MASTER

A STUDY OF TRANSMISSION AND PROTECTION ELEMENTS FOR WIND ENERGY GENERATING SYSTEMS

VOLUME I

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APRIL 1978

PREPARED FOR THE
NATIONAL CENTER FOR ANALYSIS OF ENERGY SYSTEMS

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ABSTRACT

Results are reported of a study at Cornell University on transmission, distribution, and protection systems for large wind-energy generators (WEG) connected to an electric utility grid. Configurations for wind farms on flat terrain, mountain-peak clusters, and installations along a ridge were examined. Computer studies of load-flow and short-circuit behavior confirmed the technical feasibility of the proposed systems. Realistic unit costs for the projected transmission and protection schemes range from \$109 to \$317 per Kw, depending upon choice of configuration and distance from the grid. Cost of protective equipment is found to be a major factor in most cases, tending to be equal or greater than transmission line costs when the WEG units are located five miles or less from the grid. Several alternatives are suggested for future study. An alternate, less expensive, protection design involving the use of high-capacity fuses instead of oil circuit breakers, coupled with a disregard for the disconnection of one or more WEG units for considerable periods of time, is discussed.

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*Volume II may be obtained from Harry Davitian, Brookhaven National Laboratory, Upton, New York 11973. (BNL 24345)

INTRODUCTION

This report contains the results of a study of transmission and distribution systems for large wind-energy generators (WEG) performed by members of the School of Electrical Engineering at Cornell University, Ithaca, N.Y., in the summer of 1976. The objectives of the study were two-fold:

- a. To design characteristic transmission, distribution, and system-protection configurations that are to be operated in parallel with established electric utility grids.
- b. To determine realistic unit costs (in dollars per kilowatt) for the projected transmission and protection schemes.

Technical and economic aspects of this study were limited to these two objectives. Problems directly related to the wind turbines and associated generators, such as type of blades, tower design, interaction with adjacent towers, machine costs, maintenance, noise, T-V and microwave relay interference, use of windmills as fuel savers, and other pertinent topics are under intensive study by various groups in this country and abroad, and were not considered. Problems related to electric-utility concerns such as energy storage, spinning-reserve requirements, economic dispatch, and cost of standby service are also under study by others and were not included in this effort. On the other hand, the effects of unit size, unit spacing, unit siting, electrical interaction with utility grids, short-circuit ratings, interrupting capacity, control and synchronizing factors, and protective-equipment specifications are all detailed in this study.

In order to obtain up-to-date cost information that would also be

realistic from the viewpoint of an electric utility, the configurations, load-flow analyses, and short-circuit studies of the summer program were presented to the planning and protective relay divisions of New York State Electric and Gas Corporation (NYSEG). These groups performed an extensive examination of several of the alternatives, provided detailed lists of equipment and components that would be compatible with company practice, and supplied cost figures based on 1976 prices. This excellent cooperation of NYSEG with the Cornell group has made it possible to generate a block of information on WEG transmission, distribution, and protection that should be considered as a dependable base for the economic evaluation of these components of projected wind-energy systems. Tables, charts, and calculations that display these results are contained in the body of this report. A semi-formal document, prepared by NYSEG, has been designated as Appendix II of the report.

SUMMARY AND RESULTS OF THE STUDY

The basic WEG unit was assumed to be a 3-phase, 1500 Kw, 1700 Kva, 4.8 Kv synchronous a-c alternator with self-contained exciter. Several types of WEG sites were considered, as indicated in Table I, to follow, all arranged to operate in parallel with an electric utility grid to supply a single load from a collector bus. Load-flow and fault studies were conducted for the condition of maximum simultaneous power output of all units in a given system, for all the listed cases. The generalized standard network shown in Figure 1 was used throughout the study for load-flow and fault studies, with equal load division assumed between the grid and the WEG complex.

Figure 1. Typical configuration for the study

Distance D_1 was taken to be 5 miles for most studies, but 50-mile lengths were used in some cases to determine the effect on overall costs. Distance D_2 was kept at 20 miles except when system-terrain assumptions dictated shorter distances. Although the output of a single WEG unit may be brought to a load through several miles of 4.8 Kv line, the combined output of multi-connected units would require conductors of either large cross section, or several conductors in parallel, to

TABLE I

SUMMARY OF TRANSMISSION SITES AND UNIT COSTS

Case No.	Number of Units	Unit Spacing (feet)	Total MW	Site	Distance from load (Miles)	Unit Cost \$/kW
I(a)	1	-	1.5	open	0.5 ^x	147
I(b)	1	-	1.5	open	5.0 ^x	225
II	3	2000	4.5	Single peak	5.0 ^y	164
III	9	2000	13.5	Three* peaks	5.0 ^z	145
IV	10	2000	15.0	Ridge	5.0 ^z	191
V(a)	10	2000	15.0	Flat	5.0 ^y	111
V(b)	10	4000	15.0	Flat	5.0 ^y	120
V(c)	30	1500	15.0	Flat	5.0 ^y	247
VI(a)	20	2000	30.0	Flat	5.0 ^y	109
VI(b)	20	4000	30.0	Flat	5.0 ^y	117
VI(c)	60	1500	30.0**	Flat	5.0 ^y	253
VII(a)	60	2000	90.0	Flat	5.0 ^z	119
VII(b)	60	4000	90.0	Flat	5.0 ^z	132
VII(c)	180	1500	90.0**	Flat	5.0 ^z	278
VIII(a)	60	2000	90.0	Flat	50.0 ^z	158
VIII(b)	60	4000	90.0	Flat	50.0 ^z	171
VIII(c)	180	1500	90.0**	Flat	50.0 ^z	317

* Mountain peaks assumed to be 1.5 miles apart
 ** 500 Kw WEG Units

x - 4.8 Kv Transmission
 y - 4.8/34.5 Kv Transformer
 z - 4.8/138 Kv Transformer

TABLE II: TRANSMISSION & PROTECTION COSTS (1976 \$)

[ONE 1.5 MW WEG 0.5 MILES (0.8KM) FROM LOAD]

WEG UNIT SUBSTATION -----	106,533
WEG/LOAD SUBSTATION -----	66,500
GRID-LOAD SUBSTATION REVISION -----	14,000
AUTOMATIC SYNCHRONIZER -----	6,000
SUPERVISORY CONTROL AND TELEMETERING -----	14,700
1/2 MILE OF 2/0 ACSR 4KV).H.	
LINE (CONTRACT LABOR) @ \$26,000/MILE -----	13,000
	<hr/>
TOTAL -----	\$220,733

$$\text{UNIT COST} = \frac{220733}{1500} = \$147/\text{KW}$$

NOTE: DETAILS AND PRICES SUGGESTED BY NYSEG.

achieve reasonable operation. To avoid the high cost of multi-conductor lines, and to take advantage of lower current levels, transformers, indicated as T in Figure 1, were specified for various arrangements and load levels of the study to allow bulk transmission of WEG power output at typical electric-utility voltages. In general, transmission for distances greater than 1.5 miles was assumed to be at either 34.5 Kv or 138 Kv, depending upon the load level of a particular case. Three standard conductors (2/0, 3/0, and 556/5 MCM ACSR) were used throughout the study at appropriate voltage and current-transmission levels.

