Long-Distance Power Transmission

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Many conclusions, which may guide new system design, can be drawn from recent studies of the performance of long-distance transmission systems. These studies were made on lines 600 miles long and cover both lines which had intermediate generation as well as those without.

MANY STUDIES have been made recently to determine the performance characteristics of long-distance transmission systems. This particular analysis considered straightaway transmission systems of 600 miles in length, a distance which is representative of transmission now under study and in actual development.[1,3] The system characteristics and requirements for economic transmission outlined here may be used to guide the future development of long-distance as well as moderate-distance transmission systems.

The first section of the article is devoted to straightaway transmission as far as 600 miles and considers the effect of intermediate switching stations, series capacitor compensation, intermediate synchronous condenser and shunt capacitor compensation, fault switching times, excitation system characteristics, generator and receiving system reactances, and inertias.

The second section gives consideration to 600-mile-long lines having intermediate generation. Power transmission systems 600 miles long use intermediate generation as a point for interconnection.[1,2] To determine the effect of intermediate generation on the over-all transmission of power it was assumed that this generation or system capacity existed at the half-way point. Several general conclusions can be drawn which may be used to indicate an expected trend in the development of such long-distance transmission systems.

RESULTS OF THE ANALYSIS

FROM the results of this analysis of 600-mile transmission the following conclusions have been drawn. The first two conclusions are a reaffirmation of previous studies.[2,4–6]

1. Intermediate switching stations constitute a very effective and practical way to increase the transmission-line loadings and reduce the cost of transmission.
2. Special means to overcome the stability limitations (commonly called compensation means) are also necessary to reduce the cost of long-distance straightaway transmission.
3. Series capacitors may be used as a basis for evaluating the expected cost of long-distance transmission.
4. Other methods of compensation, such as intermediate synchronous condensers and controlled shunt capacitors, may be comparable in cost to series capacitors. Their application will depend upon the amount of intermediate loading on the system under consideration.
5. Interconnection to intermediate system capacity is a practical and economical method to increase the power limits of long-distance transmission systems. When such intermediate capacity already exists this may constitute the most economical method of attaining low transmission costs.
6. A measure of the transmission system economy is the design loading of the circuits. There no longer appears to be any justification for design or maximum loadings below the surge impedance loading for any circuit, even if 600-mile-long circuits are required to withstand the loss of any one transmission-line section.
7. The higher voltages, 287 kv and 360 kv, with their high kilowatt loadings for optimum economy, essentially will be limited in their use for delivery of power to large integrated systems capable of absorbing large blocks of power, such as 400 to 800 megawatts per pair of circuits (see Table I).
8. With the continued growth, development, and interconnection of electric systems, the ability to absorb large blocks of transmitted energy is increasing.
9. Comparisons of a-c transmission with other methods of transmitting energy long distances should be persistently reappraised in view of the continued progress in the transmission art and the development of electric systems.

TRANSMISSION WITHOUT INTERMEDIATE GENERATION

Comparison of 200-Mile and 600-Mile Straightaway Transmission-System Power Limits. Figure 2 gives the results of differential analyzer studies of the power limit of 200-mile (Figure 2*A*) and 600-mile (Figure 2*B*) transmission sys-

Table I. Per Unit Bases Used in Calculation of Line Performance

Circuit (Kilovolts)	Per Unit Kilowatts* and Kilovolt-Amperes [5 (Kv)²]
360	650,000**
287	412,000
230	264,000
161	130,000
115	66,000
69	24,000

* This column corresponds to the total surge impedance kilowatt loading of two circuits when each circuit has a surge impedance of 400 ohms.

** If a dual conductor[1,8] is used, the per unit power is increased approximately 25 per cent above the values shown so that at 360 kv the per unit power becomes 813,000 kw.

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tems. These studies were made for a double-circuit system with an intermediate switching station every 100 miles. The system shown in Figure 1 is the same as that used to obtain the data for Figures 2 and 8 with the following exceptions: to obtain the data for Figure 2*A* the transmission was limited to 200 rather than 600 miles, and the series capacitors (shown dotted) were used only for the data of Figure 8. The results of Figure 2 are for an uncompensated line; $x_c=0$. The differential analyzer method of analysis is described in reference 7. Figure 2 shows the effect of fault clearing time on the power limit, where the power limit is given in per unit sending-end power on a 5-kv² base. For example, per unit power for a 287-kv system is $5\times(287)^2$ or 412,000 kw. See Table I.

