Practical Concepts in Capability and Performance of Transmission Lines

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THE tremendous growth in power loads and corresponding generating capacity during the past few years has brought about a heavy increase in power-transmission requirements. At least three different methods have been used to obtain the increased transmission capability necessary to do this job. These methods are:

1. Increased loading of existing lines.
2. Building of new lines or circuits at existing voltages.
3. Superposition of higher voltages on existing systems.

All of these approaches have been used or are under way on the American Gas and Electric System. Existing 132-kv lines originally intended for loads of 50,000 kw to 60,000 kw per circuit have carried peak loads up to 150,000 kw per circuit. Many new 132-kv lines have been constructed to supplement existing lines. And now a 330-kv system is being superimposed on the existing system. On a number of other systems, 230-kv backbone lines are being superimposed on existing networks ranging from 69 kv to 138 kv.

All of this expansion, with the very heavy expenditures required to bring it about, necessitates careful planning based upon clear concepts as to the performance and inherent capabilities of transmission lines. It is not intended to suggest at this point that there is any lack of adequate technical literature on this subject. On the contrary, transmission theory and practice has been well covered by many excellent books, papers, lecture courses, etc. Neither is it presumed to suggest that any revolutionary new theory will be offered here.

It is believed, however, that it will be helpful to clearer thinking and planning if some of the more important concepts regarding the capabilities, limiting factors, and performance of transmission lines are discussed from a practical application standpoint. It is hoped that clearer understanding can be further promoted if the comparative capabilities and performance of transmission lines at various voltages and distances can be presented in a form that is concise, comprehensive, and easy to apply. The simplified curves presented herewith have been designed to accomplish this purpose.

Limiting Factors in Transmission-Line Capability

There are a number of basic factors which limit or determine the capability of a transmission line. Some of these factors and the manner in which transmission capability is affected thereby will be discussed from a practical standpoint.

VOLTAGE LEVEL

Voltage level is undoubtedly the biggest factor of all. To begin with, however, we can eliminate voltage as a variable in the paper and figures by accepting the substantially correct assumption that load capability will vary directly as the square of the voltage and by expressing kilowatt load in terms of kv². We could stop with that, but it is convenient to go a step further and to express load in terms of the so-called surge impedance loading, (SIL), which is approximately 2.5 kv² for conventional 60-cycle single-conductor transmission lines. For divided-conductor lines, the SIL will be some 25 to 30 per cent higher, depending upon the number and arrangement of conductors. At SIL, the I^2X or kilovar loss in a line is substantially equal to the line-charging kilovars, a relationship that has useful applications which will be pointed out later.

STABILITY

At any given voltage, stability is probably the most important limiting factor for lines of longer lengths, at least for 200 miles and above. Many excellent papers and a number of very good books have been written on this subject dealing with all aspects of the stability problem.[1-4] What it really means practically is that a transmission line is essentially a reactance and as such requires the voltage at the sending end to be advanced in angle over the receiving-end voltage to bring about flow of power over the line. Obviously, the combined reactance of step-up transformers and generators as well as of receiving systems must be considered also, since these add more or less directly to the reactance of the line. A practical criterion or bench mark which has been established, both by analysis as well as by actual experience, is a capability of 1.0 SIL for a 300-mile conventional line operating at 60 cycles. This is a loading which can be carried within a steady-state stability margin on the order of 25 per cent on a 300-mile line with representative terminal impedance conditions.[5]

In this connection, it may be contended that for extra-high voltages, unless an extra premium is paid to avoid the normally higher reactance of transformers at these voltages, the full benefit of the squared-voltage relationship will not be realized and the 300-mile criterion may be too optimistic. In answer to this, it is believed that at such distances line costs will tend to reflect such a high proportion of total cost, including transformer and other terminal costs, that it will be good economy to spend something extra on transformers and perhaps on other terminal equipment, such as special regulating systems on generators, to maintain the higher stability limit. Also, in many instances, the terminal impedance may be reduced by the number and arrangement of transformers bussed in parallel. In this paper, therefore, and in the capability curves in Figs. 1, 2, and 3, the

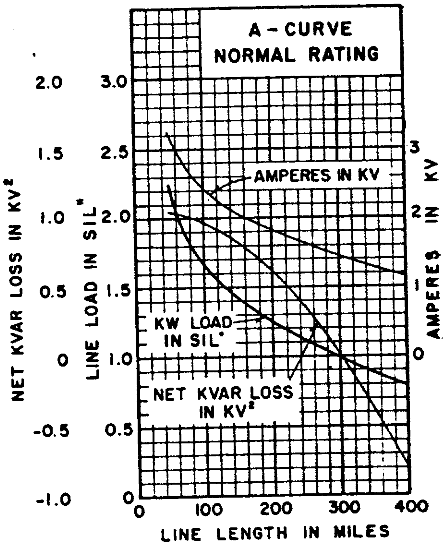

Fig. 1. Capability (A curve normal loading) of transmission lines in terms of SIL. Net kilovar loss in terms of kv². Amperes in terms of kv

* Note: SIL = approximately 2.5 kv²

Paper 53-338, recommended by the AIEE Transmission and Distribution Committee and approved by the AIEE Committee on Technical Operations for presentation at the AIEE Pacific General Meeting, Vancouver, B. C., Canada, September 1-4, 1953. Manuscript submitted June 8, 1953; made available for printing July 21, 1953.

