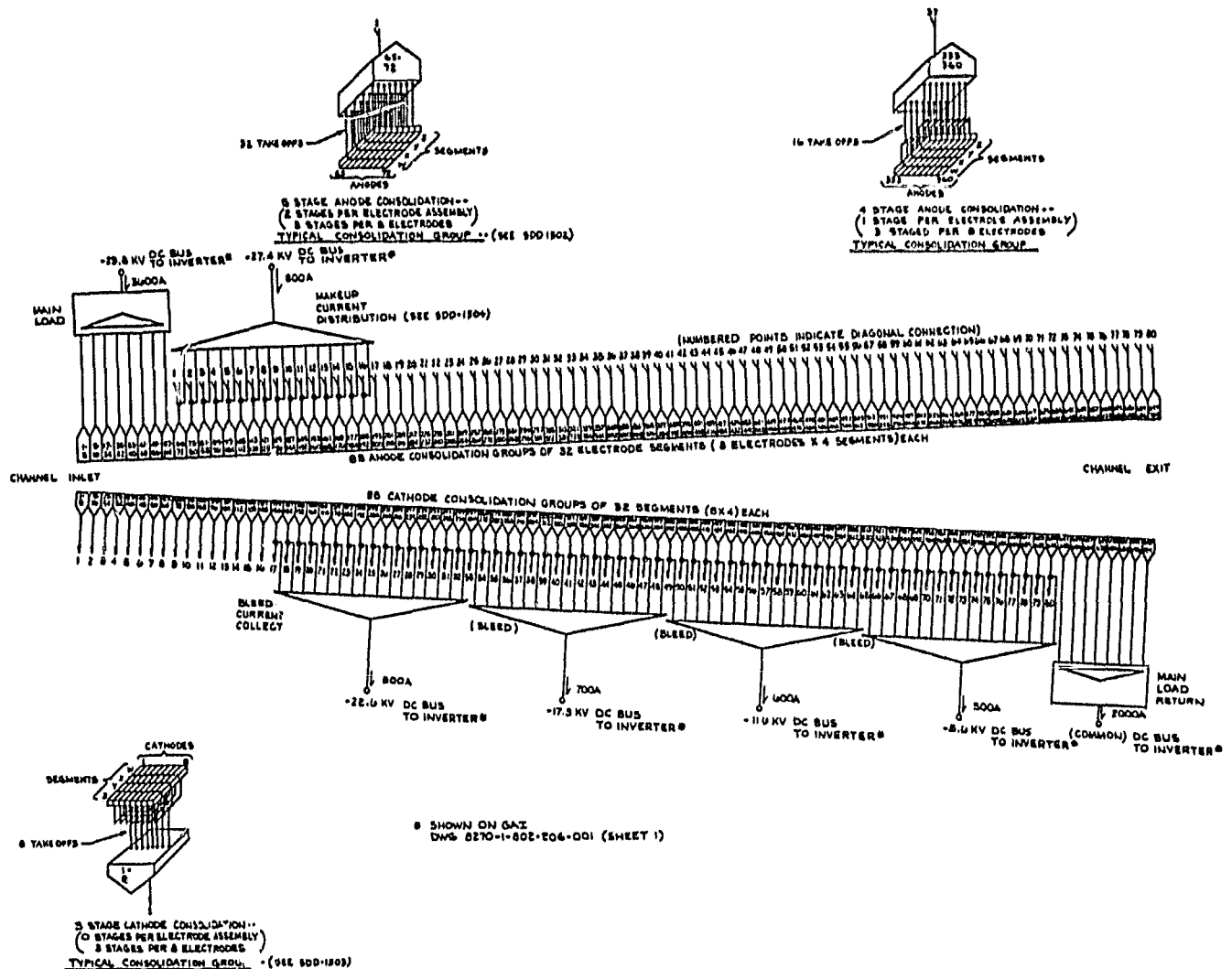


Fig. 1 ETF-MHD Generator Consolidation Network Connection Diagram.

CASE III - This design forces uniform current distribution throughout the entire channel. The 2500 volt/meter Hall field limit is exceeded. All three cases were designed to the same channel length and magnet field profile. The electrode pitch was not changed, even though the channel lofting varied. Mass flow and thermal inputs were kept the same. Cases II and III were not optimized and, therefore, only serve to illustrate changes associated with uniform current distribution. Table 1 summarizes the three cases.