The results shown can be interpreted directly for any circuit with a single conductor per phase from Table I, which gives the per unit power and kilovolt-amperage for the higher voltages. If dual conductors are used, the per unit power and kilovolt-amperage will be increased approximately 25 per cent.[8]

As shown in Figure 2*A*, for the 200-mile line the power limit for 0.06-second fault clearing time and an exciter time constant of 0.68 second (per unit response of approximately unity) is 1.065 per unit or 440,000 kw for a 287-kv system. (That is, 692,000 kw for a 360-kv system and 866,000 kw for a 360-kv system with dual conductors.) This represents fairly good loading for a double-circuit 200-mile system. Figure 2*B* shows that the 600-mile uncompensated line ($x_c=0$), with the same amount of connected generation as for the 200-miles ystem, has a power limit equal to 0.735 per unit or 303,000 kw for 287-kv system. Therefore, the 600-mile line has a power limit of only 69 per cent of the 200-mile line, other conditions being kept constant. It should be noted that this comparison is on the basis of the same sending-end reactance for each case, or for the same equivalent generation.

If the generation had been reduced correspondingly to the reduced limit for the 600-mile case, in order to maintain the same per unit reactance per kilovolt-ampere of generat-

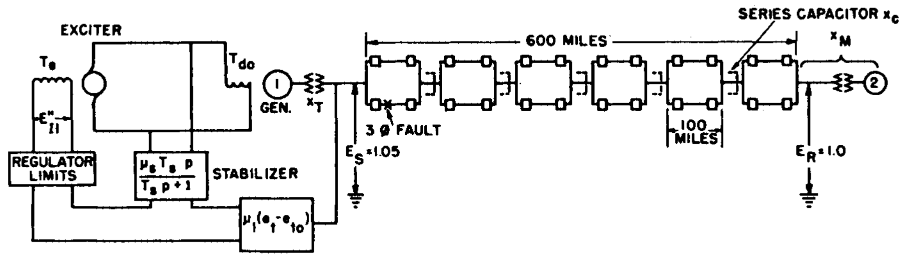

Figure 1. 600-mile transmission system. All quantities expressed in per unit are on a base of 5 (kv)². For a 287-kv transmission system this corresponds to 412,000 kw and 412,000 kva. The system constants are

Generator:	*$x_d=0.63$ per unit* *$x_q=0.42$ per unit*	*$x_d'=0.21$ per unit* *$H_g=5$ seconds*	*$T_{do}=5$ seconds*
Transformer:	*$x=0.10$ per unit*		
Line:	*$x=0.8$ ohm per mile per line* *$y=5.2\times10^{-6}$ mho per mile per line*		*$r=0.12$ ohm per mile per line*
System:	*$x_m=0.2$ per unit (includes receiving-end transformer reactance)*		*$H_2=50$ seconds*
Regulating System:	$\mu_1=20$ $\mu_2=4$ *$T_s=0.47$ second for 200-mile line*		*$E''_{max}=+2.25$ per unit, regulator* *$E''_{min}=-0.30$ per unit, limits* *$T_s=0.93$ for 600-mile line*
System Damping:	**Torque Coefficients**	**Fault On**	**Fault Cleared**
	T_{d11}	1	4
	T_{d12}	0	3
	T_{d21}	0	3
	T_{d22}	15	18