Estimated costs of a typical electric utility protection scheme, as suggested by NYSEG, are shown in Table II for one 1500 Kw WEG located one-half mile from a load in the configuration of Figure 1. These data pertain to Case I(a), as described in a later section of this Report. Similar computations for other cases are also presented, in detail, in the same section.

The information displayed in Table I summarizes the results of the load-flow, fault, and economic analyses performed on the various system configurations within the stated constraints. The unit costs of Table I are based on:

- a. the transformer and transmission-line design requirements that result from the system studies, and
- b. the protection and control equipment suggested by NYSEG as typical components that would be rigidly specified if similar WEG units were installed on their system.

Approximately one-half of the stated unit costs must be credited to the requirements of (b), which, of course, are keyed to the guidelines established for the local utility. The figures are considered to be typical enough, however, to serve as a basis for cost estimates for similar WEG installations elsewhere. Study procedures and detailed information on all of the major portions of the investigations are contained in succeeding sections of this report.

DIMENSIONS OF THE STUDY

The central issue in this study is to examine the technical and economic constraints that apply to the physical connection of large wind-energy generators to electric utility grids. When WEG units are to be operated as such alternate energy sources, a number of specific factors must be considered as follows:

- a. WEG characteristics including nature of speed and power controls, type of electric generator, and voltage, Kva, and Kw ratings.
- b. Number of units, their relative spacing, and the nature of the site terrain.
- c. Distance of the units from a common collector terminal or bus, as well as the distance of the collector bus from the nearest load bus, which, in turn, is assumed to be already connected to the electric utility grid.
- d. Nature of synchronizing, control, and supervisory equipment for each unit.
- e. Voltage and Kva ratings of necessary transformers.
- f. Voltage and current ratings and lengths of required transmission and distribution lines from the units to collector and load busses.
- g. Equipment requirements for voltage regulation and var support.
- h. Ratings of protective switchgear and associated protective relaying at each unit and at collector and load busses.
- i. Use of current-limiting reactors for short-circuit current control.

Each of these items will be discussed in terms of the given quantities and dimensions of this study.

a. WEG Characteristics

The basic unit was taken to be a three-phase, 1500 Kw, 1700 Kva, 4 Kv, synchronous a-c alternator with self-contained exciter. The wind turbine was assumed to have adjustable blades, with associated mechanical controls, to allow rated power output at the design wind speed. All load-flow and fault studies were conducted for the condition of maximum simultaneous power output of all units in a given system. Several alternate studies were performed using 4 Kv units rated at 500 Kw and 565 Kva.

b. Number, Siting and Spacing of Units

Several types of WEG sites were considered as follows, all arranged to operate in parallel with the grid:

1. Single unit feeding a load.
2. Three 1500Kw units, atop a mountain peak, feeding a load from a collector bus.
3. Three mountain-peak sites, each with three 1500 Kw units, feeding a load from a collector bus.
4. Ten 1500 Kw units along a ridge feeding a load from a collector bus.
5. "Wind Farm" configurations, located on flat terrain, in various combinations from 10 to 60 units, feeding a single load from a collector bus.

The 1500 Kw units were assumed to be separated by 2000 feet in one set of studies and by 4000 feet in an alternate set. The 500 Kw units were assumed to be separated by 1500 feet.

c. Distances to Load Busses

The loads were assumed to be located at 5-mile distances from the collector busses for most cases, but 50-mile lengths were used in several studies to determine the effect on overall cost.

d. Synchronizing, Control, and Supervisory Concerns

At this point it is appropriate to provide a brief description of the manner in which WEG units would be expected to operate when connected to the grid. It is possible to think of an electric "grid" as a huge ring which collects energy from all available sources in an indiscriminate manner and then dispenses energy, in discrete amounts, to the various loads. In reality, the grid is far less compact, consisting of large numbers of widely dispersed sources and loads, interconnected with each other to form several alternate feeder paths for each load, in order to provide reasonable reliability in the event of the failure of a given link. For example, several "trunk" lines may be brought out of a major generation station and injected into separate points in the network, via transmission lines, so as to supply a portion of the load at each point. Since WEG output is relatively small by comparison, the units would be inserted in the network at some point that would not be too distant from an appropriately-sized load. This dispersed operation is directly analogous to the manner in which distribution networks are formed to serve the many dispersed loads in a system, except, of course, that the energy would be supplied to the connection point rather than being withdrawn from the point, as in load distribution. Further, the nature of WEG generation is spasmodic (unless storage capability is also available at each unit - an assumption that has not been made

in this study). Consequently, the grid must be capable of supplying the full demand of a load when the wind energy is not available. These considerations have been used throughout this study, and form the basis for all of the load-flow and fault studies, and other calculations performed in this project. Since the WEG units will be going on and off the line in a random fashion, it is necessary to provide automatic synchronizing equipment at each unit, as well as voltage and power-control facilities. In addition, it is necessary for power-control and dispatching centers to know the exact status of each unit at all times, so that relatively elaborate supervisory equipment, including leased communications channels, must be provided.

e. Transformer Ratings

Since the rated voltage of the WEG units is to be 4Kv, the rated line current for one 1500 Kw unit is about 200 amperes at this voltage level. While the output of one unit may be brought to a grid/load bus over several miles of 4 Kv line without undue losses, the combined output of several units, such as would be found in mountain-peak configurations, ridges, and wind farms, would require conductors of large cross section, or several conductors in parallel (bundled conductors), to perform the same task with reasonable losses and minimal voltage drop. Such multi-conductor schemes are likely to be several times as expensive as standard lines. In order to keep transmission costs and operating characteristics within bounds, by taking advantage of lower current levels, it is necessary to turn to higher voltage operation by means of suitable transformers. For this study, 34.5 Kv and 138 Kv have been assumed for transmission of power from multi-connected WEG units. These two levels

are typical of electric-utility practice. Several standard transformer ratings were chosen, as follows, for the various configurations of the study:

