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CONVERSION

MODEL FOR THE READY DEFINITION AND
APPROXIMATE COMPARISON OF ALTERNATIVE
HIGH VOLTAGE TRANSMISSION SYSTEMS

Phases II and III. Application to Electric Systems Within
the Contiguous United States

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August 1979

Work Performed Under Contract No. AC05-78ET29305

Gilbert/Commonwealth
Commonwealth Associates Inc.
Jackson, Michigan

U. S. DEPARTMENT OF ENERGY

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ASSISTANT SECRETARY FOR ENERGY TECHNOLOGY
DIVISION OF ELECTRIC ENERGY SYSTEMS
WASHINGTON, D.C. 20545

MODEL FOR THE READY DEFINITION
AND APPROXIMATE COMPARISON
OF ALTERNATIVE HIGH VOLTAGE TRANSMISSION SYSTEMS

PHASES II AND III - APPLICATION TO
ELECTRIC SYSTEMS WITHIN THE
CONTIGUOUS UNITED STATES

AUGUST 1979

Prepared by Commonwealth Associates Inc.

Jackson, Michigan 49201

Under Technical Support Contract ET-78-C-05-5916

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ABSTRACT

This report is the result of work done by Commonwealth Associates Inc. under Department of Energy Contract ET-78-C-05-5916. Under this contract, Commonwealth is to provide "Technical Support in the Assessment of Power Delivery Alternatives" to the Division of Electric Energy Systems by whom this work is funded.

The first phase of this work assigned to Commonwealth was to develop a model of overhead transmission systems in the range of 362 to 1200 kV ac, and +400 to +800 kV dc. Such systems included (a) transmission from generation to load, and (b) interconnection of two large integrated systems, with and without the existence of an underlying lower voltage network in either case. This phase has been completed.

The second and third phases involved application of the model to electric systems within selected regions of the United States, and the entire United States, respectively, dealing with real situations and including projected expansion to year 1987. The potential benefits and costs of using higher than existing transmission voltages were to be evaluated on this basis. Additionally, the most advantageous new voltage was to be determined taking into account direct and indirect benefits and costs.

This report presents the results of the second and third phases.

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INTRODUCTION

This report is the result of work done by Commonwealth Associates Inc. under Department of Energy Contract ET-78-C-05-5916. Under this contract, Commonwealth is to provide "Technical Support in the Assessment of Power Delivery Alternatives" to the Division of Electric Energy Systems by whom this work is funded.

The overall objectives of the work to be performed by Commonwealth are as follows:

1. To quantify the dollar benefits and costs of alternative overhead transmission line voltages within the range of 362 to 1200 kV ac, and +400 to +800 kV dc,
2. To similarly quantify the irreducible benefits and costs with respect to such things as energy conservation, land use, materials use, environmental impact, new technology integration, service reliability, and reduction in the amount of new generating capacity needed,
3. To use these data to project the advantageous role of each transmission voltage in the future growth of power systems within the United States,
4. To thus provide a basis whereby DOE can arrive at the proper allocation of resources for future research and development among the included voltage classes.

To further these objectives, Commonwealth was assigned phases to perform as follows:

Phase I Develop a model to analyze and quantify the relative dimensions, costs, and benefits of EHV/UHV transmission systems.

Phase II Apply the model to electric systems within selected regions of the United States, dealing with real systems, but including the projected expansion to year 1987. On this basis, evaluate the potential benefits and costs of using higher than existing transmission voltages, and further determine the most advantageous new voltage, taking into account dollar and irreducible benefits and costs.

Phase III Extend the scope of Phase II to cover virtually all of the United States, for the purpose of making a gross estimate of the future role of facilities within each included voltage class.

This report presents the results of Phases II and III of the work. A report covering the results of Phase I was previously prepared and submitted to DOE for publication. The model presented therein was used in implementing both Phases II and III and the results are presented in this report.

UNDERLYING CONCEPT

This investigation is concerned with projecting and comparing alternative high capacity UHV ac and dc systems with the objective of identifying the economic voltage for a trans-national electric power transmission (TEPT) system. Such a system may consist of long transmission lines, in the range of 600-1000 miles each, spanning the continental United States. Only one or two terminal points will be provided within the region of each reliability council (see Exhibit 1) and the underlying, lower voltage networks will be depended upon to deliver power to, and distribute power from these terminal points. This is the concept hypothesized for this study.