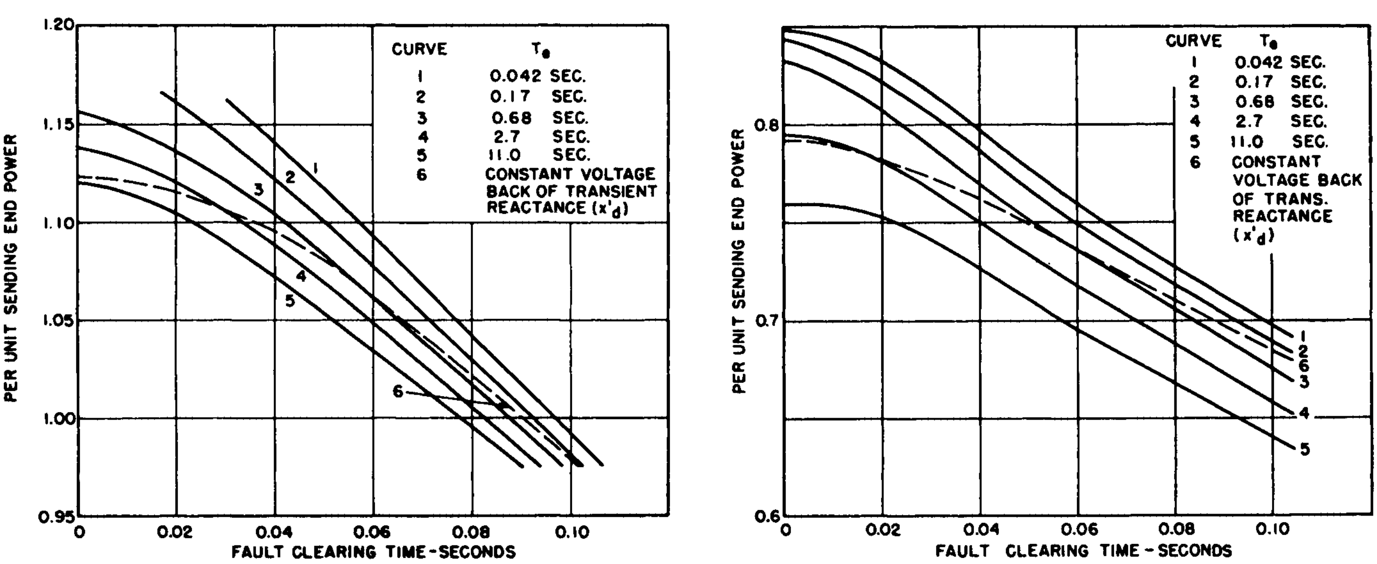

Figure 2. Sending-end power versus fault clearing time for stability with 3-phase fault at sending end showing the effect excitation system time constant with a switching station every 100 miles. A (left). 200-mile line. B (right). 600-mile line system of Figure 1

ing capacity, the power limit difference between 200- and 600-mile lines would have been increased. In making this study, the per unit generator power is assumed to be 5 kv^2, which is about the economical loading for a 600-mile double-circuit line (single conductor per phase) corresponding to 1.0 per unit power generation.

Effect of Intermediate Switching Stations. In the foregoing comparison of 200- and 600-mile transmission, the results are presented for the case of using intermediate switching stations every 100 miles, as this was considered the most economical number of intermediate switching stations.

Figure 3 shows how the power limit increases with an increasing number of switching stations. For this case the system shown in Figure 5 was used, assuming an equivalent voltage behind transient reactance x_d' and a total fault duration of three cycles. It can be seen readily that for the case of the 600-mile line the number of intermediate stations appreciably increases the power limit. The power limit more than doubles when five intermediate switching stations are used instead of none, and the received power limit is increased from 0.30 to 0.65 per unit, or from 124,000 to 268,000 kw, for a 287-kv system.

Assume that the transmission line costs \$30,000 per circuit mile for a 287-kv system, \$36,000,000 for the two circuits; and the transmission-line circuit-breaker positions cost \$200,000 per switch position, a total of \$800,000 for four circuit breakers when no intermediate stations are used and \$4,800,000 for 24 circuit breakers when five intermediate stations are used. Then the cost per kilowatt for the transmission, not including the terminal transformers and their circuit breakers, is

$$\frac{36{,}800{,}000}{124{,}000} = \$297 \text{ per kilowatt, no intermediate switching stations}$$

$$\frac{40{,}800{,}000}{268{,}000} = \$152 \text{ per kilowatt, five intermediate switching stations}$$

This result is not surprising, as it is well known that the use of intermediate switching stations is an economical means to increase the reliable power limit of high-voltage transmission systems.[2,6] In this study intermediate stations were assumed to be spaced every 100 miles.

Series Capacitor Compensation. Figure 4 shows the increase in transient power limit with increased series capacitor compensation. Per cent series compensation is taken in this article to mean the per cent compensation of the reactance of the line; that is, for a 600-mile double-circuit line with 0.8 ohm reactance per mile, 75 per cent compensation distributed in five intermediate stations is

$$x_c = \frac{600 \times 0.8 \times 0.75}{2 \times 5} = 36 \text{ ohms per phase per station or 0.18 per unit on a base of } 5\text{ kv}^2$$

Figure 5 is the system studied for this case. At 75 per cent line compensation, the sending-end power is 1.10 per unit power, and the receiving-end power is 0.98 per unit power. A 75-per cent compensation of the line, therefore, results in practically 1.0 per unit power transfer. For a 287-kv system this is $0.98 \times 412{,}000 = 403{,}000$ kw.