5 Mva, 7.5 Mva and 17.5 Mva at 4.16/34.5 Kv.

15 Mva and 17.5 Mva at 4.16/138 Kv

10 Mva at 34.5/138 Kv.

All of these transformers were assumed to have 0.1 per unit impedance on their own rating. In general, transmission for distances greater than 1.5 miles was assumed to be at either 34.5 Kv or 138 Kv, depending upon the particular case.

f. Transmission-Line Ratings

In principle it is possible to design transmission lines for a wide range of currents by choosing the optimum-sized conductor for each line. In practice, however, it is usually more economical to specify only a few standard conductors and devise the transmission network from this stock. Labor, poles, towers, insulators, and other hardware constitute the major costs of a line so that the differences between conductor prices may be quite unimportant in relation to the other costs. In this study, for the most part, only three standard conductors of aluminum-conductor-steel-reinforced (ACSR) were used throughout, as follows:

<u>Conductor Size</u>	<u>Outside Diameter (inches)</u>	<u>Current Rating (amperes)</u>
2/0 ACSR	0.447	270
3/0 ACSR	0.502	300
556.5 MCM* ACSR	0.953	730

* MCM denotes "thousand circular Mil", a unit of cross-sectional area.

Since all of the lines used in the study are relatively short, the resistance and capacitive-reactance components of the lines are essentially negligible. Consequently, the principal impedance of the lines is inductive reactance. An inspection of the values of this parameter for the three conductor sizes that were used indicates a maximum difference of about 20 percent between the smallest and the largest conductor. Thus the choice of the optimum-sized conductor for each line would make very little difference, both in the representation of the impedances of the lines and in the total costs of the line. The major cost difference, of course, is related to the choice of the voltage level to be used at a given line location. Early in the study some attention was given to the use of "compact" lines or "spacer-cable" lines for aesthetic purposes. Costs of such lines, as projected by NYSEG, would be some three times the cost of standard lines; hence the concept was abandoned for this study. Adoption of such configurations on a large scale in the future, possibly due to environmental pressures, could eventually bring down the cost, and their possible use should be considered in carry-on studies.

g. Voltage Regulation and Reactive Power (Var) Support

One of the main advantages of using synchronous machines as the generator component of a WEG unit is the opportunity afforded for use of the generator exciters as generous sources of reactive power (vars). This capability of the synchronous machine is further enhanced by the short, low-impedance lines which characterize the WEG systems considered in this study. The net result of these combined factors is that the

WEG system would have excellent voltage regulation under conditions that could be either, controlled by the power center in the grid, or by automatic voltage-regulator equipment in each WEG substation. This mode of operation means that each WEG is being used as a synchronous condenser, thus reducing the necessity for large investment in shunt capacitors and tap-changing transformers under load. In the load-flow studies of this project, the WEG units were constrained to supply vars to the entire system with a corresponding reduction in the amount of vars required from the grid. If the WEG-unit vars were allowed to "swing" along with the grid, the WEG units invariably would absorb vars, a condition that is usually avoided in practice, whenever possible, since it tends to cause synchronous-machine instability due to the inherent under-excitation of the rotor. It appears that each WEG could be scheduled to supply its maximum var capability at full load (1700 Kva) and the grid system could be arranged to absorb vars from the WEG network, thus improving its own voltage regulation and reducing the need for capacitor or synchronous-condenser installations within the grid - a definite cost benefit that could amount to as much as \$10/Kw for capacitors, and several times that amount for synchronous condensers. In addition, the WEG units could also be used as synchronous reactors (within safe stability limits) if the grid has an excess of vars during off-peak conditions. An intriguing possibility for synchronous condenser operation of WEG's is that the units need never stop rotating. When the wind fails, the machine rotors would continue to turn (as very-lightly-loaded synchronous motors) provided some form of clutch arrangement disengages the windmill blades until the wind velocity again rises to the required level for energy conversion. The

previously-mentioned supervisory controls and regulatory equipment (item d) would again be vital to this mode of operation. Future studies should investigate the technical and economic possibilities of the use of WEG units as continuously controlled var sources.

Special Note:

It is pertinent at this point to comment on the suggested use of types of generators other than constant-speed-constant-frequency (CSCF) synchronous machines. Variable-speed-constant-frequency (VSCF) machines are known to abstract more power from the wind than can be obtained from a CSCF unit. These suggested devices usually involve either induction generators, a-c field-frequency modulation with a-c to d-c to a-c converters, or straight d-c generators with d-c to a-c inverters. The principal characteristic of these generators is that they all require substantial amounts of vars that must be supplied by the grid, or by locally-switched static capacitors, or both. Since this additional var load adds to the voltage regulation problems of the grid, there is some question as to whether the additional power benefits would offset the added cost of the auxiliary equipment and complicated electronics required for the VSCF approaches. The cost benefits to be derived from the technically desirable synchronous-condenser operation of CSCF units must also be included in such an economic analysis.

h. Protective Switchgear and Relaying

One of the most formidable constraints on the use of the WEG units in conjunction with a large grid is the strict requirement for adequate switchgear and ancillary protective-relaying equipment. The basic problem is that the oil circuit breakers (OCB) must be capable of

interrupting the full momentary short-circuit current that the grid and all of the local network of WEG units can supply to a dead three-phase short circuit at the terminals of any one of the WEG units, or at one of the adjacent collector busses. If only one WEG unit is connected to the grid the transmission line must be relatively short if the unit is to have a reasonable unit cost. Therefore, the line impedance cannot be expected to provide much of a limit to the short-circuit current that can be drawn from the grid if the WEG bus is faulted. This condition offers a very persuasive reason for not connecting a unit directly to the major grid (in spite of rather glib statements to that effect that are usually made in discussion of WEG utilization). If such direct connections were in fact made, the required OCB for the single WEG unit would have to be of the same magnitude as for generators rated at hundreds of megawatts, an obviously untenable economic position. Consequently, a single WEG unit must be connected to the grid at some low-capacity point where the short-circuit duty will be reasonable. Electric utilities tend to specify standard ratings for OCB's, at the required voltage levels, as a matter of prudent economics, just as they do for conductor stockpiles. For WEG protection, NYSEG (See Appendix II) suggested 4.8 Kv, 250 Mva generator breakers in a metalclad outdoor installation, including overcurrent phase and ground protective relays, with a 1200-ampere continuous rating. The short-circuit studies, for most of the configurations, indicated that this breaker would be satisfactory for both WEG and grid fault contributions. For certain of the large-scale WEG systems, either higher rated OCB's, or current-limiting reactors would be required. It is important to note

that reducing the size of the individual WEG unit from 1500 to 500 Kw would triple the cost of the protective gear for the same total power output, since the OCB rating would not be changed. Supervisory equipment and remote control systems must also be included in the cost of the overall protective-relaying and switchgear system.