It is pointed out that this is not the only concept applicable. Others, such as networks consisting of shorter transmission lines, e.g. 100 to 300 miles each, overlaying and interconnecting the lower voltage networks at many points may also be considered.

The projected TEPT systems would be useful in providing alternative power supply in case of widespread interruption of a particular fuel or process used for the generation of electricity. It would also provide alternative power supply to avert or mitigate blackouts of regional proportions for any cause. Energy from western geothermal sources, or increased electricity generation in the western coal fields, may also

be transported via this TEPT system to places of its consumption. During normal conditions, a strong transmission network would also be available to optimize the utilization of critical fuels on a national scale.

TRANSMISSION LINK CAPACITY

Exhibit 2 shows the generating capabilities by fuel types, and the peak demands projected for each reliability council in 1987. This exhibit suggests that total interruption of any particular fuel or generating process will result in widespread shortages of electric power, but it also suggests that the effect might be mitigated significantly if there were a way in which regions mainly reliant on different fuels could share the remaining generating capacity. The purpose of TEPT would be to facilitate such interchange in large quantity.

For the Eastern United States, transmission links capable of transferring 10 GW were hypothesized. This results in a maximum permissible interruption of nuclear, oil, gas, or coal-fired generating capacity in amounts of 81, 72, 57, and 38 percent, respectively, as demonstrated in Exhibit 3.

Transmission links with 5 GW transfer capability would have resulted in generally lower permissible interruptions, e.g. 71 percent for nuclear, 56 percent for oil, 48 percent for gas, and 37 percent for coal-fired generation. In this case significant surplus capacity would remain unutilized. On the other hand, transmission links with 15 GW transfer capability would allow for 88 percent nuclear, 88 percent oil, 66 percent gas and 38 percent coal interruption. This would not represent

great improvement overall compared with the 10 GW ties. Although arbitrarily selected, the 10 GW transfer capability appears to provide reasonable balance between surplus capacity and regional deficits in the Eastern United States.

The system developed for the Western United States provided for transmission link capabilities of 5 GW. This is based on transfer capabilities already envisioned for future systems in that region.

FORMULATION OF ALTERNATIVES

The Model prepared in Phase I was used to define and compare alternative TEPT systems for 800 kV ac, 1200 kV ac, +400 kV dc, +600 kV dc and +800 kV dc. The transmission links were modeled using a pool to pool transfer scenario. The underlying system was ignored due to the magnitudes of the power transfers and distances involved.

A diagram and tabulation of the postulated TEPT systems are presented in Exhibit 4. This exhibit depicts the number of transmission lines and amount of series compensation required for the ac lines. Series compensation was limited to 40 percent since higher amounts of series compensation increases the likelihood of sub-synchronous resonance.

A maximum of six parallel single circuit ac or bipolar dc lines were considered. Thus, transmission voltages of +400 kV dc in both the Eastern and Western United States and 800 kV ac in the East were not considered feasible due to their requirement for more than six parallel lines.

EVALUATION OF ALTERNATIVES

The alternative TEPT systems were evaluated from two perspectives. First, line, transformer, and corona losses were compared to determine the most efficient transmission voltage. This is an important aspect due to the need to conserve energy resources. Exhibit 5 graphically depicts the relative losses.

The second perspective on which to judge the alternatives is their total life cycle cost. These are presented in Exhibit 6. These costs were broken down into their three basic components; transmission line (depreciable and non-depreciable costs), ac substation or dc terminals, and losses. This breakdown allows the reader some insight into which is the most significant component of the cost of each alternative.

SENSITIVITY ANALYSIS

Indications are that dc is still a maturing technology, despite recent advances and applications. For example, technological breakthroughs are conceivable that could result in lower terminal costs and improved conversion efficiencies. In addition, future fuel cost escalation and system loss factors are subject to uncertainties. For these reasons a sensitivity analysis was performed to determine the effect of various assumptions on the relative life cycle costs of the alternatives. The effect of these parameters on the comparative life cycle costs is presented in Exhibit 7.

