APPLICATION OF LINE LOADABILITY CONCEPTS TO OPERATING STUDIES

Richard Gutman
Senior Member, IEEE

American Electric Power Service Corporation
Columbus, Ohio

Abstract - This paper describes a methodology for determining the loading limits of extra-high-voltage transmission lines, taking into account the system environment under which these lines operate. This methodology is based on the line loadability concepts developed for planning applications [1,2] and extends their use to operating studies. For this purpose, specific line and system parameters are used to construct curves of thermal duty, bus voltage, and steady-state stability as a function of the power carried by the line. These curves, referred to as the operating loadability characteristics, not only make it possible to quickly identify the principal operating limitations to line loadability, but also provide a convenient mechanism for quantifying the trade-offs which exist between a given choice of system operating criteria and line loadability.

Keywords: Line loadability, St. Clair curves, SIL, thermal-voltage-stability limits, operating studies.

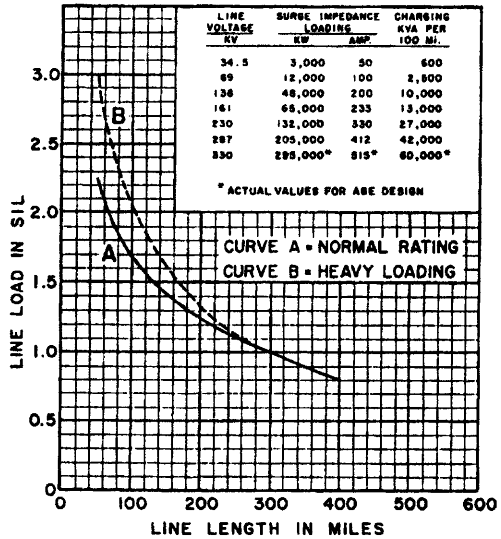
INTRODUCTION

To assess the power-carrying capability of the transmission system, the capabilities of specific transmission lines must be known. Generally, the capability of a transmission line is limited by the thermal rating of the conductor or associated terminal equipment. In some situations, however, operating criteria such as voltage limits and stability margins constrain the line loading to a level below the thermal rating. The loading level at which the thermal rating or an operating criterion -- whichever is more constraining -- limits the load-carrying ability of a line is known as the line loadability.

The subject of transmission line loadability was investigated by St. Clair in 1953 [1]. Based on practical considerations and experience, generalized curves of load-carrying capability (expressed in per unit of surge impedance loading, SIL) vs. line length were developed for lines up to 330 kV (Figure 1). These curves are referred to as "St. Clair curves." In 1979, Dunlop, et al. [2] provided an analytical basis for St. Clair's "heavy loading" curve and extended its application to transmission lines in the 765-1500 kV range. The analytical basis utilized a simplified representation of the system, including both line and system parameters, to derive line loadability characteristics subject to assumed performance criteria (Figure 2). It was shown that, for a specific set of assumptions for system parameters and performance criteria, line loadability characteristics are nearly identical to the original St. Clair curve.

The generalized line loadability characteristics described in [2] were intended primarily as a tool for the planning engineer to illustrate how the maximum load-carrying ability of a line is related to both line length and the assumed set of performance criteria. A significant benefit was the ability to identify the principal limitations to line loadability --

Source: H. P. St. Clair [1]



LINE VOLTAGE KV	SURGE IMPEDANCE LOADING KW	SURGE IMPEDANCE LOADING 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

Figure 1. Capability of transmission lines in terms of SIL.

Source: R. D. Dunlop, R. Gutman, P. P. Marchenko [2]

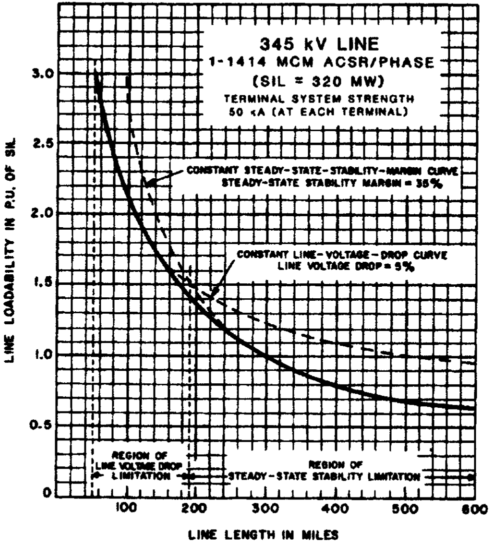


Figure 2. Loadability curve derived analytically.