i. Current Limiting Reactor Considerations

The use of current-limiting reactors to reduce short-circuit currents introduces changes in electrical behavior of a system as well as adding to the cost of the installation. The reactors must be present in the lines at all times since it is not technically feasible to switch them into the system upon demand. (Investigations into switched current-limiting devices are in progress in some quarters but the state-of-the-art is still in an early stage). The presence of a fixed reactor in each line would increase the effective transmission-line length between each WEG unit, with corresponding increases in line voltage drop and line var requirements, so that the voltage regulation of the system becomes somewhat more of a problem than it is without the reactors. The vars that WEG units can supply to the grid, when acting as synchronous condensers, is also reduced. These changes would be relatively minor, however, with respect to the overall behavior of the system. Since the units would be more isolated from one another than before, the power flow in individual units of a multi-WEG system would probably be easier to control and dispatch since the units would have less tendency to "swing" together, that is, to act as one large unit. On the other hand, if the latter mode of operation is desired, then the presence of the reactors is a deterring factor. Another important point,

with regard to selection of the type of generators, can be made in the context of this current-limiting reactor discussion: In theory, VSCF generators should not contribute very much to the short-circuit duty of the system. Since they are asynchronous machines they are not coupled to each other, and to the grid, so that their internal impedances tend to remain high, whereas the internal impedances of synchronous machines are substantially reduced when faults occur. With machines at the 1500 Kw level, however, inertia effects of the rotor and blades may add to the system fault current. The short-circuit behavior of VSCF machines was not part of this project but should be investigated in future WEG studies. It is possible that their use may eliminate the need for current-limiting reactors. Ratings of individual unit OCB's would still have to be sufficiently high to protect against the fault current contribution from the grid. Also, the possible benefits from synchronous-condenser operation would be lost with the VSCF machine.

STUDY PROCEDURES AND RESULTS

Following the general guidelines that are discussed in the previous section, the study was performed by executing the following tasks in the given sequence:

1. Circuit Designs

Circuit configurations were designed to meet the study specifications that limited investigation to:

- (a) Flat-terrain "wind farms"..
- (b) Mountain-peak clusters.
- (c) Units along a ridge.

Since the first objective was to devise circuits which would display the electrical behavior of the systems by means of computerized load-flow studies, the transmission patterns were built up around suitable generator, transformer, conductor, and load ratings. Protection schemes were left for the later portions of the study after short-circuit conditions had been established. Particular attention was given to conductor arrangements, transformer placement, voltage levels and rated currents. A number of alternate schemes are shown in Appendix I. Basic configurations were chosen for the three major site forms, and the necessary calculations were performed to transform these circuits into the equivalent models that were to be studied by means of the computer..

2. Load-Flow Studies

A large number of load-flow studies were performed on each of the major designs. The objective was to determine if the electrical behavior of the chosen circuits was compatible with the standard performance of more conventional systems. Questions of voltage regulation, power and var flow, current ratings and current

distribution could be answered by examining the results. The studies were limited to the behavior of the system under full-load conditions, with each WEG unit constrained to provide its maximum power output into a fixed load at the grid/load bus. The load was adjusted so that one-half of its requirement came from the WEG units with the other half provided by the grid. Transmission losses were naturally distributed throughout the system, so that the grid usually supplied somewhat more than one-half of the total load to compensate for the losses from WEG units to the load.

A typical load-flow result is displayed in the following pages with Figure 2 exhibiting an arrangement for a 10-unit wind-farm module feeding a load, (Bus 13), that is located at a distance of 5 miles from collector bus No. 11. The grid infinite bus (Bus 14) is also located at a distance of 5 miles from the load. Study quantities are given in per unit (p.u.) which can be converted into real quantities by multiplying by the "base" quantities given in the table in the figure. A computer printout of this study is contained in the charts following the figure. Note the presence of the 4.16/34.5 Kv transformer between Bus 11 and Bus 12 which allows 14.4 Mw to be transmitted over the 5-mile line at 34.5 Kv. The line current in this case is approximately 250 amperes. If transmitted at 4.16 Kv the current would have been 2100 amperes. Total real power loss in this system, including the grid portion, is 1.6 Mw or 5.3% of the total load requirement of 30 Mw. Note also that the voltage at load Bus No. 13 is only 0.94 p.u. whereas a level approaching 1.0 p.u. is more desirable. Vars supplied by each WEG, with the exception of the "Swing Machine" G-10, are only 0.026 p.u. (0.26 Mw)

whereas the ultimate capability is about 0.065 p.u. (0.65 Mw) without exceeding the 1.7 Mva rating. Thus this study shows that by causing each WEG to increase its var output (by an increase in the d-c current in the

Figure 2. Typical load-flow study

WEG exciter) the voltage on the load bus could be brought to the desirable 1.0 p.u. and quite likely it would also be possible to transfer vars into the grid system, thus illustrating the use of the WEG units as synchronous condensers. If the WEG units were VSCF machines for this case, the voltage and var picture would be far different. Each WEG would require vars from the grid, the load would continue to require vars which would