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squared relationship between voltage and capability is assumed to be valid at all voltages, certainly through 330 kv or 345 kv, and the capability of a 300-mile line without series-capacitor compensation is taken as 1.0 SIL (2.5 kv^2 for single-conductor line at 60 cycles).

LINE CURRENT

Line current in itself should not constitute a limiting factor, except perhaps for relatively short lines. In connection with losses, both I^2R and I^2X, however, line current can be an important factor. An elemental relationship which is sometimes overlooked is the direct rise in current with voltage level as transmission voltages are increased. In other words, to utilize the inherent capability, which varies directly with the square of the voltage, the line current must go up in direct proportion to the voltage. Fortunately, the necessity for larger conductor diameter for corona reasons tends to facilitate the larger conductivity required at higher voltages.

NET REACTIVE LOSS

As pointed out in the foregoing, the net reactive loss is zero on a line carrying 1.0 SIL, which is the practical limit or bench mark for a 300-mile line. For shorter lines, however, as the load in terms of SIL goes higher, the I^2X loss may become a very important limiting factor. This is one of the reasons why it is not feasible to extend the 300-mile loading criterion in terms of kilowatt-miles to the shorter lines. For example, if this relationship were valid, a 100-mile line would be expected to carry 3.0 SIL. The I^2X losses at that loading, however, would be nine times the charging kilovolt-amperes, leaving a net kilovar loss of eight times charging kilovolt-amperes. Actually, due to departures from unity power factor, the I^2X loss would be even greater than this. (Practically, as will be shown later, this loading of 3.0 SIL is quite severe even for a 50-mile line and the 100-mile line will be heavily loaded at 2.0 SIL).

RESISTANCE LOSS

Unlike I^2X losses, resistance loss can be controlled within limits by the size of conductor used. In designing a new line, therefore, the I^2R losses may be largely an economic problem rather than a distinct limiting factor in line capability. On the other hand, with an existing line the energy losses along with conductor temperature may be decidedly controlling limitations if the conductor size was not originally chosen to be commensurate with the inherent capability of the line.

ACTUAL TEMPERATURE RISE

The actual temperature rise in line conductors may be a limiting factor where short lines may be called upon to carry loads well beyond those originally contemplated and where the accompanying high I^2R and I^2X losses can be tolerated. Here again, experience has shown that it is almost invariably a mistake not to keep in mind the inherent capability of a given line when selecting the original conductor size. In other words, conductor size should not be allowed to become a bottleneck, at least for lines 50 miles or more in length.

Capability and Loss Curves for Lines 50 to 400 Miles in Length

Of the several limiting factors discussed, four of them are probably the most controlling in determining capability of a line of given length. These four are voltage, stability limit, reactive loss, and, in the case of shorter lines, current in conductors. In order to set up a simple curve of capability against line length the voltage factor has already been eliminated by expressing kilowatt load in terms of kv^2. We can also express reactive loss in terms of kv^2 and current in terms of kv.

One point on this curve, shown in Fig. 1, was located quite definitely by using the bench mark previously discussed of 1.0 SIL loading for a 300-mile line.[5] The practical basis for setting up the remainder of the curve, taking into account the limiting factors discussed here, will now be explained.

Offhand, it might be assumed that the entire curve above and below 300 miles could be constructed on the basis of a constant kilowatt-mile product equal to that at the 300-mile point inasmuch as stability limit is basically a matter of total reactance from generator to load. This kilowatt-mile product in terms of kv^2 would be 300×2.5 kv^2 (1.0 SIL = 2.5 kv^2), or 750 kv^2. At shorter distances, however, the line capability will be affected by some of the other limiting factors such as reactive and resistance losses or even thermal limitations for very short lines. For example, at the 50-mile point a kilowatt-mile loading of 750 kv^2, or 6.0 SIL, would involve kilovar losses on the order of 10 kv^2 in numerical value. At 230 kv this would represent approximately 800,000 kw with a reactive loss of more than 500,000 kva and a line current in excess of 2,000 amperes. This loading is obviously impracticable not only from a current and loss standpoint but also from the standpoint of reasonable amounts of power to be concentrated in a single circuit, with due regard to service and reliability.