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i.e., thermal limitation for relatively short lines, voltage drop limitation for medium-length lines, and steady-state stability limitation for long lines.

As helpful as these loadability characteristics have been in planning applications, they are not well suited for use with transmission lines which operate in a system environment different from that assumed for the generalized loadability characteristics. To overcome this limitation, the loadability analysis described in this paper is "customized" to reflect the specific operating conditions for a given line. The result is a set of operating loadability characteristics, which provide a better understanding of, and a comparative measurement of, the overall transmission limitations to power transfer across lines or system interfaces.

LINE LOADABILITY ANALYSIS - MODIFIED APPROACH

In establishing the analytical basis for the St. Clair curve, Dunlop, et al. [2] used a simplified system model which included an equivalent-Π representation for a transmission line of variable length. The sending- and receiving-end systems to which the line was connected were represented as positive-sequence Thevenin equivalents.

To replicate St. Clair's "heavy loading" curve, a mature (50 kA fault duty) system at each end of the line was assumed. Other key assumptions involved the performance criteria imposed upon the model. Specifically, a 5% voltage drop across the line and a 35% stability margin were considered. By varying these criteria, the loadability of a line can be changed. Making the criteria more restrictive (i.e., decreasing the allowable voltage drop or increasing the required stability margin) can improve system reliability, but will generally result in a reduced loadability of the transmission line.

In actual system operation, system parameters and performance criteria can vary depending on where in the system the transmission line is located and how it is operated. Through variations in system strength, performance criteria, and line length, specific scenarios can be formulated showing that the loadability of a line can be significantly lower than its thermal capability (Figure 3). Thus, to obtain a measure of practical capability of a line, the loadability analysis must be customized to reflect the operating conditions for each transmission line.

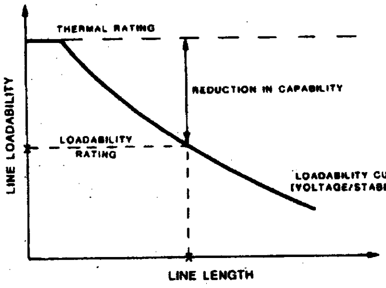


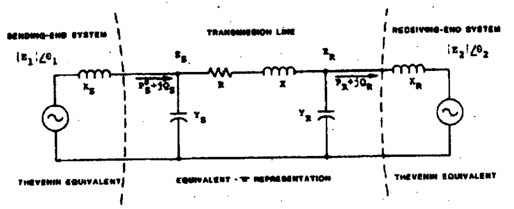
Figure 3. Reduction in line capability due to limitations imposed by system performance criteria.

Model Construction

To customize the loadability analysis, a model for evaluating the loadability of specific transmission lines was developed. This model is similar to the generalized model discussed in [2], but includes the following modifications:

- the use of specific line configuration, line length, and shunt reactor compensation for each line studied;
- the use of specific system strength at each terminal of the line based on known system conditions;
- the effect of voltage regulation, if any, at the line terminals;
- the effect of transmission paths parallel to the line under study;
- the effects of critical system contingencies which, by increasing the line flow and reducing the system strength, bring the loading of the line closer to the loading limit.

In the modified model, shown in Figure 4, the transmission line is represented by an equivalent-Π with the terminal systems modeled as Thevenin equivalents. The transmission line equivalent is comprised of positive-sequence inductive and capacitive parameters associated with the specific line of interest. Shunt compensation that is physically located on the line is combined with the line charging at the appropriate line terminal. The Thevenin equivalent reactances are determined from the short circuit strengths of the sending- and receiving-end systems.