CHART No. 1

STARTING TIME = 0.0 SECONDS LOAD-FLOW STUDY FOR 30-MW LOAD WITH

WINDMILL FARM 4.16/34.5 KV TRANSFORMER AT COLLECTOR BUS II.									
10 UNITS MODULE SYSTEM WITH 15MW FROM GRID.									
0X									XX
0	13	14	10	00000	34.50000	0.00010	0.0	0.0	1.20 10 0 0 0 300
1 PER UNIT = 10 MVA									
1	1	11	0	0.002840	0.002860	0.000002	11	1.000	0 1
2	2	11	0	0.002840	0.002860	0.000002	11	1.000	0 1
3	3	11	0	0.002840	0.002860	0.000002	11	1.000	0 1
4	4	11	0	0.002840	0.002860	0.000002	11	1.000	0 1
5	5	11	0	0.000710	0.000630	0.000000	11	1.000	0 1
6	6	11	0	0.001420	0.001280	0.000001	11	1.000	0 1
7	7	11	0	0.001420	0.001280	0.000001	11	1.000	0 1
8	8	11	0	0.001420	0.001280	0.000001	11	1.000	0 1
9	9	11	0	0.001420	0.001280	0.000001	11	1.000	0 1
10	10	11	0	0.000710	0.000630	0.000000	11	1.000	0 1
11	11	12	0	0.0	0.050000	0.0	12	1.000	0 0
12	12	13	0	0.030000	0.032300	0.000203	13	1.000	0 1
13	14	13	0	0.030000	0.032300	0.000203	13	1.000	0 1
1	2			10.00000	1.00000	0.0	0.15000	0.02600	
2	2			10.00000	1.00000	0.0	0.15000	0.02600	
3	2			10.00000	1.00000	0.0	0.15000	0.02600	
4	2			10.00000	1.00000	0.0	0.15000	0.02600	
5	2			10.00000	1.00000	0.0	0.15000	0.02600	
6	2			10.00000	1.00000	0.0	0.15000	0.02600	
7	2			10.00000	1.00000	0.0	0.15000	0.02600	
8	2			10.00000	1.00000	0.0	0.15000	0.02600	
9	2			10.00000	1.00000	0.0	0.15000	0.02600	
10	0			0.0	1.00000	0.0	0.0	0.0	← SWING MACHINE
11	2			10.00000	1.00000	0.0	0.0	0.0	
12	2			10.00000	1.00000	0.0	0.0	0.0	
13	2			10.00000	1.00000	0.0	-3.00000	-0.56000	← LOAD BUS (DATA ARE IN PER UNIT)
14	1			0.0	1.00000	0.0	1.65000	0.0	← GRID INFINITE BUS

END OF INPUTS, TIME = 3.7500 SECONDS

END OF UNIFIED, TIME = 3.9375 SECONDS

CHART No. 1 (Continued)

NUMBER OF ITERATIONS = 25 ERROR NORM = 0.0000242 DESIRED ERROR NORM = 0.000100000

BUS NO	VOLTAGE COMPONENTS		POWER INTO NETWORK		VOLTAGE MAGNITUDE	VOLTAGE ANGLE	VOLT-AMPS	LAMBDA-1	LAMBDA-2	LAMBDA-S	LAMBDA-V
	REAL	IMAGINARY	REAL	IMAGINARY		DEGREES					
1	1.00032	0.00026	0.15000	0.02600	1.00032	0.01599	0.15224				
2	1.00032	0.00026	0.15000	0.02600	1.00032	0.01599	0.15224				
3	1.00032	0.00026	0.15000	0.02600	1.00032	0.01599	0.15224				
4	1.00032	0.00026	0.15000	0.02600	1.00032	0.01599	0.15224				
5	0.99995	0.00005	0.15000	0.02600	0.99995	0.00258	0.15224				
6	1.00007	0.00012	0.15000	0.02600	1.00007	0.00710	0.15224				
7	1.00007	0.00012	0.15000	0.02600	1.00007	0.00710	0.15224				
8	1.00007	0.00012	0.15000	0.02600	1.00007	0.00710	0.15224				
9	1.00007	0.00012	0.15000	0.02600	1.00007	0.00710	0.15224				
10	1.00000	0.0	0.15943	0.09790	1.00000	0.0	0.18769				
11	0.99132	-0.00003	0.0	0.0	0.99952	-0.00183	0.0				
12	0.98040	-0.00925	0.0	0.0	0.98445	-5.20145	0.0				
13	0.92424	-0.12899	-3.00000	-0.56000	0.93319	-7.94489	3.05182				
14	0.99517	-0.00019	1.65000	0.55615	1.00000	-5.63494	1.73930				

SWING MACHINE

LOAD BUS (DATA ARE IN PER UNIT)

GRID INFINITE BUS

LINE NO	LINE END	LINE END	POWER INTO LINE AT END 1		POWER INTO LINE AT END 2		LINE POWER LOSS		CURRENT COMPONENTS INTO LINE AT END 1		CURRENT COMPONENTS INTO LINE AT END 2	
			WATTS	VARS	WATTS	VARS	WATTS	VARS	REAL	IMAG	REAL	IMAG
1	1	11	0.15307	0.025946	-0.150240	-0.025387	0.000666	0.000060	0.150266	-0.025896	-0.150266	0.025696
2	2	11	0.150307	0.025946	-0.150240	-0.025387	0.000666	0.000060	0.150266	-0.025896	-0.150266	0.025696
3	3	11	0.150307	0.025946	-0.150240	-0.025387	0.000666	0.000060	0.150266	-0.025896	-0.150266	0.025696
4	4	11	0.150307	0.025946	-0.150240	-0.025387	0.000666	0.000060	0.150266	-0.025896	-0.150266	0.025696
5	5	11	0.151201	0.025916	-0.151185	-0.025901	0.000017	0.000015	0.151210	-0.025810	-0.151210	0.025610
6	6	11	0.150529	0.026006	-0.150495	-0.025976	0.000033	0.000030	0.150521	-0.025986	-0.150521	0.025986
7	7	11	0.150529	0.026006	-0.150495	-0.025976	0.000033	0.000030	0.150521	-0.025986	-0.150521	0.025986
8	8	11	0.150529	0.026006	-0.150495	-0.025976	0.000033	0.000030	0.150521	-0.025986	-0.150521	0.025986
9	9	11	0.150529	0.026006	-0.150495	-0.025976	0.000033	0.000030	0.150521	-0.025986	-0.150521	0.025986
10	10	11	0.160591	0.097549	-0.160566	-0.097527	0.000025	0.000022	0.160591	-0.097549	-0.160591	0.097549
11	11	12	1.511889	0.329122	-1.511889	-0.329119	0.0	0.141303	1.512144	-0.329229	-1.512144	0.329229
12	12	13	1.512145	0.187548	-1.450275	-0.108970	0.071570	0.078574	1.512428	-0.328978	-1.512428	0.328978
13	13	14	1.650243	0.556508	-1.559451	-0.451243	0.096792	0.099265	1.586215	-0.709885	-1.586215	0.709885

TOTAL TRANSMISSION POWER LOSS IS (0.163100 WATTS, 0.319541 VARS)

ITERATION STAGE	ERROR NORM
16	0.00123402
17	0.00003489

also come from the grid, and the voltage at Load Bus No. 13 would be considerably lower than in the given case, thus requiring additional vars from the grid, or the equivalent installation of static capacitors at Bus No. 13.