Previous studies[5,9] have indicated that systems may be built with as much as 75-per cent compensation and satisfactory operation can be expected. Line compensation of 75 per cent for this system at 287 kv requires about 0.90 per unit capacitive kilovolt-amperes in series capacitors and 0.90 per unit reactive kilovolt-amperes in shunt reactors or 370,000 kilovolt-amperes of each. If the series capacitor and shunt reactor compensation is assumed to cost a total of \$12 for each capacitive kilovolt-ampere plus each reactive kilovolt-ampere, the compensation for a 287-kv line is $370{,}000 \times \$12$, or about \$4,500,000. Using the previous example, the cost for transmission with five intermediate switching stations (excluding the terminal transformers and their circuit breakers) plus the compensation, is \$40,800,000 plus \$4,500,000, or \$45,300,000. The received power limit is increased from 268,000 kw to 403,000 kw. The cost per kilowatt is reduced accordingly from \$152 to \$112. This figure of \$112 per kilowatt can be used in comparison with other methods of increasing the power limit. Studies of this system with series capacitors were made also without shunt reactors.

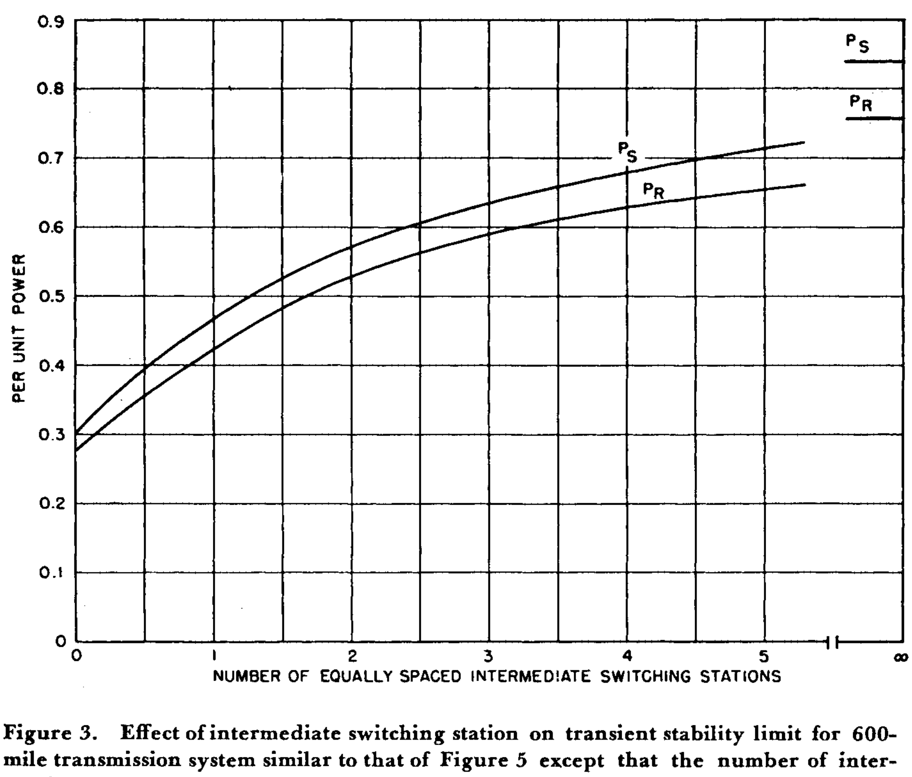

Figure 3. Effect of intermediate switching station on transient stability limit for 600-mile transmission system similar to that of Figure 5 except that the number of intermediate switching stations was varied and series and shunt compensation was not used

$V_R = V_S = 1.0$ $\quad H_g = 5.0$ $\quad H_m = \infty$ $\quad x_g = 0.30$ $\quad x_m = 0.25$