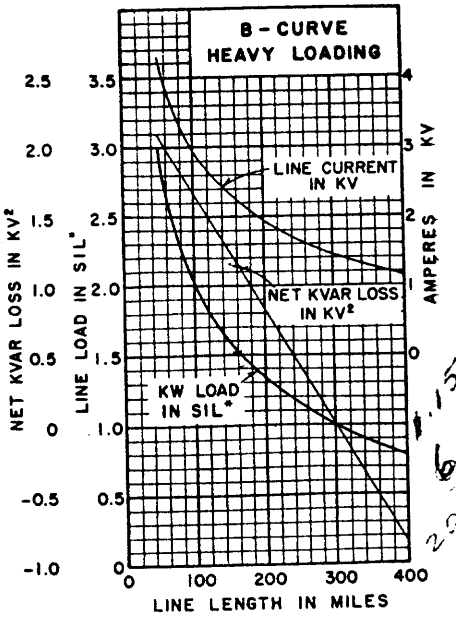
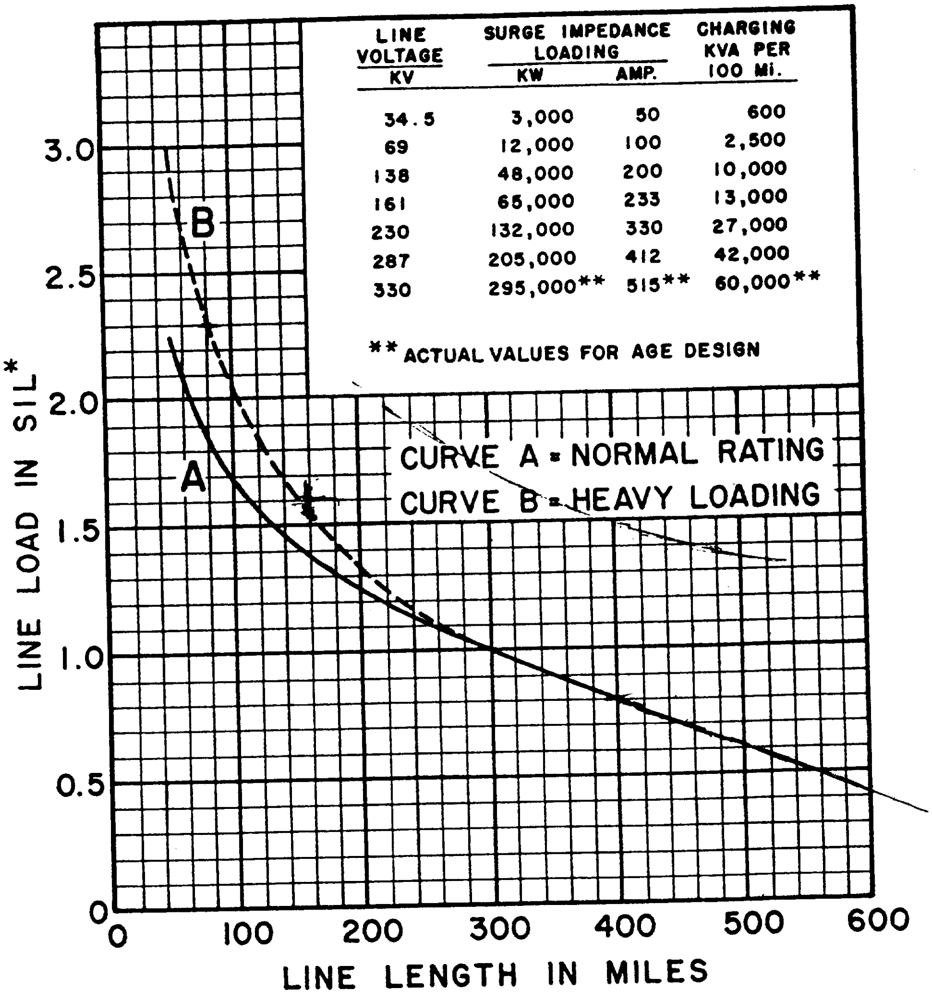


Fig. 2. Capability (B curve heavy loading) of transmission lines in terms of SIL. Net kilovar loss in terms of kv^2. Amperes in terms of kv