INPUTS

Transmission Line Parameters	R, X, Y_S, Y_R	
Thevenin Equivalents:		
Reactances	X_S, X_R	
Voltages	$\lvert E_1\rvert, \lvert E_2\rvert$	
System Angles	θ_1	(Varied from 0° to 90°)
	$\theta_2 = 0°$	(Reference Point)

OUTPUTS

Bus Voltages	$\lvert E_S\rvert, \lvert E_R\rvert$
Sending-End Flow	$P_S + jQ_S$
Receiving-End Flow	$P_R + jQ_R$
Angular Difference Across Model	$(\theta_1 - \theta_2)$

*NOTE: LINE LOADABILITY = P_S (MW)

Figure 4. Model for line loadability analysis.

The voltages behind the Thevenin equivalent reactances are held fixed at values determined for a particular system state, i.e., "base flow" condition. The Thevenin equivalent voltages are determined by reflecting the bus voltage and real/reactive power flow (base flow) at the line terminals through the Thevenin equivalent reactances. The system state selected represents a heavy loading condition consistent with the line loadability determination. This requires the use of a peak load system condition, with both contracted and expected economy sales, to obtain a high base flow level. This base flow serves as the starting condition for the line loadability analysis.

Special Features

The model has the ability to account explicitly for voltage regulation at either or both terminals of the line. This feature is particularly useful for transmission outlets from the generating plants. Voltage regulation in the model is represented by variable reactive support at the regulated bus, with the maximum support equal to the reactive capability of the regulating device. The effect of voltage regulation on line loadability is illustrated in Figure 5. Up to the limit of reactive support, Q_{Max}, the bus voltage is maintained at a fixed level equal to the scheduled voltage of the regulating device. After that point, the bus voltage declines at an increasing rate until it reaches a "critical value," set by the steady-state stability limit of the system, beyond which no further increases in steady-state line loading are physically possible. Voltage regulation helps to support the bus voltage as the loading level increases, resulting in higher (and more realistic) line loading limits. Accurate modeling of voltage regulation is especially important for lines which are susceptible to low voltages during heavy loading conditions.

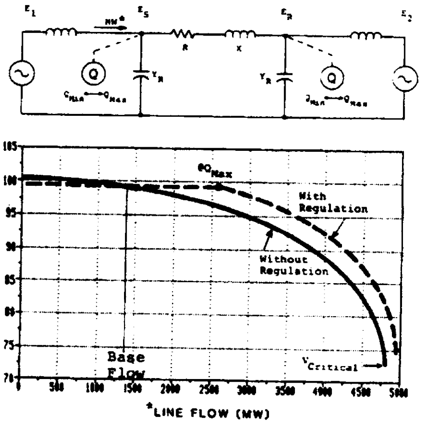


Figure 5. Effect of voltage regulation on line loadability.

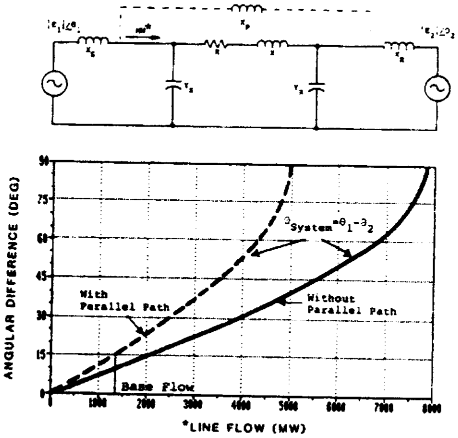


Figure 6. Effect of parallel transmission path on line loadability.

In the context of an interconnected power system, the transmission system surrounding the line of interest forms a parallel path for the power flow. This aspect of the system is represented in the model by an equivalent reactance in parallel with the line under study (Figure 6). The presence of the parallel path increases the total amount of power that can be transferred from the sending end to the receiving end of the line by lowering the effective reactance between the two terminals. However, for a given angular displacement across the system (Θ_{System}), which is related to the desired margin of steady-state stability, the loading on the line will decrease due to the sharing of power flow between the line and the parallel path.