Overall, the results of the load-flow studies for all cases indicated that the WEG systems can be made to operate in a very satisfactory manner within the usual criteria of steady-state power-system operation. Var flow and voltage regulation, however, would require careful monitoring. A substantial number of cases were also found to be sensitive to small changes in power-flow requirements, so that careful adjustments were needed in order to cause the system to converge properly during a study. This behavior indicates that the actual system would require substantial supervision by automatic control devices, either at each station, or at the dispatching center, or both, in order to provide consistent and reliable operation. This difficulty would probably be accentuated by the presence of a large number of WEG units in a service area.

3. Short-Circuit Studies

Following the load-flow studies, fault studies were performed on all of the configurations designed for this project. The objective was to determine maximum interrupting duty for three-phase short circuits located at various critical points in each network. In this way it was possible to determine the fault current contributed by each WEG unit in the system, plus the grid contribution, for a fault at the terminal bus of one of the WEG units, or on a collector bus for several combined units. The standard fault-study procedure was followed which involved determination of the subtransient reactance

for each synchronous machine, calculating the voltages behind subtransient reactances, and then using the computer to find the current magnitude throughout the network for a fault at a given location. To determine the interrupting Mva, a multiplier of 1.4 was applied to the calculated fault current to account for the presence of the d-c decrement in the initial fault-current waveform. This is the standard multiplier used in the industry for circuit breakers of this class.

The results of a typical fault study are shown in Figure 3 and adjacent pages. Three mountain peaks with three WEG units on each peak are feeding the usual load at a point 5 miles distant from the collector bus. Note that in this case the grid infinite bus is assumed to be 20 miles from the load. Also in this case, the longer lines are operating at 138 Kv with a 15 Mva, 4/138 Kv transformer between Bus No. 13 and Bus No. 14. The fault is assumed to be located at Bus No. 4 which is the internal collector bus on Mountain peak No. 1.

The total current at the fault is found to be 6.77 p.u. For this case the 1 p.u. base current at the 4 Kv voltage level is calculated on an assumed 30 Mva base as follows:

$$I_{\text{Base}} = \frac{30 \times 10^6}{\sqrt{3} \times 4,000} = 4340 \text{ amperes}$$

Then: $I_{\text{Fault}} = 4340 \times 6.77 = 29,500 \text{ amperes}$

and $I_{\text{momentary}} = 29,500 \times 1.4 = 41,000 \text{ amperes}$

The interrupting Mva would then be:

$$41,000 \times \sqrt{3} \times 4,000 = 284 \text{ Mva}$$

CHART No 2

*****FTC0001 *****RM1.P41 ***FMT <00>* *****227 LINES *** 11:20.35PM 21 SEP 76 UPSON

YENSAKUL.P.

3-Phase Fault on Collector Bus No 4

[1 p.u. current on 4 kv. Base = 4340 ampere.]

LINE AND GENERATORS MANTAIN PEAK CASE WITH A 15 MVA 4/138 KV TRANS.