Using the data from the channel design and performance analysis, the electrical characteristics of the channels can be shown by profile plots of electrode voltage and current as a function of axial position. These profiles are what the consolidation networks must accommodate and maintain. The Hall gradient (from Reference 4), also plotted with position, is a measure of how heavily the interelectrode gaps are stressed.

In Case I, shown in Figure 2, the stress is kept below the accepted safe limit by increasing load factor as the channel is traversed. The current is at its peak near the inlet and falls to nearly half that value at the exit. Since the exit end is grounded, the first anode is the most negative, and anode voltage does not lower to the first cathode voltage level until about a meter past the inlet. The voltages taper parallel to each other downstream with nearly constant slope, since the Hall gradient is held constant. In order to limit the power dissipated by shorting between adjacent electrodes and because electrode current reaches a peak of 75 amperes near the inlet, the anodes in this region are split into four segments. Due to the variation of electrode current along the generator length, no equipotential cathode to anode connection can be made without adding or removing current from that connection.

Table 1 Summary of ETF Channel Designs for Uniform Electrode Current Distribution Comparison.

Channel Design	Case I baseline, maximum net electrical power extraction from plant, maximum Hall field 2.5 kV/m, non-uniform electrode current distribution	Case II uniform current distribution until 2.5 kV/m Hall field limit is reached	Case III uniform electrode current distribution throughout channel, Hall field limit is ignored
Channel Length	11.98 m	11.99 m	12.00 m
Mass Flow	161.1 kg/sec	161.1 kg/sec	161.1 kg/sec
Volume % O <sub>2</sub>	30	30	30
Thermal Input	539.81 MW <sub>t</sub>	539.01 MW <sub>t</sub>	539.81 MW <sub>t</sub>
Combustor Press.	4.5 atm	4.0 atm	4.2 atm
Inlet Mach #	.89	.89	.89
Peak Hall Field	2.5 kV/m	2.5 kV/m	3.5 kV/m
Exit Stagnation Pressure	1.104 atm	1.105 atm	1.104 atm
Temperature	2339°K	2353°K	2348°K
Channel Heat Loss	20.96 MW <sub>t</sub>	21.65 MW <sub>t</sub>	22.70 MW <sub>t</sub>
Net MID Power	89.5 MW <sub>e</sub>	86.5 MW <sub>e</sub>	85.1 MW <sub>e</sub>

Case II, shown in Figure 3, shows the effects of forcing uniform current distribution, and simultaneously imposing an upper limit on the Hall field. Since current in this case is fixed (no peak), anode/anode fault power can be limited by dividing into only two segments. Also, the Hall gradient rises more slowly than in Case I. The generator is not as heavily loaded at the inlet, and so Faraday voltage is higher but Hall voltage is less. Less power is extracted from the inlet region. The 2500 volts/meter Hall gradient limit is eventually reached near mid-channel, however, and in order to prevent it from being exceeded the current must be lowered.

Case III, (Figure 4) represents the effect of uniform current distribution without imposing the Hall limit. Electrode currents throughout the generator are equal, but at the expense of a Hall field that exceeds 3500 volts/meter. This occurs near the channel exit, however, not the inlet region where electrode damage usually occurs. Due to the varying channel load factor and Hall gradient that uniform current distribution imposes, the anode and cathode voltage lines are not nearly so parallel as in Case I, nor do they show constant slope. The axial distance (or number of electrodes between) cathode and anode at the same potential varies considerably along the generator length. This means that, as the diagonal connection angle changes, some cathodes will have to be omitted from connection and taken out separately. These cathodes, called bleed cathodes, occur every seven or eight electrodes with this channel.

Case II and Case III are departures from Case I, which was carefully optimized with respect to net electric power output from the combined cycle plant. Generator performance is reduced, and when electrode currents are forced equal over the

entire generator length, the exit end Hall gradient is approximately one and one half times the allowed limit of the baseline channel. Comparison was made only at ETF size, however, and not over a range of channel sizes. Demirjian and Pian (Reference 5) performed comparisons at 500 MW that also indicated a reduction in performance for the uniform current case but do not indicate an excessive Hall field. Therefore, it is premature to conclude that uniform current distribution always degrades channel performance and safety factors. Similar design studies, performed at a larger channel size (and volume) may show less severe degradation and perhaps make uniform current distribution a more attractive feature as channel size is increased.