An important consideration in developing the operating loadability characteristics is the effect of system contingencies. Typically, systems are planned and operated on the basis of at least a single contingency. Consequently, high or critical facility loadings will generally occur while another facility is out of service. This suggests that the assessment of line loadability should also include the effect of critical contingencies in order to maximize the flow on the line and/or to reduce the strength or reactive support of the terminal systems. In this way, the conditions under which the line loadability is of greatest interest will be captured in the analysis. An added benefit of including the contingency effect in the model is that higher initial loading levels (i.e., base flows) will result. Since the model is an approximation, the closer the base flow level is to the prospective line loadability, the more accurate are the results.

OPERATING LOADABILITY CHARACTERISTICS

Derivation of Curves

Operating loadability characteristics, as distinguished from the generalized characteristics developed by St. Clair, reflect the specific system conditions under which a given line operates. An analytical procedure to develop the operating loadability characteristics is summarized in Figure 7. Three types of data are required for the analysis: line parameters, system parameters, and operating parameters.

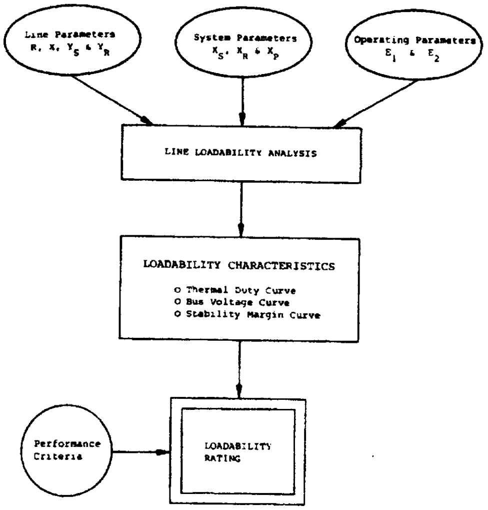


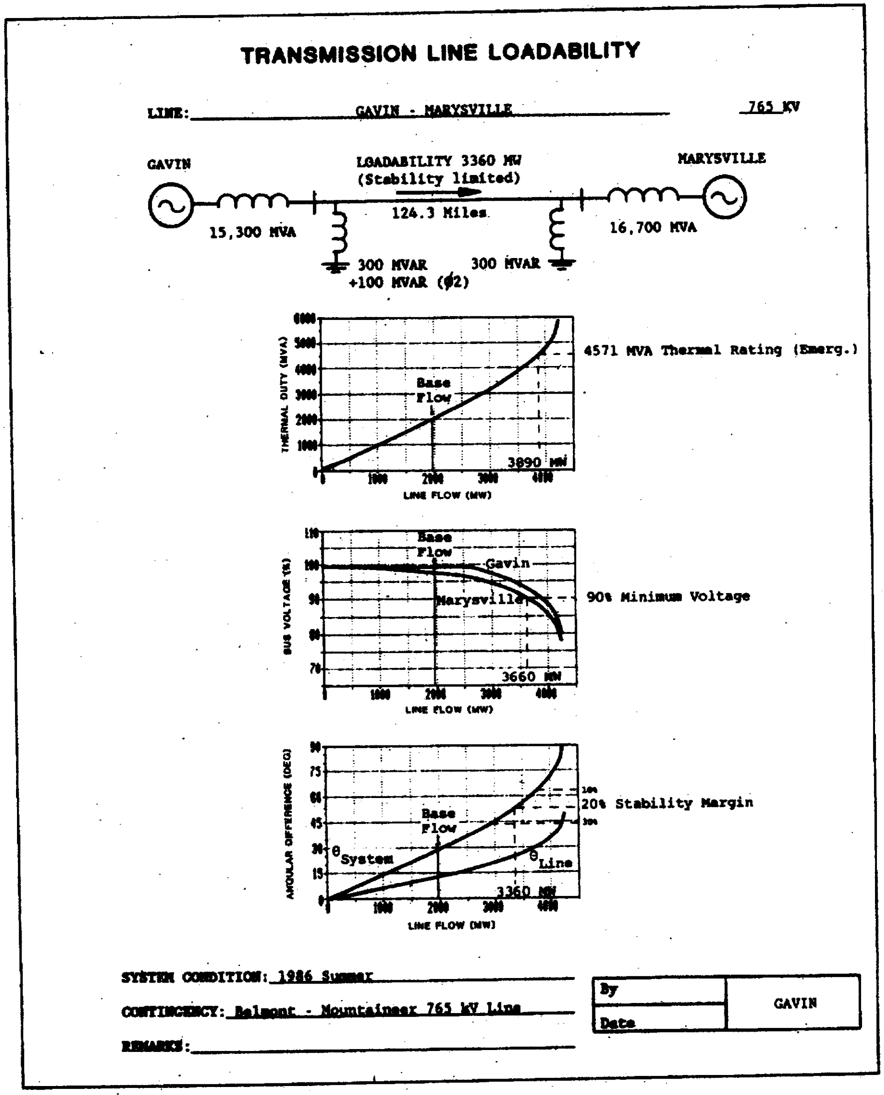
Figure 7. Analytical procedure for determining line loadability.