* Note: SIL = approximately 2.5 kv^2

It is rather obvious, therefore, that the kilowatt-mile product must be reduced progressively below 300 miles as distances become shorter. The extent of this reduction is a matter of judgment based upon practical considerations and experience rather than upon ultimate stability limitations. Thus, for the 50-mile point at the lower end of the heavy-loading curve, Fig. 2, a value of 3.0 SIL, or a kilowatt-mile product of 375 kv^2, has been chosen. While this does not represent the maximum loading that could be carried on a 50-mile line under favorable conditions such as a large conductor and an abundant kilovar supply, nevertheless it is a severe load for any line, even though the kilowatt-mile product is only one-half of the 750 kv^2 indicated at 300 miles. Both the feasibility and the severity of this loading have been demonstrated by actual experience. For example, a load of 140,000 kw per circuit on the American Gas and Electric System carried on the double-circuit 138-kv Sporn-Turner line, approximately 50 miles in length, represents approximately 3.0 SIL. In this case, I^2R energy losses due to the 397,500-steel-reinforced-aluminum-cable conductor used were uncomfortably high but the capability of 3.0 SIL was fully demonstrated. In this case also, the reactive losses were very heavy but were taken care of adequately by the kilovar capacity



LINE VOLTAGE KV	SURGE IMPEDANCE LOADING KW	AMP.	CHARGING KVA PER 100 MI.
34.5	3,000	50	600
69	12,000	100	2,500
138	48,000	200	10,000
161	65,000	233	13,000
230	132,000	330	27,000
287	205,000	412	42,000
330	295,000**	515**	60,000**

** ACTUAL VALUES FOR AGE DESIGN

Fig. 3. A and B curves, normal and heavy loading basis for capability of transmission lines in terms of SIL

* Note: SIL = approximately 2.5 kv^2 (except 330-kv design = 2.7 kv^2)

available in the 600,000-kw Sporn Plant. As indicated in Fig. 2, net reactive losses per circuit at 50 miles would be more than 2 kv^2, or something over 100,000 kilovars on a 230-kv line carrying 3.0 SIL or 400,000 kw. At 330 kv this loading of 3.0 SIL would represent over 800,000 kw and the reactive loss would be approximately 225,000 kilovars. Although the corresponding line current of some 1,400 amperes seems high for a conventional transmission line, it is not beyond the capability of actual conductors used, and currents of this magnitude under emergency conditions have been contemplated in 330-kv system planning.

With the 300-mile and 50-mile points established, the intermediate points for this curve were determined by taking a uniform rate of reduction in the kilowatt-mile product between 750 kv^2 and 375 kv^2. Also, by coincidence, the corresponding curve of net kilovar (I^2X) loss for the *B*-curve loading turns out to be a straight line.

The *A*-curve loading, shown in Fig. 1, represents a more conservative evaluation of capability for lines under 300 miles and was formulated by a progressive reduction in the kilowatt-mile product from 750 kv^2 at 300 miles to 282 kv^2 or 2.25 SIL at 50 miles. This loading is approximately the same as that used for the capability curve presented by the author in a previous paper[6] and is believed to be a better guide in most cases for design purposes in view of the high losses incurred at the heavier loading of the *B* curve.

At the other end of the curve, as line lengths increase, it becomes more and more imperative to develop loadings at more practical values since over-all maximum practical values since over-all costs go up and capabilities go down with increasing distance. In extending the curve beyond 300 miles, therefore, it has been assumed that somewhat higher loadings in terms of normal stability limits will be used, even at the cost of adopting special measures if necessary, such as reduced-reactance transformers, high-speed dynamic types of generator voltage regulators, etc. On this basis the 400-mile point on the curve was chosen at a kilowatt-mile value of 800 kv^2, or an SIL value of 0.8. This is believed to be a feasible and practical limit which can be attained in most cases without extra-cost low-reactance transformers.

While series-capacitor compensation has not been included in either the *A* or *B* curves, Figs. 1 and 2, it may be justified to increase line capability for distances above 300 miles and perhaps in some cases below 300 miles. The economic and technical phases of such capacitor compensation have been discussed extensively in the literature and will not be treated in further detail here, except to point out that adequate conductor size becomes doubly important if such compensation is to be used. In other words, if the line reactance is to be cut down to one-half or two-thirds of its natural value of around 0.8 ohm per mile, it is important from every standpoint, such as current capacity, economics of I^2R losses, and the performance characteristics of the line as determined by the ratio of resistance to reactance, to maintain a proper relationship between the actual line resistance and the compensated line reactance. The effect on line performance of too high a resistance/reactance ratio, in addition to energy losses involved, will be to require an excessive amount of power-factor correction or kilovar supply to the line at the receiving end in order to overcome the resistance drop in the line and to maintain voltage.