Fuel cost escalation decreases the relative economic advantage of dc when compared to ac because the dc system involves higher losses for equal power transfer levels. The effect of the fuel escalation rate can be offset by a lower system loss factor or a higher conversion efficiency for the dc terminals.

Variation of the capital cost of the dc terminals also affects the relative economics of ac and dc transmission systems. Higher dc terminal costs make the dc system marginally less competitive with ac and vice versa. However, these effects become less significant at higher fuel cost escalation rates.

CONCLUSIONS

The results of this study indicate that:

1. If a high capacity, trans-regional EHV/UHV network such as postulated here is desired, and if the overall rate of fuel price escalation does not exceed 12 percent per year, then dc transmission in the range of ± 600 to ± 800 kV dc is the most favorable alternative.

2. However, if fuel escalation rates exceed 12 percent, 1200 kV ac becomes the economic choice.

The conclusions presented above are based on the concept of TEPT described as a network of very long transmission lines with relatively few terminal points. Extension of these findings to different types of networks may lead to erroneous conclusions. For example, a need for many intermediate switching stations and step-down transformers could drastically alter the findings herein.

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ECAR	- EAST CENTRAL AREA RELIABILITY COORDINATION AGREEMENT	SERC	- SOUTHEASTERN ELECTRIC RELIABILITY COUNCIL
MAIN	- MID-AMERICA INTERPOOL NETWORK	SPP	- SOUTHWESTERN POWER POOL
MAAC	- MID-ATLANTIC AREA COUNCIL	ERCOT	- ELECTRIC RELIABILITY COUNCIL OF TEXAS
MARCA	- MID-CONTINENT AREA RELIABILITY COORDINATION AGREEMENT	WSCC	- WESTERN SYSTEMS COORDINATING COUNCIL
NPCC	- NORTHEAST POWER COORDINATING COUNCIL		

REGIONAL ELECTRIC RELIABILITY COUNCILS

EXHIBITS

PROJECTED GENERATING CAPABILITY AND PEAK DEMANDS IN 1987^(a)
CONTIGUOUS U.S.A.
(Gigawatts)

Generation	<u>ECAR</u>	<u>ERCOT</u>	<u>MAAC</u>	<u>MAIN</u>	<u>MARCA</u>	<u>NPCC</u>	<u>SERC</u>	<u>SPP</u>	<u>WSCC</u>
Nuclear	18.3	5.9	15.7	17.7	4.8	15.6	49.5	10.1	23.0
Hydro/Pumped Storage	4.4	0.2	2.5	1.1	2.8	8.0	16.5	2.7	47.8
Coal	99.0	19.8	18.4	36.2	22.0	6.5	75.0	32.8	33.7
Oil	9.9	0.1	21.1	9.7	3.7	31.3	30.9	6.4	34.4
Gas	0.9	29.3	0.2	0.1	0.2	-	0.2	28.9	2.9
Other	<u>0.5</u>	<u>-</u>	<u>0.1</u>	<u>0.1</u>	<u>-</u>	<u>-</u>	<u>-</u>	<u>-</u>	<u>2.8</u>
Total	133.0	55.3	58.0	64.9	33.5	61.4	172.1	80.9	144.6
Peak Load	<u>103.9</u>	<u>45.9</u>	<u>45.7</u>	<u>55.2</u>	<u>30.3</u>	<u>48.7</u>	<u>142.0</u>	<u>67.0</u>	<u>108.2</u>
Reserve Generation	29.1	9.4	12.3	9.7	3.2	12.7	30.1	13.9	36.4

(a) From the NERC 8th Annual Review, August 1978.

See Appendix, Sheets 1 and 2, for generation and demands in 1977, and projected increases from 1977 to 1987.