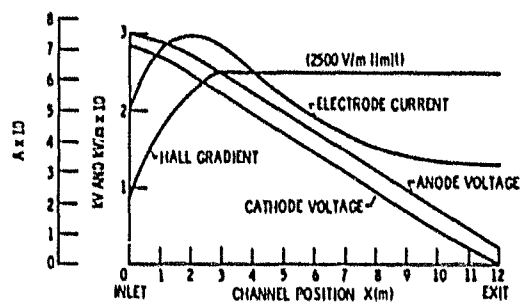


Fig. 2 Case I Electrode Voltage and Current Distribution.

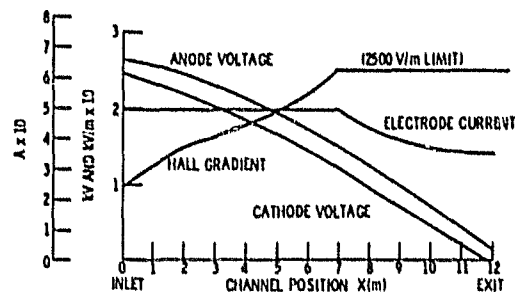


Fig. 3 Case II Electrode Voltage and Current Distribution.

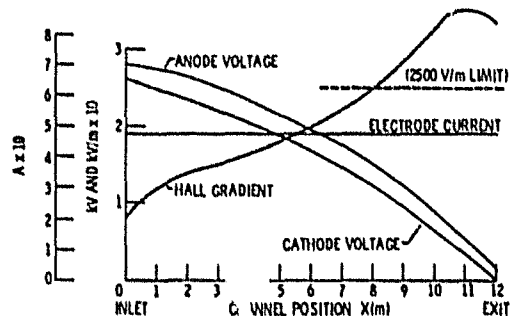


Fig. 4 Case III Electrode Voltage and Current Distribution.

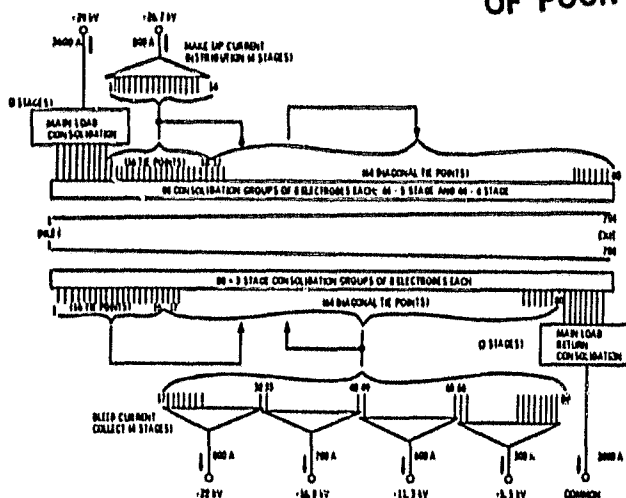


Fig. 5 Consolidation Network for Case I.

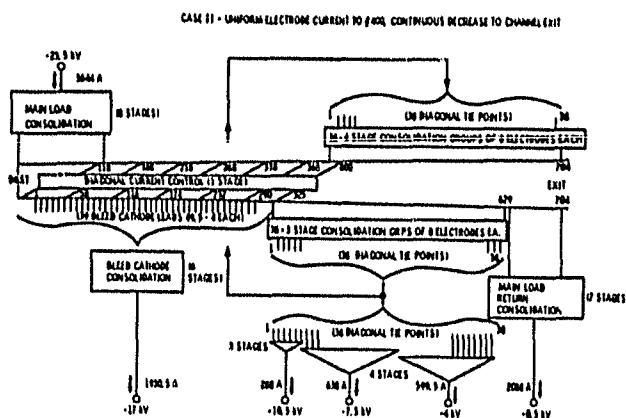


Fig. 6 Consolidation Network for Case II.