FAULTED BUS COLLECTION BUS

0 20 27 10.0000 132.0000 0.00010 0.0 0.0 1.40 50 0 1 0 100

1 1 4 1 0.000308 0.000279 0.000871 1 1.000 0 1

2 2 4 1 0.000308 0.000279 0.000871 2 1.000 0 1

3 3 4 1 0.000308 0.000279 0.000871 3 1.000 0 1

4 4 4 1 0.000308 0.000279 0.000871 4 1.000 0 1

5 5 4 1 0.000308 0.000279 0.000871 5 1.000 0 1

6 6 4 1 0.000308 0.000279 0.000871 6 1.000 0 1

7 7 4 1 0.000308 0.000279 0.000871 7 1.000 0 1

8 8 12 1 0.000308 0.000279 0.000871 8 1.000 0 1

9 9 12 1 0.000308 0.000279 0.000871 9 1.000 0 1

10 10 12 1 0.000308 0.000279 0.000871 10 1.000 0 1

11 11 12 1 0.000308 0.000279 0.000871 11 1.000 0 1

12 12 13 1 0.000543 0.000737 0.008496 4 1.000 0 1

13 13 13 1 0.000543 0.000737 0.008496 12 1.000 0 1

14 14 13 1 0.000543 0.000737 0.008496 8 1.000 0 1

15 15 14 0 0.0 0.200000 0.0 13 1.050 0 0

16 16 15 1 0.007050 0.005688 0.019925 14 1.000 0 1

17 17 15 1 0.010775 0.024045 0.071436 16 1.000 0 1

18 18 16 0 0.0 0.040000 0.0 17 1.030 0 0

19 19 16 0 0.0 0.408920 0.0 15 1.000 0 0

20 20 2 0 0.0 2.598150 0.0 18 1.000 0 0

21 21 2 0 0.0 2.598150 0.0 19 1.000 0 0

22 22 3 0 0.0 2.598150 0.0 20 1.000 0 0

23 23 5 0 0.0 2.598150 0.0 21 1.000 0 0

24 24 6 0 0.0 2.598150 0.0 22 1.000 0 0

25 25 7 0 0.0 2.598150 0.0 23 1.000 0 0

26 26 9 0 0.0 2.598150 0.0 24 1.000 0 0

27 27 10 0 0.0 2.598150 0.0 25 1.000 0 0

28 28 11 0 0.0 2.598150 0.0 26 1.000 0 0

29 29 17 0 0.0 0.060000 0.0 27 1.000 0 0

30 30 4 0 0.000000 0.000000 0.0 4 1.000 1 0

← Faulted Bus

1 2 10.0000 1.00000 0.0 0.0 0.0

2 2 10.0000 1.00000 0.0 0.0 0.0

3 2 10.0000 1.00000 0.0 0.0 0.0

4 2 10.0000 1.00000 0.0 0.0 0.0

5 2 10.0000 1.00000 0.0 0.0 0.0

6 2 10.0000 1.00000 0.0 0.0 0.0

7 2 10.0000 1.00000 0.0 0.0 0.0

8 2 10.0000 1.00000 0.0 0.0 0.0

9 2 10.0000 1.00000 0.0 0.0 0.0

10 2 10.0000 1.00000 0.0 0.0 0.0

11 2 10.0000 1.00000 0.0 0.0 0.0

12 2 10.0000 1.00000 0.0 0.0 0.0

13 2 10.0000 1.00000 0.0 0.0 0.0

14 2 10.0000 1.00000 0.0 0.0 0.0

15 2 10.0000 1.00000 0.0 0.0 0.0

16 2 10.0000 1.00000 0.0 0.0 0.0

17 2 10.0000 1.00000 0.0 0.0 0.0

18 0 0.0 1.05310 8.13233 0.0 0.0

19 0 0.0 1.05310 8.13233 0.0 0.0

20 0 0.0 1.05310 8.13233 0.0 0.0

21 0 0.0 1.05310 8.13233 0.0 0.0

22 0 0.0 1.05310 8.13233 0.0 0.0

23 0 0.0 1.05310 8.13233 0.0 0.0

24 0 0.0 1.09132 5.59142 0.0 0.0

25 0 0.0 1.05350 7.47493 0.0 0.0

26 0 0.0 1.05350 7.47493 0.0 0.0

27 0 0.0 1.01635 2.63898 0.0 0.0

CHART No 2 (Continued)

NUMBER OF ITERATIONS = 95 ERROR NORM = 0.00009002 DESIRED ERROR NORM = 0.0001000000

BPS VOLTAGE COMPONENTS		POWER INTO NETWORK		VOLTAGE	VOLTAGE	
NO				MAGNITUDE	ANGLE	
	REAL	IMAGINARY	REAL	IMAGINARY	DEGREES	VOLT-AMPS

1	-0.00304	-0.00369	0.0	0.0	0.00479	50.53362	0.0
2	-0.00304	-0.00369	0.0	0.0	0.00479	50.53362	0.0
3	-0.00304	-0.00369	0.0	0.0	0.00479	50.53362	0.0
4	-0.00313	-0.00369	0.0	0.0	0.00479	48.47925	0.0
5	-0.00214	-0.00703	0.0	0.0	0.00734	-73.09624	0.0
6	0.00214	-0.00703	0.0	0.0	0.00734	-73.09624	0.0
7	0.00214	-0.00703	0.0	0.0	0.00734	-73.09624	0.0
8	0.00200	-0.00493	0.0	0.0	0.00721	-73.85706	0.0
9	0.00213	-0.00706	0.0	0.0	0.00738	-73.18858	0.0
10	0.00213	-0.00706	0.0	0.0	0.00737	-73.17612	0.0
11	0.00213	-0.00706	0.0	0.0	0.00737	-73.17612	0.0
12	0.00200	-0.00695	0.0	0.0	0.00724	-73.92300	0.0
13	0.00152	-0.00643	0.0	0.0	0.00652	-60.97008	0.0
14	0.00203	-0.00373	0.0	0.0	0.60316	-3.55255	0.0
15	0.61799	-0.50593	0.0	0.0	0.62083	-5.48886	0.0
16	0.78232	-0.00606	0.0	0.0	0.70753	-7.02576	0.0
17	0.01047	-0.01066	0.0	0.0	0.81346	-4.91226	0.0
18	1.04251	0.14697	0.00131	0.42828	1.05310	8.13233	0.42828
19	1.04251	0.14697	0.00131	0.42828	1.05310	8.13233	0.42828
20	1.04251	0.14697	0.00131	0.42828	1.05310	8.13233	0.42828
21	1.04251	0.14697	0.00294	0.42639	1.05310	8.13233	0.42640
22	1.04251	0.14697	0.00294	0.42639	1.05310	8.13233	0.42640
23	1.04251	0.14697	0.00294	0.42639	1.05310	8.13233	0.42640
24	1.04455	0.13705	0.00304	0.45779	1.09132	5.59142	0.45780
25	1.04455	0.13705	0.00295	0.42669	1.05350	7.47493	0.42670
26	1.04455	0.13705	0.00295	0.42669	1.05350	7.47493	0.42670
27	1.01520	-0.04660	0.54657	3.44776	1.01635	-2.63898	3.49081

LINE E1 E2				REAL AND REACTIVE CURRENTS IN LINES				RMS CURRENT	
				END 1	END 2		END 1	END 2	
				REAL AND REACTIVE POWER INTO LINE				POWER LOSS IN LINE	
				END 1	END 2		WATTS	VARs	
1	1	4	0.066759	-0.407942	-0.066756	0.407940	0.413369	0.413365	
			0.001304	-0.001487	-0.001251	0.001535	0.000053	0.000048	
2	2	4	0.066759	-0.407942	-0.066756	0.407940	0.413369	0.413365	
			0.001304	-0.001487	-0.001251	0.001535	0.000053	0.000048	
3	3	4	0.066759	-0.407942	-0.066756	0.407940	0.413369	0.413365	
			0.001304	-0.001487	-0.001251	0.001535	0.000053	0.000048	
4	5	8	0.071126	-0.390001	-0.071120	0.390003	0.396434	0.396435	
			0.002892	0.000333	-0.002844	-0.000289	0.000048	0.000044	
5	6	8	0.071126	-0.390001	-0.071120	0.390003	0.396434	0.396435	
			0.002892	0.000333	-0.002844	-0.000289	0.000048	0.000044	
6	7	8	0.071126	-0.390001	-0.071120	0.390003	0.396434	0.396435	
			0.002892	0.000333	-0.002844	-0.000289	0.000048	0.000044	
7	9	12	0.054734	-0.406774	-0.054728	0.406775	0.410439	0.410440	
			0.002991	0.000482	-0.002939	-0.000435	0.000052	0.000047	
8	10	12	0.066555	-0.390776	-0.066549	0.390778	0.396403	0.396404	

CHART No. 2 (Continued)