SURPLUSES AND SHORTAGES OF GENERATION WITH RESPECT TO PEAK DEMANDS
 ASSUMING INTERRUPTIONS OF ELECTRIC ENERGY SOURCES
 SUMMER 1987
 (Gigawatts)

SURPLUS (SHORTAGE)
 WITHOUT INTER-REGIONAL TRANSMISSION

Reliability Council	Interrupted Energy Source (Permissible Degree of Interruption) (a)			
	Nuclear (81%)	Oil (72%)	Gas (57%)	Coal (38%)
ECAR	14.3	22.0	28.6	(8.5)
ERCOT	4.6	9.3	(7.3)	1.9
MAAC	(0.4)	(2.9)	12.2	5.3
MAIN	(4.6)	2.7	9.6	(4.1)
MARCA	(0.7)	0.5	3.1	(5.2)
MPCC	0.1	(9.8)	12.7	10.2
SERC	(10.0)	7.9	30.0	1.6
SPP	5.7	9.3	(2.6)	1.4

SURPLUS (SHORTAGE)
 WITH INTER-REGIONAL TRANSMISSION

Reliability Council	Interrupted Energy Source (Permissible Degree of Interruption) (a)			
	Nuclear (81%)	Oil (72%)	Gas (57%)	Coal (38%)
ECAR	0	9.3	18.7	0
ERCOT	4.6	9.3	0	0
MAAC	0	0	12.2	0
MAIN	0	2.7	9.6	0
MARCA	0	0.5	3.1	0
NPCC	0	0	12.7	2.6
SERC	0	7.9	30.0	0
SPP	4.4	9.3	0	0

(a) Such that there are no shortages with interconnections as shown in Exhibit 3, each inter-regional link having a capacity of 10 GW in the east and 5 GW in the west.

TRANSMISSION LINE ALTERNATIVES

TRANSMISSION LINE ALTERNATIVES
(TABULATED)

Eastern United States - 10 GW Power Transfer Level			
Line	Number of Lines (Percent Series Compensation)		
	1200 kV ac	±600 kV dc	±800 kV dc
Montana/Wyoming- North Central	6 (28%)	4	2
North Central- Midwest	5 (30%)	3	2
Montana/Wyoming- South Central	6 (40%)	4	3
South Central- Midwest	6 (40%)	4	3
Midwest- Southeast	6 (40%)	4	3
Midwest- Northeast	6 (40%)	4	3

Western United States - 5 GW Power Transfer Level				
Line	Number of Lines (Percent Series Compensation)			
	800 kV ac	1200 kV ac	±600 kV dc	±800 kV dc
Montana/Wyoming- Pacific Southwest	5 (37%)	3 (38%)	3	2
Montana/Wyoming- Pacific Northwest	5 (24%)	3 (23%)	3	2
Pacific Northwest- Pacific Southwest	6 (33%)	4 (21%)	3	2

POWER LOSSES

EXHIBIT 5

EASTERN UNITED STATES

WESTERN UNITED STATES

LIFE CYCLE COSTS
(Millions of 1985 Dollars)

EASTERN UNITED STATES

<u>Voltage</u>	<u>Transmission</u>	<u>Substation</u>	<u>Losses</u>	<u>Total</u>
1200 kV ac	60,593	6,166	2,656	69,415
+600 kV dc	12,909	13,560	12,603	39,072
+800 kV dc	14,100	13,560	9,530	37,278

WESTERN UNITED STATES

<u>Voltage</u>	<u>Transmission</u>	<u>Substation</u>	<u>Losses</u>	<u>Total</u>
800 kV ac	17,342	1,291	1,556	20,189
1200 kV ac	21,262	2,035	743	24,040
+600 kV dc	6,076	3,390	2,799	12,265
+800 kV dc	6,349	3,390	2,229	11,968

See Appendix, Sheet 3, for breakdown of life cycle costs by transmission links.

SENSITIVITY ANALYSIS OF LIFE CYCLE COSTS
TO FUEL COST ESCALATION

EASTERN UNITED STATES

SENSITIVITY ANALYSIS OF LIFE CYCLE COSTS
TO LOSS FACTOR

EASTERN UNITED STATES

SENSITIVITY ANALYSIS OF LIFE CYCLE COSTS
TO D.C. TERMINAL LOSSES

EASTERN UNITED STATES

SENSITIVITY ANALYSIS OF LIFE CYCLE COSTS TO D.C. TERMINAL COST

EASTERN UNITED STATES

APPENDIX

INSTALLED GENERATING CAPABILITY AND PEAK DEMANDS IN 1977^(a)
CONTIGUOUS U.S.A.
(Gigawatts)