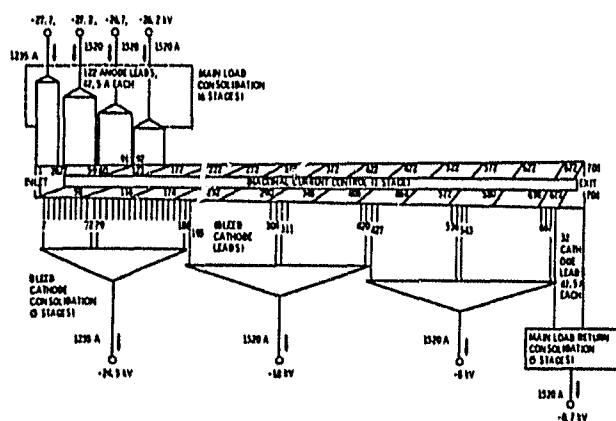


Fig. 7 Consolidation Network for Case III.

## Consolidation Network Designs

The Case I consolidation network arrangement is depicted schematically in Figure 5. Anodes and cathodes are arranged into 88 separate consolidation groups of eight electrodes each. Depending on generator position, the consolidation groups are 3, 4, or 5 stage units that provide current distribution and control to the electrode segments. Two stages are used to consolidate anodes near the inlet, one stage is used beyond the current peak, and individual cathodes are not consolidated since they do not require electrical segmentation. Within each group the electrodes (or segments) are transformer coupled to each other, for stabilization. Diagonal connection and current summing/subtraction is accomplished at the 80 diagonal tie points which link a cathode group to an anode group at the same average voltage. In order to diagonally transverse the channel once, electrode current must pass through three stages of cathode consolidation (current control), enter and leave the diagonal tie point (to resolve the differences in current), and pass through four or five more stages of anode consolidation (segment current control). The summing/subtraction junctions are served by makeup current distribution and four bleed current collectors identical to the electrode consolidation groups but larger in scale.

Figure 6 shows the consolidation network that accommodates the Case II channel. Over the uniform current distribution portion of the generator, simple diagonal connection can be used with current control via transformer coupling, equivalent to a single stage of consolidation, between adjacent diagonal currents. Since the equipotential (diagonal connection) angle is changing, however, there are 29 bleed cathodes which must be taken out and consolidated in some fashion to reduce the number of terminals. The exit half of the channel must be handled in the same manner as Case I, since the current from each electrode is less than the preceding one.

The Case III uniform current distribution consolidation network is shown in Figure 7. No consolidation groups are needed for current control since the diagonal currents themselves are controlled by transformer coupling to each other. Interelectrode fault power is limited by splitting the electrode and diagonal currents in two. Bleed cathode currents, arising from the angle change previously discussed, are collected by three five stage consolidation networks (similar to a Case I anode consolidation group and carrying roughly the same current) and another five stage, main load return consolidation. For convenience, the main load consolidation (which injects current into the generator) is split into four separate units that are sized to match the four current collectors. By doing this, independent load connection is possible and two higher level consolidation stages are avoided.

## Equipment Requirements

We can assess the hardware savings associated with uniform current distribution quantitatively by dividing the consolidation network function into three areas:

1. Introduction of load current into the generator at the inlet region.

2. Circulation of diagonal current, adding or removing current from each connection as required.

3. Removal of load current from the generator at the exit region and elsewhere as required.

To determine the hardware required to accomplish each of these functions for the three cases, we must make an arbitrary definition of size for the consolidation network elements at their various levels.

Since every consolidation stage combines two sources into one, and since the electrode is the original source, we define a level one consolidation as that equipment which is required to consolidate the current from one electrode into a single terminal connection. For example, the element which combines the currents from two anode segment pairs into a single anode current is a level one consolidation (see Table 2). An ETF anode consolidation group of eight anodes contains levels 0 through 4 (5 stages in all) because it begins by combining 32 individual anode segment currents and ends with a single terminal output from eight anodes. A level two consolidation is the equipment that combines two electrode currents into one output, level three combines four electrode currents (two pair) and so on. For the ETF network, anode consolidation begins at level 0

Table 2  
Consolidation Levels

Level 0 Consolidation	:	2 segments to 1 segment pair	1/2 electrode consolidated
1	:	2 segment pairs to 1 electrode assy.	1 electrode consolidated
2	:	2 electrodes to 1 pr. electrodes	2 electrodes consolidated
3	:	4 electrodes to 1 terminal	4 electrodes consolidated
4	:	8 electrodes to 1 terminal	8 electrodes consolidated
5	:		16 electrodes consolidated
6	:		32 electrodes consolidated
7	:		64 electrodes consolidated
8	:		128 electrodes consolidated
9	:		256 electrodes consolidated

(Diagonal Current Control is Equivalent to Level 1)

near the inlet and level one near the exit, and cathode consolidation begins at level two. As Table 3 shows, composition of the previous five stage anode consolidation group is 16 - level 0 elements, 8 - level one elements, 4 - level two elements, 2 - level three elements and one level four element. The diagonal tie points themselves are served by relatively low level consolidation since the bleed (current inject/collect) units do not carry all current from a cathode consolidation group to an anode group, but only the difference in current that results from the non-uniform distribution.