		0.002900	0.000364	-0.002851	-0.000320	0.000048	0.000044
9	11 12	0.066555	-0.390776	-0.066549	0.390778	0.396403	0.396404
		0.002900	0.000364	-0.002851	-0.000320	0.000048	0.000044
10	4 13	-0.216314	5.540401	0.216357	-5.540411	5.544621	5.544633
		-0.019187	0.018372	0.035871	0.004273	0.016684	0.022645
11	12 13	0.178791	-1.201127	-0.178734	1.201139	1.214360	1.214364
		0.008712	0.001164	-0.007912	-0.000078	0.000800	0.001086
12	8 13	0.204345	-1.182763	-0.204288	1.182775	1.200285	1.200288
		0.000601	0.000956	-0.007819	0.000105	0.000782	0.001061
13	13 14	0.153089	3.004625	-0.153089	-3.004625	3.008523	3.008523
		-0.020136	-0.004260	0.020136	1.814502	-0.000000	1.810241
14	14 15	0.153213	3.004782	-0.152249	-2.992628	3.008685	2.996498
		-0.020067	-1.814601	0.083626	1.858424	0.063559	0.043823
15	16 15	0.369901	-3.314020	-0.364689	3.361176	3.334599	3.380902
		0.546555	2.295160	-0.424969	-2.055481	0.121587	0.239679
16	17 16	0.369906	-3.314040	-0.369906	3.314040	3.334620	3.334620
		0.546561	2.739963	-0.546561	-2.295175	0.000000	0.444788
17	15 0	0.516947	-0.368580	-0.516947	0.368580	0.634890	0.634890
		0.341351	0.197077	0.0	0.0	0.341351	0.197077
18	18 1	0.058759	-0.402421	-0.058759	0.402421	0.406688	0.406688
		0.001308	0.428280	-0.001308	0.001441	0.000000	0.429721
19	19 2	0.058759	-0.402421	-0.058759	0.402421	0.406688	0.406688
		0.001308	0.428280	-0.001308	0.001441	0.000000	0.429721
20	20 3	0.058759	-0.402421	-0.058759	0.402421	0.406688	0.406688
		0.001308	0.428280	-0.001308	0.001441	0.000000	0.429721
21	21 5	0.060042	-0.400428	-0.060042	0.400428	0.404905	0.404905
		0.002942	0.426394	-0.002942	-0.000433	-0.000000	0.425961
22	22 6	0.060042	-0.400428	-0.060042	0.400428	0.404905	0.404905
		0.002942	0.426394	-0.002942	-0.000433	-0.000000	0.425961
23	23 7	0.060042	-0.400428	-0.060042	0.400428	0.404905	0.404905
		0.002942	0.426394	-0.002942	-0.000433	-0.000000	0.425961
24	24 9	0.043645	-0.417218	-0.043645	0.417218	0.419495	0.419495
		0.003041	0.457794	-0.003041	-0.000582	0.000000	0.457212
25	25 10	0.055466	-0.401213	-0.055466	0.401213	0.405028	0.405028
		0.002950	0.426686	-0.002950	-0.000465	0.000000	0.426222
26	26 11	0.055466	-0.401213	-0.055466	0.401213	0.405028	0.405028
		0.002950	0.426686	-0.002950	-0.000465	0.000000	0.426222
27	27 17	0.381015	-3.413452	-0.381015	3.413452	3.434651	3.434651
		0.546570	3.447765	-0.546570	-2.739955	0.0	0.707810
28	4 0	0.410776	-6.756235	-0.410776	6.756235	6.768709	6.768709
		0.022931	-0.022931	0.0	0.0	0.022931	-0.022931

← Faulted Bus

(Current in Per Unit)

TOTAL TRANSMISSION POWER LOSS IS (0.568145 WATTS, 7.322385 VARS)

ITERATION	ERROR
STAGE	NORM
46	0.01819369
47	0.01672196
48	0.01531572
49	0.01397711
50	0.01270850
51	0.01151205
52	0.01039152
53	0.00934783
54	0.00837835
55	0.00748659
56	0.00666801
57	0.00592019
58	0.00524114
59	0.00462419
60	0.004077345
61	0.00358783
62	0.00315019

CHART No. 2 (continued)

63	0.00275489
64	0.00240916
65	0.00200144
66	0.00183956
67	0.00160297
68	0.00155659
69	0.00143176
70	0.00132517
71	0.00123939
72	0.00114867
73	0.00106240
74	0.00097852
75	0.00089026
76	0.00082284
77	0.00075877
78	0.00068258
79	0.00062037
80	0.00055320
81	0.00049027
82	0.00045422
83	0.00040762
84	0.00036243
85	0.00032259
86	0.00028734
87	0.00025541
88	0.00022317
89	0.00019421
90	0.00017414
91	0.00015176
92	0.00012179
93	0.00011037
94	0.00010137
95	0.00009092

Using similar computations based on line currents determined from the fault study, the individual contribution from each machine is 17 Mva, and the contribution from the grid is 131 Mva. A 250 Mva, 4 Kv OCB located at each WEG unit would give adequate protection for a three-phase fault at any point in the WEG system.

4. Calculation of Transmission and Protection Costs

Appendix I contains detailed calculations for 17 separate configurations that were examined in the study, as summarized in the previous Table I on page 4. Computations are followed by sketches of each of the case configurations, applicable assumptions, and lists of the necessary system constituents and their costs.

RECOMMENDATIONS FOR FUTURE STUDY

During the conduct of this study several interesting alternatives have become evident which are worthy of additional study. The design of future large-scale WEG systems could depend heavily upon the technical and economic findings of a number of suggested investigations, as follows:

- a. Comparison of the relative merits and benefits of the use of CSCF and VSCF generators from the standpoint of transmission-network operation. CSCF machines may be operated as synchronous condensers to provide var support. These machines, however, contribute to fault currents and may require current-limiting reactors in the systems for adequate fault protection. VSCF machines require additional var support from the grid but are unlikely to contribute to fault current, thus tending to reduce the cost of network and unit protection.
- b. Comparison of cost benefits of compact transmission lines with standard construction for WEG installations. In this study, compact lines and overhead spacer-cable lines were considered to be non-standard items and were therefore much more costly than conventional construction. Compact lines developed as standard practice for large-scale WEG systems may produce worthwhile cost benefits. Technical feasibility in the range of 4 Kv to 138 Kv has already been established.
- c. Comprehensive studies of the effect of large numbers of current-limiting reactors on the electrical behavior of the system, assuming CSCF generators are used. The Cornell study does not include this feature except that a projection is made of the

probable cost of a specific system operating in this mode. (Case VI-C page - 45) Specifications for the reactors and estimates of their probable cost would also be included in this study.

- d. Evaluation of large-scale, remotely located wind farms, combined with storage facilities, which would transmit large blocks of energy to a grid by means of high-voltage-direct-current (HVDC) techniques.