Description and Application of Capability Curves

It will be seen from the foregoing that the *A* and *B* curves differ only at the shorter distances below 300 miles, but coincide at the 300- and 400-mile points. This is shown in Fig. 3 which combines the *A* and *B* curves on one sheet for a ready comparison. Fig. 3 also includes a table showing at various transmission voltages the corresponding SIL loading in kilowatts and amperes as well as charging kilovolt-amperes per 100 miles of single circuit line, assuming, of course, conventional single-conductor 60-cycle lines.

As pointed out before, the *A* curve represents the more conservative basis o rating or capability. Using this curve a 230 kv, for example, the 300-mile ratin of 1.0 SIL would be 132,000 kw, while th 50-mile rating would be approximatel 300,000 kw. The net kilovar loss curv in Fig. 1 indicates a net loss of 1. kv^2 at 50 miles and, of course, zero a 300 miles. At 230 kv this 50-mile los would be approximately 54,000 kilovars o approximately 18 per cent of the kilowatt loading. This loss is over and above the charging kilovolt-amperes of the line and must be supplied at either the sending or receiving end. The larger the conductor size, the greater will be the proportion of this loss that can be supplied from the generating end for a given voltage gradient. Current values at 230 kv for the 300-mile and 50-mile lines would be approximately 340 amperes and 750 amperes respectively.

At 330 kv, corresponding values from the *A* curve would be 275,000 kw at 300 miles and 620,000 kw at 50 miles. Line currents would be approximately 500 amperes and 1,100 amperes respectively; net reactive loss for the 50-mile line would be approximately 115,000 kilovars.

As pointed out, the severe loading represented by the *B* curve, Fig. 2, has been found both by analysis and actual operating experience to be practicable if conductor sizes are not inadequate and if the higher reactive losses can be tolerated and supplied. In some cases economics may favor the use of the *B*-curve loading on a design or planning basis, even after including the cost of the kilovar capacity required and the value of the additional kilowatt losses. On the other hand, the *A*-curve loading has the advantage when applied to a growing power system of allowing additional room for growth. Certainly, during the last few years of heavy load growth, such additional margin in line capacity has saved the day in many situations even where line conductors were smaller than they should have been for such loading. One way of looking at the difference between the two curves would be to compare the *A* curve with the self-cooled rating of a transformer with the *B* curve corresponding to a forced-air rating. The additional kilovars of reactive capacity required to go from the *A* to the *B* curve would correspond to the cooling facilities required to be added to the self-cooled transformer.

With continuity of service in mind, it is customary to provide sufficient transmission capability in a given system to carry the entire load with a minimum of one line or line section out of service. To meet this criterion a minimum of two circuits must be provided, and for distances of the order of 100 miles or more sectionalizing will be justified.

The reduction in capability brought about by switching out a line section may be taken roughly as the ratio of the overall transmission impedances before and after the outage. In other words, for two circuits in parallel without sectionalizing, the capability would be reduced to one-half. Reduction factors for other combinations of lines and sectionalizing stations are given in Table I. In using the *A* or *B* curves to determine the reliable capability of a combination of parallel lines with or without sectionalizing stations, the aggregate capability of the individual circuits would then be reduced by the appropriate reduction factor from this table. After determining the net capability in this manner it may be of interest to check the severity of the line-outage condition from the data given on the curves. One check that can be made is to determine the change in total net reactive requirements caused by the switching out of the line section.

As a typical example, assume two circuits in parallel, 140 miles in length, with one intermediate sectionalizing station, as shown in Fig. 4. Using the *A* curve, we have a capability of approximately 1.5 SIL per circuit or a total capability of 3.0 SIL without any outages. From Table I the effective capability with one 70-mile section switched out would be $2/3\times3.0$ or 2.0 SIL. At 230 kv this would be 264,000 kw. Since this load represents only 1.0 SIL per circuit with all sections in service, the normal net reactive loss is zero. If one 70-mile line section goes out the net reactive loss goes up in the remaining line section which now carries 2.0 SIL over one circuit. From Fig. 3 the charging kilovolt-amperes for a 70-mile 230-kv line would be $70/100\times27{,}000$ or 19,000 kilovars. At 2.0 SIL the total I^2X loss in this section will be four times charging kilovolt-amperes, leaving a net loss of $3\times19{,}000$ or 57,000 kilovars. This amount of additional kilovar loss will be incurred by the switching out of the 1-line section.

A convenient equation which is approximately correct for net I^2X loss in conventional transmission circuits in terms of SIL and voltage is as follows

$$\text{Net } I^2X \text{ loss} = 0.52\times\frac{1}{100}\,[(\text{SIL})^2-1]\text{kv}^2$$

where 1 = line length in miles.