Table 3

Consolidation Equipment Requirements for Case I

# of Units		(Element composition of each unit by level)							
		0	1	2	3	4	5	6	7
Current Into MID Generator	1						4	2	1
	4	16	8	4	2	1			
	1			8	4	2	1		
Diagonal Traverse	44		8	4	2	1			
	36	16	8	4	2	1			
	80			4	2	1			
Current Out of MID Generator	4			8	4	2	1		
	1					4	2	1	
	8			4	2	1			
Total No. Elements at Each Level:		704	704	744	372	186	10	4	2

Table 4

Consolidation Equipment Requirements for Case II

# of Units		(Element composition of each unit by level)							
		0	1	2	3	4	5	6	7
Current Into MID Generator	1		112	56	28	14	7	4	2
	288		1						
Diagonal Traverse	38		8	4	2	1			
	38			4	2	1			
Current Out of MID Generator	1				20	10	5	3	2
	1				3	2	1		
	2				8	4	2	1	
	1				37	19	10	5	3
Total No. Elements at Each Level:		0	704	397	238	120	20	12	6

Table 5

Consolidation Equipment Requirements for Case III

# of Units		(Element composition of each unit by level)							
		0	1	2	3	4	5	6	7
Current Into MID Generator	1		26	13	7	4	2	1	
	3		32	16	8	4	2	1	
Diagonal Traverse	572		1						
Current Out of MID Generator	1				13	7	4	2	1
	3				16	8	4	2	1
Total No. Elements at Each Level:		0	694	122	62	32	16	8	



The current control elements used for direct diagonal connections (uniform current distribution) are equivalent to level one consolidation since in this case the cathode segments are taken individually to corresponding anode segments, then transformer coupled to the adjacent diagonal connection. For example, the first half channel diagonal connections of Case II (cathodes 1 through 325 minus the bleeds connected to anodes 113 through 410) require only 233 - level one elements.

The hardware requirements for providing the three functions in each consolidation network are shown in Tables 3, 4, and 5. The last line in each table shows the total number elements of each type; these totals are also summarized in Table 6.

Table 6  
Cost Breakdown Comparison - Total Number of Elements  
Required for Each Consolidation Network According to Level

	Level of Element								
	0	1	2	3	4	5	6	7	8
Case I	704	704	744	372	186	10	4	2	
Case II		704	397	238	120	20	12	6	3
Case III		694	122	62	32	16	8		

Clearly fewer elements, and fewer high level elements denote cost advantage. If we make the simple assumption that the cost of each element varies with its current capacity, we obtain cost multipliers 1.0, 0.82, and 0.33 respectively for Cases I, II and III.

#### Impacts Upon the Plant

It is not clear that the possible consolidation network equipment savings justifies the performance penalty against the plant which may result. As we have seen previously, uniform current distribution limits the current which is drawn from that portion of the generator most able to supply it, and draws more current from the exit portion of the channel. Hall gradient and heat loss are higher, but enthalpy extraction is reduced. As the combined cycle simulation results show in Table 7, the lowered channel

Table 7  
Uniform Electrode Current Distribution Impact  
on ETF Plant Performance

	cycle MHD		bottoming		steam	gross	net
	coal	power	cycle		cycle	AC	AC
	Input		Input		output	power	power
	MW <sub>t</sub>	MW <sub>e</sub>	MW <sub>t</sub>		MW <sub>e</sub>	MW <sub>e</sub>	MW <sub>e</sub>
Case I	539.8	89.5	426.4		133.3	221.8	202.3
Case III	539.8	85.1	429.6		135.3	219.5	200.0

performance translates inevitably to lowered plant efficiency. The electrical power output

difference between Case I and Case III channels is 4.5 MW. But since the bottoming cycle dominates the heat balance at ETF size, the net loss in plant output is only 2 MW, or one percent. If the uniform current case had been optimized for this plant or if the plant had been larger in size, this performance reduction might not be as severe. However, it appears at first glance that incorporation of uniform current distribution as a design feature would have negative impact on overall performance despite the positive impact on capital cost.