Per unit power and kva = (5kv)^2 Fault clearing time = 0.05 second

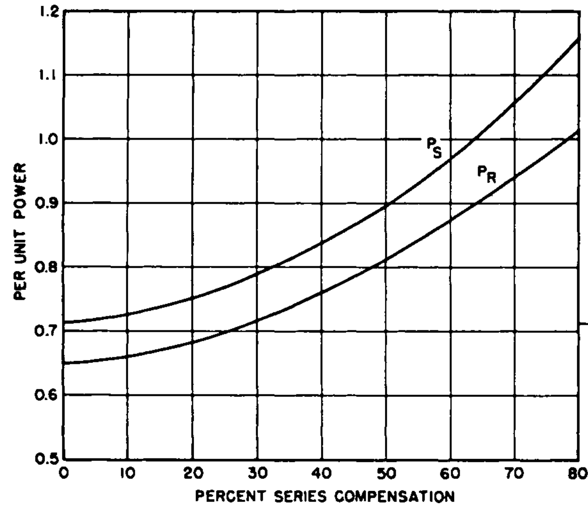

Figure 4. Transient stability limit of 600-mile line with the per unit power generated and received as a function of per unit series capacitor compensation. There are five intermediate switching stations. See Figure 5 for the system

$V_S = 1.05$ $V_R = 0.95$ $x_g = 0.30$ $H_g = 5.0$ $x_m = 0.25$ $H_m = \infty$

Per unit power and kva = 5 (kv)². The shunt reactor compensation equals the series capacitor compensation so that at normal frequency the surge impedance of the compensated line is 400 ohms. Fault clearing time = 0.05 second. Capacitor reinsertion time assumed to be zero

Figure 6 is a summary of a differential analyzer study which shows the variation in power limit in per unit as a function of switching time and exciter time constant for a 600-mile line (system of Figure 1) with 75-per cent series capacitor compensation without the use of shunt reactor compensation.

When Figure 6 and Figure 2*B* are compared, a good comparison is obtained of the effect of series capacitor compensation, as all of the other system characteristics (Figure 1) were kept constant except for a change in voltage regulator stabilizer time constant T_s. The sending-end power limit for a fault-clearing time of 0.06 second and an exciter time constant of $T_e = 0.68$ second has been increased from P_S of 0.735 to 1.07. The latter value is practically the limit obtained for the same conditions for a 200-mile uncompensated line, Figure 2*A*. In other words, the effect of 75-per cent series capacitor compensation has, in effect, increased the power limit of the 600-mile line to that of an uncompensated 200-mile line.

Intermediate Synchronous Condenser Compensation. A study of the effect of intermediate synchronous condenser capacity was made to determine the effectiveness of this method in increasing the power limits of the 600-mile system. Previous steady-state stability studies[10] have indicated the desirability of keeping the transient reactance of the intermediate synchronous condenser as low as practicable and distributing the synchronous condenser capacity along the line. The present transient stability study of the 600-mile-line case also showed the desirability of keeping the reactance as low as practicable and distributing the available capacity at more than one intermediate location. The optimum distribution for the transient case is dependent, among other factors, on the location of the faulted line section. For example, if an intermediate synchronous condenser is placed at the mid-point of the system of Figure 5, having a per unit rating of 1.25 and a transient reactance including its high-voltage transformers of 0.25 on its own rating, the sending power limit is increased from 0.71 per unit ($x_g = 0.30$) to 0.90. Whereas, if the same condenser capacity is equally distributed at the five intermediate stations, the sending-end power limit is increased to 0.98. If the synchronous condensers were distributed to obtain the highest power limit for a given system, the received power limit would be still further increased to at least 1.03 for this particular amount of synchronous-condenser capacity.

If the system has intermediate loads requiring synchronous-condenser voltage and reactive kilovolt-ampere control at intermediate points, then the benefits of the synchronous condenser are increased.