If the system of Fig. 4 is evaluated on the basis of the *B* curve, we obtain 1.68×2, or 3.36 SIL with no outages, which reduces to 2.24 SIL or 296,000 kw with one 70-mile section out. Using the equation just given, the total net kilovar loss under normal operating conditions without any line outage would be approximately 19,000 kilovars. With one 70-mile section out of service the net loss in the remaining circuit carrying 2.24 SIL would be 77,500 kilovars. This loss added to the normal loss of 9,500 kilovars in the remainder of the system results in a total net loss of 87,000 kilovars. The difference between this figure and the normal loss of 19,000 kilovars is a net incremental loss due to the line outage of 68,000 kilovars.

Table I. Reduction Factors for Line Section Outages

Number of Sectionalizing Stations	Number of Circuits in Parallel		
	2	3	4
1	2/3	4/5	6/7
2	3/4	6/7	9/10
3	4/5	8/9	12/13

As to which of the two ratings should be used, that is, the *A*-curve rating of 264,000 kw or the *B*-curve rating of approximately 300,000 kw, it is believed that the higher value would be entirely feasible with favorable terminal conditions including adequate reserves of kilovar capacity. Obviously, the curves will not take the place of more complete studies in a given case, particularly if it is desired to operate a system as close to the limit as possible. As a guide for a quick and fairly close approximation of transmission capability, however, they have been found very useful.

In using the approximate value of 2.5 kv^2 for the SIL of a conventional single-conductor 60-cycle line, it should be pointed out that this figure is more nearly correct for rather large ratios of conductor spacing to conductor diameter and that it tends to be somewhat low for modern designs of transmission lines using medium to large conductors. A significant commentary on this is the fact that the relatively smaller spacing used on double-circuit construction tends to increase the SIL and with it the inherent capability of such lines as compared with lines of single-circuit construction. For example, the 330-kv double-circuit lines with 1.6-inch-diameter conductors as adopted on the American Gas and Electric System will have an SIL of approximately 2.7 kv^2 instead of 2.5. The corresponding single-circuit tower construction would have given an SIL of somewhat less or approximately 2.6 kv^2. For most of the 138-kv designs used on our system the SIL appears to be closer to 2.6 kv^2 than the 2.5 kv^2 figure.

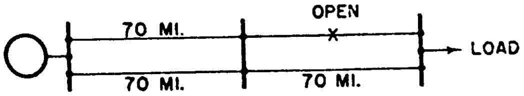


Fig. 4. Typical 140-mile transmission system with one sectionalizing station

The fact that SIL varies significantly for different designs of transmission lines does not in any way affect the validity of the *A* and *B* curves. It simply means that for a specific line a more nearly correct value for SIL can be determined and used with the curves if additional refinement is desired. It is also obvious that if the SIL is higher than the 2.5 kv^2 the corresponding charging kilovolt-amperes will also be somewhat higher than the values given on Fig. 3. Incidentally, it will be noted that the values of SIL and charging kilovolt-amperes given for 330 kv on Fig. 3 have been corrected to the actual values obtained with the 330-kv design of our System. Current values for SIL at different voltages will also be increased in direct proportion to any increase above 2.5 kv^2.

In conclusion, it might be pointed out that this tendency for SIL to go up with increased conductor diameters should be added to the other advantages of using larger conductors, such as higher thermal limits, lower resistance losses, and better line performance from the standpoint of dividing the reactive requirements of the line more equitably between generating and receiving ends. In other words, the larger conductor provides, in addition to these benefits, a definite increase in capability from the standpoint of inherent stability limitations.

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Discussion

J. G. Holm (New York, N. Y.): About 10 years ago statements were made in the engineering literature to the effect that a line loading equal to 1.0 SIL may be applied to single-circuit lines shorter or longer than 300 miles, and that the loading criterion, in terms of kilowatt-mile product, good for 300-mile lines may be extended to lines of any length, with a uniform margin of steady-state stability. Mr. St. Clair pointed out clearly that such statements constitute not only oversimplifications of the stability problem but lead to misleading conceptions and are erroneous. By dissipating the wrong concepts and making his statements in a very lucid manner, Mr. St. Clair has rendered a valuable service to the engineering profession.

In the companion paper by B. G. Rathsman and G. Jancke[1] the loading capacity of the 400-kv single-circuit 300-mile Midskog-Hallsberg line is given at 650,000 kw when the line has a 40-per-cent series-capacitor compensation and at 800,000 kw when the compensation is increased to 55 to 60 per cent, with "reasonable margin of stability" maintained in both cases. In terms of the SIL the loading of the Swedish line in the two cases is 1.625 SIL and 2.0 SIL respectively. Recognizing that this line has series-capacitor compensation, that it has bundle conductors, and operates at a lower frequency (probably 50 cycles), what in Mr. St. Clair's opinion would be its loading in the two cases, in terms of SIL, when reduced to the bases assumed in Fig. 3 of his paper?