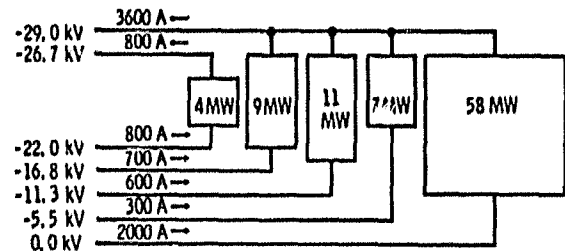


Fig. 8 Inverter Unit Arrangement and Connections for Case I Powertrain.

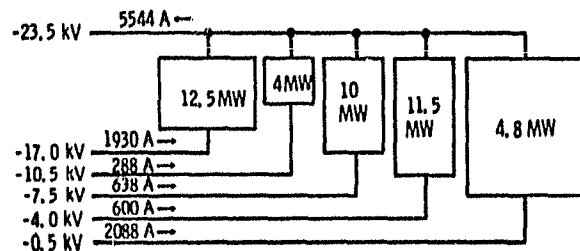


Fig. 9 Inverter Unit Arrangement and Connections for Case II Powertrain.

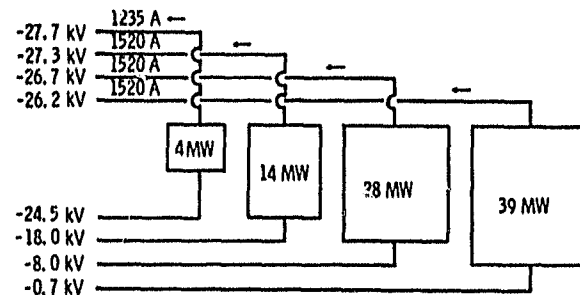


Fig. 10 Inverter Unit Arrangement and Connections for Case III Powertrain.

Are there impacts upon the inverter system? The consolidation network removes small increments of power distributed over the entire generator according to the voltage and current profiles, and presents this power in concentrated blocks to the inverter system. The number of blocks, their size and distribution depends mainly upon the current profile.

Since the diagonally connected Faraday generator cannot have both uniform electrode current distribution and constant diagonal connection angle, the inverter system which serves it is typically composed of a main load unit which handles the bulk current traversing the entire generator length, and several smaller auxiliary units which take consolidations of the bleed currents that exit the generator in mid-section. When the current distribution is non-uniform the bleed currents, taken from the diagonal tie points, are unequal. The bleed consolidation unit itself will have an output current that depends on both the number of bleeds consolidated and their location in the generator. Since it is always desirable to make the number of bleeds consolidated per unit an integer power of two, and since there is a tradeoff between the allowable number of bleed unit consolidation stages versus the allowable number of auxiliary inverters, the net result is that the output from each bleed consolidation unit will be different. Each auxiliary inverter string thus carries a different current. When current distribution is uniform, however, all the bleed currents are equal and their consolidation units can draw from any location in the generator, either to provide the most convenient mid-tap voltages or to divide the total current into equal blocks. If the latter course is followed, all of the inverter units can be of equal, or nearly equal, current rating.

Figures 8 and 9 show the required inverter arrangement for the non-uniform current distribution cases (I and II respectively). Note the variation in currents between the inverter strings. Additional consolidation stages could have been used to combine some of the terminals but, since the added equipment is equivalent to another inverter unit, there are many terminals. The Case III inverter system is shown in Figure 10. All units are of the same nominal rating (1500 AMP).

#### Concluding Remarks

From the analysis and discussion we can assess the impacts of incorporating uniform electrode current distribution as a design feature of the ETF-MHD generator:

1. A slight reduction in generator and overall plant performance.
2. An increase in electrical stress due to Hall voltage.
3. A reduction of electrode consolidation network size, complexity and hardware content.
4. Fewer constraints imposed upon inverter system configuration.

The performance and electrical stress impacts are not absolute but apparently depend on generator size. The power conditioning simplification impacts are valid at all sizes.

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