Generation	<u>ECAR</u>	<u>ERCOT</u>	<u>MAAC</u>	<u>MAIN</u>	<u>MARCA</u>	<u>NPCC</u>	<u>SERC</u>	<u>SPP</u>	<u>WSCC</u>
Nuclear	2.6	-	6.2	6.5	3.5	7.5	13.2	.8	2.5
Hydro/Pumped Storage	3.3	.2	2.2	1.4	2.9	7.9	10.4	2.5	38.1
Coal	64.6	4.1	15.1	26.9	11.1	3.7	51.3	5.2	16.2
Oil	7.5	.1	20.5	5.0	3.3	30.9	26.8	5.6	29.3
Gas	.9	32.2	.2	.2	.3	-	.3	29.8	2.6
Other	<u>-</u>	<u>-</u>	<u>-</u>	<u>.1</u>	<u>-</u>	<u>-</u>	<u>-</u>	<u>-</u>	<u>.6</u>
Total	78.9	36.6	44.2	40.1	21.2	50.0	102.0	43.9	89.3
Peak Load	<u>62.0</u>	<u>26.3</u>	<u>32.3</u>	<u>33.4</u>	<u>17.3</u>	<u>35.4</u>	<u>79.4</u>	<u>36.8</u>	<u>64.3</u>
Reserve Generation	16.9	10.3	11.9	6.7	3.9	14.6	22.6	7.1	25.0

(a) From the NERC 8th Annual Review, August 1978.

PROJECTED CHANGES IN GENERATING CAPABILITY AND PEAK DEMAND - 1977 THROUGH 1987
CONTIGUOUS U.S.A.
(Gigawatts)

Generation	<u>ECAR</u>	<u>ERCOT</u>	<u>MAAC</u>	<u>MAIN</u>	<u>MARCA</u>	<u>NPCC</u>	<u>SERC</u>	<u>SPP</u>	<u>WSCC</u>
Nuclear	15.7	5.9	9.5	11.2	1.2	8.1	36.3	9.3	20.5
Hydro/Pumped Storage	1.1		0.3	-0.3	-0.1	0.1	6.1	0.2	9.7
Coal	34.4	15.7	3.3	9.3	10.9	2.8	23.7	27.6	17.5
Oil	2.4		.6	4.7	0.4	0.4	4.1	.8	5.1
Gas		-2.9		-.1	-.1		-.1	-.9	.3
Other	<u>.5</u>	<u> </u>	<u>.1</u>	<u> </u>	<u> </u>	<u> </u>	<u> </u>	<u> </u>	<u>2.2</u>
Total	54.1	18.7	13.8	24.8	12.3	11.4	70.1	37.0	55.3
Increase in Peak Demand	41.9	19.6	13.4	21.8	13.0	13.3	62.6	30.2	43.9

LIFE CYCLE COSTS BY TRANSMISSION LINKS
(Millions of 1985 Dollars)

EASTERN UNITED STATES

<u>Transmission Link</u>	<u>1200 kV ac</u>	<u>±600 kV dc</u>	<u>±800 kV dc</u>
Montana/Wyoming- North Central	11,256	6,258	5,623
North Central- Midwest	8,075	5,642	5,203
Montana/Wyoming- South Central	12,535	6,793	6,613
South Central- Midwest	13,153	6,793	6,613
Midwest- Southeast	12,178	6,793	6,613
Midwest- New England	<u>12,218</u>	<u>6,793</u>	<u>6,613</u>
Total	69,415	39,072	37,278

WESTERN UNITED STATES

<u>Transmission Link</u>	<u>800 kV ac</u>	<u>1200 kV ac</u>	<u>±600 kV dc</u>	<u>±800 kV dc</u>
Montana/Wyoming- Pacific Northwest	6,358	7,207	4,088	3,989
Montana/Wyoming- Pacific Southwest	5,275	6,041	3,622	3,538
Pacific Northwest- Pacific Southwest	<u>8,556</u>	<u>10,792</u>	<u>4,555</u>	<u>4,441</u>
Total	20,189	24,040	12,265	11,968