The line parameters include the positive-sequence resistance (R), reactance (X), and the sending- and receiving-end admittances (Y_S and Y_R). The effect of shunt compensation is included with the line admittances. These values are specific for each line and generally do not change over time.

The system parameters used in the model describe the Thevenin equivalent impedances at the line terminals (X_S and X_R) and the equivalent parallel path impedance (X_L). These values are obtained from short circuit analyses which reduce the system surrounding the line to a two-point equivalent to be connected at the line terminals. The equivalent system parameters are sensitive to system configuration and change with both time and system location.

The operating parameters are the Thevenin equivalent voltages (E_1 and E_2) behind the sending- and receiving-end systems. These parameters are calculated from a solved ac load flow case which is used as the base flow condition for the loadability analysis. The Thevenin equivalent voltages are calculated by reflecting the bus voltage at each line terminal back through the Thevenin equivalent impedance. The Thevenin equivalent voltages influence the bus voltages and reactive power flows in the model and are sensitive to major changes in system configuration and/or operating condition.

When all line, system, and operating parameters are combined in the loadability model, they uniquely describe a specific transmission line in a specific system location under specific operating conditions. The loadability model can then be used to simulate power flows -- higher or lower than the base flow level -- and their effects on bus voltages and system stability. The simulation results are used to generate a set of three curves that comprise the operating loadability characteristics (Figure 8). These curves describe the changes in thermal duty, bus voltage, and system angular displacement as a function of the real power (MW) flow on the line.



SYSTEM CONDITION: 1986 Summer

CONTINGENCY: Belmont - Mountaineer 765 kV Line

REMARKS:

Figure 8. Transmission line loadability characteristics.

The thermal duty curve illustrates the relationship between the required thermal capability, expressed in MVA, and a given MW line flow. The thermal duty is defined as the line current times the nominal line voltage. There are actually two thermal duty curves, one for each terminal of the line, taking into account the generally different real and reactive flows at the two line terminals. These differences are relatively small, however, and the two curves are essentially identical. The thermal duty curve is practically linear over most of its length, except in the heavy loading region, where the slope increases more rapidly due to declining bus voltages.

The bus voltage curve describes voltage performance at each terminal of the line as a function of the line flow. Generally, the receiving end of the line exhibits a greater voltage decline than the sending end, thus limiting the amount of power that the line can carry. In Figure 8 (middle curve), the Gavin bus voltage is regulated by the Gavin Plant for line loadings up to about 2600 MW -- hence, the flat voltage profile for this range of line flows. Once the limit of regulation is reached, further increases in line flow result in progressively larger bus voltage depressions, leading to a phenomenon commonly known as the "voltage collapse." While significant in terms of its system consequences, voltage collapse is only a symptom of a more fundamental problem, i.e., operation or attempted operation beyond the steady-state stability limit of the system. This suggests that the use of reactive support on the system, either fixed or controllable, can move the system closer to its steady-state stability limit.