Reference

1. Experience Gained with the Swedish 400-Kv Power Transmission and the Novel Features of the System, B. G. Rathsman, G. Jancke. *AIEE Transactions*, vol. 72, pt. III, Dec. 1953, pp. 1089–1100.

R. M. Butler (General Electric Company, Schenectady, N. Y.): Mr. St. Clair has performed a very worth-while service in discussing each of the interrelated factors which set limits to the loading capability of high-voltage transmission lines.

There are several points in the paper concerning the *A* and *B* loading curves, shown in Fig. 3, which I wish to question.

1. The author does not state with certainty which of the two loading curves he offers as the proper approximate guide.
2. It appears that in using the reduction factors shown in Table I with the curves of Fig. 3, normal line loadings will be unnecessarily low at the shorter transmission distances.

Discussing these points in their order, Mr. St. Clair states in one place that the *A* loading curve "...is believed to be a better guide in most cases for design purposes in view of the high losses incurred at the heavier loading of the *B* curve." But further in the paper with regard to the 140-mile line example, he says: "as to which of the two ratings should be used, that is, the *A*-curve rating of 264,000 kw or the *B*-curve rating of approximately 300,000 kw, it is believed that the higher value would be entirely feasible with favorable terminal conditions including adequate reserves of kilovar capacity."

With due regard for the fact that these curves are approximate and intended only as a guide, nevertheless there is considerable divergence between the curves for the shorter transmission distances. It would be helpful to know which of the two curves represent the best guide from the economic standpoint.

The author advocates the use of reduction factors to be used with the loading curves to take care of emergency operation following line outages. It does not seem reasonable to use reduction factors, particularly for the shorter transmission distances. For example, assume two parallel 50-mile transmission circuits with no sectionalizing stations. The maximum normal design loading per circuit that would be carried, including the possibility of one line outage (which calls for a reduction factor of one-half), would be about 1.1 SIL for curve *A* or 1.5 SIL for curve *B*. From the stability standpoint a loading in the range of 1.75 or 2.0 SIL could safely be carried per circuit as shown by numerous network analyser tests and by actual practice. Line losses need not prevent these higher loadings if the conductor size and reactive supply sources are adequate.

It would appear that the author has been a little too conservative and that the *A* loading curve without reduction factors would be the better guide.

I am most pleased that the author has chosen to stress the importance of using large conductors on major bulk power transmission circuits so that thermal bottlenecks and line losses will not prematurely require additional circuits to handle load growth.

The author has correctly emphasized the importance of adequate kilovar supply sources at load receiving points on the transmission system i~~s~~ heavy line loadings are to be carried. This is important not only from the standpoint of keeping losses down and delivering better voltage to the subtransmission but also is helpful in maintaining higher stability limits.

It would be appreciated if Mr. St. Clair could state from his experience approximately how low the voltage applied to bulk power substations may fall following an outage on a line supplying the substation assuming, of course, that there are two sources of supply to the substation. It is understood that this would vary depending on many factors but perhaps a general figure might be given which would be of help to others in deciding when and how much additional kilovar support might be needed for such emergencies.

J. T. Madill (Aluminum Company of Canada, Ltd., Montreal, Quebec, Canada) It is interesting to use Mr. St. Clair's concepts to check the 300-kv transmission lines being constructed for the Kemano-Kitimat development of the Aluminum Company of Canada, Ltd. The normal circuit loading for a 50-mile line consisting of 10 miles double circuit, 10 miles single circuit, and 30 miles double circuit will be 640,000 kw which is 2.8 times the SIL. The emergency loading is about 1,200,000 kw, or 5.3 times the SIL. Here, as Mr. St. Clair warns, conductor current, or strictly conductor tota temperature, is the limiting factor. Switching stations and some source of kilovars a the receiving end will reduce the reactive los and voltage drop and increase the power limit.

The author has clearly outlined the fundamental factors involved in line loading and this should serve a useful purpose.

S. B. Crary (General Electric Company, Schenectady, N. Y.): This paper presents a clear conception of the loadings which can be expected of modern transmission line. Although loading curves have been presented before, Mr. St. Clair has made a valuable contribution in explaining the basis for the normal and heavy-loading curves and the extension showing the kilovar and ampere characteristics of such loaded transmission lines. These characteristics show clearly the importance of higher current ratings as the voltage increases, which is important also from an apparatus point of view. The use of increased kilovars to obtain normal and emergency loadings of transmission circuits is a desirable feature to review, as in general the cost of kilovar supply has not increased as rapidly as other components, allowing for increases in the loading of transmission circuits above that previously considered optimum.