Intermediate Shunt Reactive Control Using Static Capacitors. Consideration has also been given to the possibilities of using intermediate controlled shunt reactive kilovolt-amperes for increasing the power limits. Dr. E. F. W. Alexanderson has proposed the use of arrangements of reactors and capacitors to obtain voltage control whereby the correction can be applied smoothly rather than in large increments.[11]

Consideration of such schemes indicates that, if the intermediate correction is distributed, higher power limits are obtained for a given total corrective capacity. Typical of the results are those shown in Figure 7 which were obtained with control only at the mid-point. With this the sending-end power limit may be increased from 0.71 to 0.95 per unit with a total resultant capacitive corrective kilovolt-amperage of 0.5 per unit. For a 287-kv system this corresponds to a capacitive kilovolt-amperage of 206,000 and a reactive kilovolt-amperage of 412,000 if the resultant capacitive kilovolt-amperage is to be controlled by variation of the reactive kilovolt-amperage. Here it was assumed that equal amounts of lagging and leading kilovolt-amperes were available at the mid-point and that they were applied instantaneously and smoothly to obtain a change in corrective current up to the limit

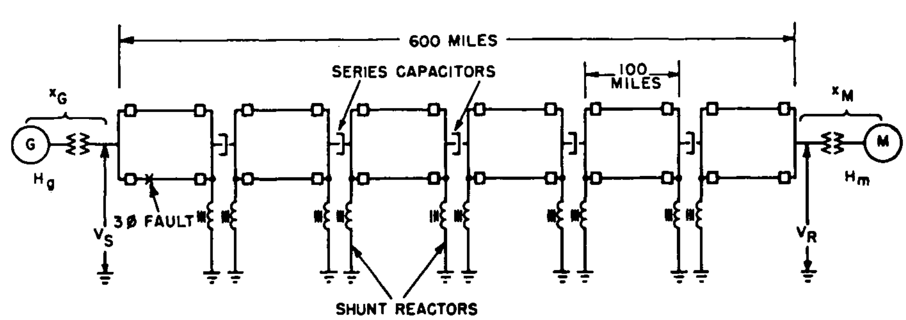

Figure 5. System diagram showing series capacitor compensation

of the capacity assumed for each case, with a regulation characteristic of 0.20 per unit for each 0.01 per unit deviation from normal voltage.

600-MILE TRANSMISSION WITH MID-POINT GENERATION

The systems studied are shown in Figure 8. Figure 8*A* shows the system which may be considered the initial development of a transmission system with a generating station 300 miles from its load center with three transmission lines and two intermediate switching stations. Figure 8*B* shows the same system but with another generating station located 600 miles from the load center and interconnected into the transmission system at the first generating station. From a study of the system of Figure 8*A*, it is found for the reactances chosen that the power limit of the sending-end power for a 3-phase fault near the sending-end bus of a duration of four cycles is 1.33 per unit; on the kilowatt base of 5 kv^2, for a 287-kv system, this is 550,000 kw.

The effects of variation in the receiving-end reactance were also studied. The power limit was reduced almost 15 per cent by a 100-per cent increase of the receiving-end reactance. It is significant that the receiving-end reactance is quite important in determining the maximum power transfer and that in the design of a system for receiving large blocks of power from distant stations it is essential for good economy to keep this receiving-end equivalent reactance as low as is practical by a rational circuit arrangement. It becomes particularly effective to bus all high-voltage circuits near the receiving end directly together. Fortunately this can now be more readily accomplished with the development and increasing use of high interrupting capacity circuit breakers.[12]

Keeping the output of the mid-station generator Number 1 at 1.33 per unit, corresponding to its maximum power limit with three lines, the system of Figure 8*B* was analyzed to determine the maximum total sending-end power that could be transmitted with stability. This limit was found to be 1.73 with 1.33 from generator Number 1 and 0.4 from generator Number 2. This corresponds to a loading on

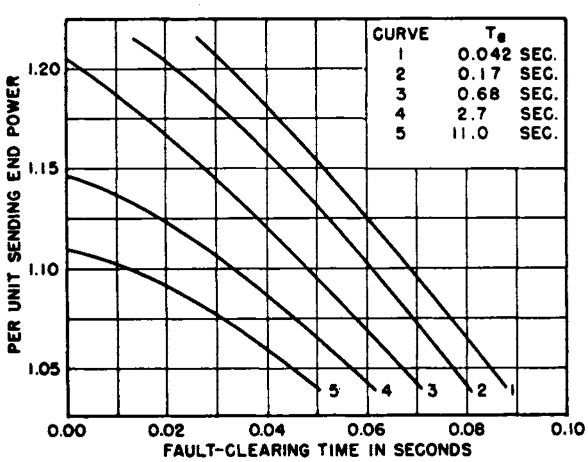

Figure 6. Transient power limit for 600-mile 75-per cent series compensated line. System conditions are the same as Figure 1 except the capacitors shown dotted in Figure 1 are assumed in the circuit. At each intermediate switching station $x_c = -0.18$

the two circuits from the distant generating point of 160,000 kw for a 287-kw system. The total received power P_R for this case is $1.62 \times 5.0 \times (287)^2 = 666{,}000$ kw. As this is a relatively light loading, the problem was studied to obtain an increase in the loading, particularly from the distant station.

If the mid-station reactance is halved and the inertia is doubled, in effect corresponding to interconnecting to a moderate amount of system capacity at this point, see Figure 8*C*, the power limit for the distant generating station is increased from 0.4 per unit to 0.85 per unit. If the mid-station reactance is further reduced to one-third of its original value and its inertia trebled, the power limit for the distant generating station is increased to 0.9. At this loading the critical fault moves from location Number 1 at the mid-station to location Number 2 at the distant generating station. With this doubling or trebling of the equivalent capacity at the mid-point, the power limits of the system approach those which may be considered reasonable from an economic standpoint. For a

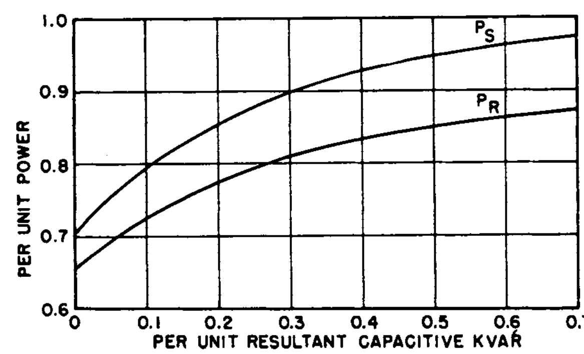

Figure 7. Transient power limit for 600-mile line using controlled capacitors and reactors at the mid-point switching station. The system consists of five intermediate switching stations similar to that of Figure 5. Corrective reactive kilovolt amperes of 0.20 per unit is applied for each 0.01 per unit of voltage variation from unit voltage at the mid-point. The total resultant reactive kilovolt-amperes are equal to the capacitive kilovolt-amperes shown on the abscissa

$H_g = 4.0$ $x_g = 0.30$ $x_m = 0.25$ $H_m = \infty$ $V_R = V_S = 1.0$

Base kilowatts = base reactive kilovolt-amperes

287-kv system the mid-generating station remains at 550,000 kw, and the output of the distant station is 370,000 kw. It is estimated that the loadings shown in Figure 8*C* would be realized if the tie is made to generating capacity of twice that of generator Number 1 and with an autotransformer bank capacity of about 300,000 kva for a 287-kv system. The additional power delivered to the load from the 600-mile-distant source of the system shown in Figure 8*C* as compared with the system of Figure 8*A* is 0.76 per unit. This was obtained by adding 900 circuit miles of line, approximately 22 circuit breaker positions, and a 300,000-kva autotransformer bank.

Assuming again a 287-kv system, the additional power delivery is 315,000 kw. The cost of the additional transmission circuits at \$30,000 per mile is \$27,000,000; the 22 circuit breakers at \$200,000 per position are \$4,400,000;