The curves in the paper also point out indirectly the importance of the series capacitor at line lengths approaching and above 300 miles in order to maintain a line capability equal to at least unit SIL. This, of course, is the region where the series capacitor becomes economical.

The author's point of using the actual SIL instead of the nominal value of $2.5\ \text{kv}^2$ is well taken and shows an additional important advantage for larger conductors and smaller spacings, thus further encouraging practical reductions in line insulation—a trend which is continuing, particularly at the high-voltage levels.

H. P. St. Clair: Mr. Holm, noting that the 300-mile Midskog-Hallsberg 400-kv (380-kv) line is rated at 650,000 kw with 40-per-cent series capacitor compensation and at 800,000 kw with 55 to 60-per-cent compensation, inquires as to what the loading would be on the basis of Fig. 3.

In applying this curve to the Swedish line, it should be pointed out that the curves are based upon 60-cycle single-conductor lines, whereas the Swedish line has divided conductors and operates at 50 cycles. Using the 300-mile point of 1.0 SIL from Fig. 3, modified by the frequency correction of 1.2 for 50 cycles, and by a factor of approximately 1.25 for divided conductors, we get a loading of $2.5\times380^2\times1.2\times1.25$ or 540,000 kw at 380 kv, without compensation. Mr. Rathsman's figure of 650,000 kw, which is some 20 per cent above the corrected Fig. 3 value, would seem to be a rather conservative evaluation of the effect of 40-per-cent line compensation. It is probably not too conservative, however, in terms of the stability margin considered necessary for the Swedish system.

Mr. Butler has asked for a clearer statement as to which of the two loading curves the author recommends as the proper guide and points out an apparent inconsistency between different portions of the paper where the author has made comments on which curve should be used.

Actually, the apparent discrepancy disappears if the basic character of the two curves is understood. These curves are intended to give the capability of a given line as an individual circuit or unit without any consideration of additional emergency loading brought about by loss of parallel circuits. Practically, however, such emergency load conditions must be taken into account in system design, and it is here that the range of load capability between the *A* and *B* curves can be used as a guide. If the emergency load condition does not exceed the *B* curve, it should be all right in most cases, but any loading above the *B* curve should be examined carefully to determine its feasibility.

This leads to Mr. Butler's second question regarding the use—or misuse—of reduction factors as given in Table I. It will be noted in reference 6 of the paper that, in assigning load capabilities for the economic studies reported there, the reduction factors for the 100-mile and 200-mile 2-circuit lines were modified for precisely the reasons Mr. Butler points out. In the 140-mile example where a reduction factor of two-thirds was applied without any modification, certainly the use of less than the *B* curve criterion would be unnecessarily conservative.

As to Mr. Butler's suggestion that reduction factors should not be used at all, particularly for shorter lines, it hardly seems reasonable to assume that one circuit can carry as much as two. Also, regardless of which loading curve is used, *A* or *B*, or whether or not reduction factors are used, the final criterion is the ability of the remaining circuit to carry the emergency loading. In the 50-mile 2-circuit example, a reduction factor of one-half is undoubtedly too conservative on the *A* curve basis, and as Mr. Butler points out, may even be too conservative for the *B* curve. On the other hand, it does not seem very sensible to say that reduction factors are unnecessary and that either *A* or *B* loadings per circuit can be doubled if one circuit goes out. Even on the *A* curve basis this would mean a load on the remaining circuit of 4.5 SIL, ordinarily an impracticable loading unless extra-large conductors and heavy reactive sources are available. At 138 kv, for example, the line current would be close to 1,000 amperes and reactive loss in the line would be at least 100,000 kilovars.

The normal and emergency circuit loadings which Mr. Madill indicated for the 50-mile 300-kv double-circuit line, under construction for the Kemano-Kitimat development, are rather high values even in terms of the *B* curve of Fig. 3. Offhand I would have hesitated to accept the feasibility of a 5.3 SIL loading on such a line even on an emergency basis without a careful study. On the other hand, with the large conductors, used, it will probably be found that the SIL for this line is considerably higher than $2.5\ \text{kv}^1$, possibly as high as $2.8\ \text{kv}.^2$ If that is so, the actual SIL would be as high as 250,000 kw, and a load of 1,200,000 kw would represent about 4.8 SIL rather than 5.3. This is still high, but with a very large conductor and ample kilovar sources, it will no doubt be feasible and within stability limits.

Mr. Crary's favorable comments on the practical usefulness of curves presented in this paper are appreciated. It was the author's objective to emphasize the importance of considering all pertinent factors in evaluating transmission-line capabilities rather than expressing capability in terms of only one or two factors, such as stability limit alone or network analyzer results which may not take into account all of these factors. If this objective has been accomplished, it may be concluded that the effort has been of some value.