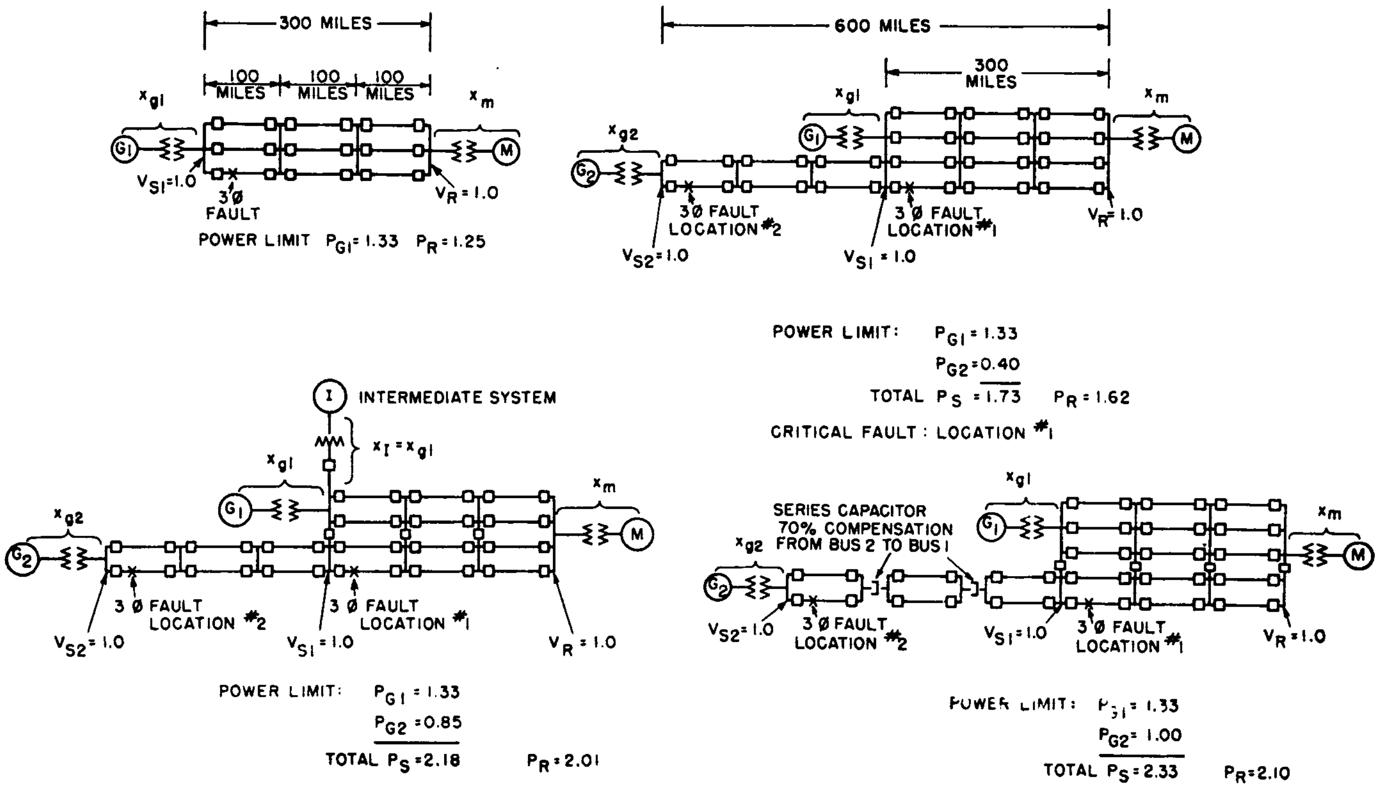

Figure 8. Transmission systems studied to determine the effect of mid-point generation. A (upper left): Initial system development. B (upper right): Initial system development plus extension of system for transmission of power from 600-mile-distant source. C (lower left): System B with intermediate system interconnection assumed equivalent to halving x_{g1} and doubling H_{g1}. D (lower right): System using series capacitors and additional 300-mile circuit added to that used by system B

Base kw = Base kva = 5 (kv)²

Generators:	*(Generator kilovolt-ampere rating assumed equal to kilowatt output at stability limit.)*		
	$x_{g1}=0.30$ *on kva rating*		$H_{g1}=5.0$ *on kva rating (seconds)*
	$x_{g2}=0.30$ *on kva rating*		$H_{g2}=5.0$ *on kva rating (seconds)*
Line:	$x=0.8$ *ohm per mile*	$r=0.08$ *ohm per mile*	$y=5.2$ *micromhos per mile*
Receiving-end System:	$X_M=\dfrac{0.50}{\textit{number of receiving-end circuits}}$		$H_M=\infty$
Fault:	*Three-phase, 0.067 second or 4 cycles*		

the autotransformer bank installed at $3.00 per through kilovolt-ampere installed is $900,000, or a total of $32,000,000. This is power transferred at 32,300,000/315,000 = $101 per kw. This figure, although only approximately obtained, indicates that the connection to intermediate system capacity when possible compares quite favorably with the straightaway compensated transmission cases previously considered and may result in the most economical transmission system.

It may be concluded here that a system of substantial line loadings per circuit can be realized even for 600 miles, if the high-tension lines are tied directly together and full use is made of the line generation or system capacity of two to four times the capacity of the distant generator source. It should be kept in mind that intermediate switching stations and a low-reactance receiving system are also necessary. The important conclusion is that by rational system design heavy line loadings are realizable at relatively small increase in cost, resulting in important reductions in the cost per kilowatt for transmission.

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