The angular displacement curve shows the phase angle difference across the line terminals (θ_{Line}) and across the complete system model (θ_{System}) as a function of the line flow. The θ_{System} and θ_{Line} curves are similar <u>only</u> when the system reactance is negligible relative to the line reactance (e.g., when a long transmission line connects two strong systems). In general, θ_{System} is significantly greater than θ_{Line} and, therefore, only θ_{System} should be used in assessing the system steady-state stability. System stability is usually measured in terms of the available stability margin, which is defined as the margin between the maximum possible power flow (P_{max}) and a given power flow (P_{given}) expressed in percent of P_{max} (Figure 9).

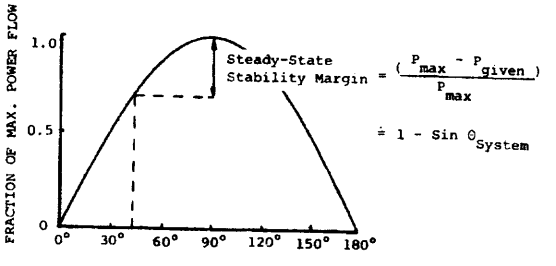


Figure 9. Steady-state stability margin.

Performance Criteria and Line Loadability

Each of the three curves, shown in Figure 8, addresses a possible limiting factor to transmission line loadability. When used in conjunction with a given set of performance criteria, these curves serve to establish a single-valued loadability rating for the line. The loadability rating incorporates the following three performance criteria:

1. Emergency thermal rating of a line or associated terminal equipment, whichever is lower. The emergency rating, rather than normal rating, is used assuming that sufficient time will exist following a contingency to reduce the line flow to a level below the normal rating.

2. Minimum acceptable bus voltage of 90% at each end of the line.

3. Steady-state stability margin of 20%. This margin is in addition to the critical contingency considered in line loadability calculations and, therefore, is not directly comparable to the 30-35% margin inherent in the St. Clair curves (which did not consider the contingency effects).

The latter two criteria reflect the desired level of operating reliability and should not be viewed as rigid limits. These criteria make it possible to set the maximum loading limits based on acceptable transmission system stress, as determined from the loadability characteristics. Since these criteria relate only to the steady-state conditions on the system, and do not indicate whether the system can or cannot reach a new steady-state condition following a disturbance, the line loadability analysis should not be treated as a substitute for comprehensive dynamic studies.

The loadability rating for a line is determined as the highest real power (MW) which the line can carry and still satisfy all of the established performance criteria. In Figure 8, for the Gavin-Marysville 765 kV line, this loading level is 3360 MW as limited by the 20% stability margin. Note that the line thermal rating (4571 MVA) and the minimum bus voltage criterion (90%), taken individually, allow higher loading levels (3890 MW and 3660 MW, respectively), but in both cases the steady-state stability margin would be less than the desired margin of 20%. If a smaller stability margin, say 10%, were considered adequate, a line loading of 3780 MW would be possible, assuming that the minimum bus voltage criterion could also be relaxed to 88%. In this manner, the three curves in Figure 8 can be used to quantify the trade-offs which exist between a given choice of operating criteria and line loadability.

It is important to remember that the loadability ratings -- unlike the thermal ratings -- are unidirectional and must be recomputed when the direction of the power flow is reversed. In practice, however, those lines which experience the power flow reversal are usually lightly loaded, and thus, accurate knowledge of the loadability rating for those lines is not essential.

Verification

A rigorous ac load flow analysis of the interconnected system performance was used to verify the accuracy of the operating loadability characteristics. For this verification, the bus voltages and angular displacement across the line (θ_{Line}) were selected. The choice of these quantities was based on their sensitivity to the power flow, especially at heavy loading. Also, θ_{Line} was selected because θ_{System} is not available from the ac load flow analysis. It should be noted, however, that θ_{System} (not θ_{Line}) provides a measure of system stability.

For the verification of the loadability characteristics, a long (148.2 miles) 345 kV line, Amos-Matt Funk, was used to amplify potential differences between the line loadability analysis and the ac load flow analysis. As shown in Figure 10, the bus voltage curves from the loadability analysis (solid lines) track well those obtained from the rigorous ac load flow analysis (dashed lines). A similarly close comparison is evident between the θ_{Line} curves using the two approaches. This is particularly true in the region near the base flow level, underscoring the need to use a base flow level as close as possible to the prospective line loadability.

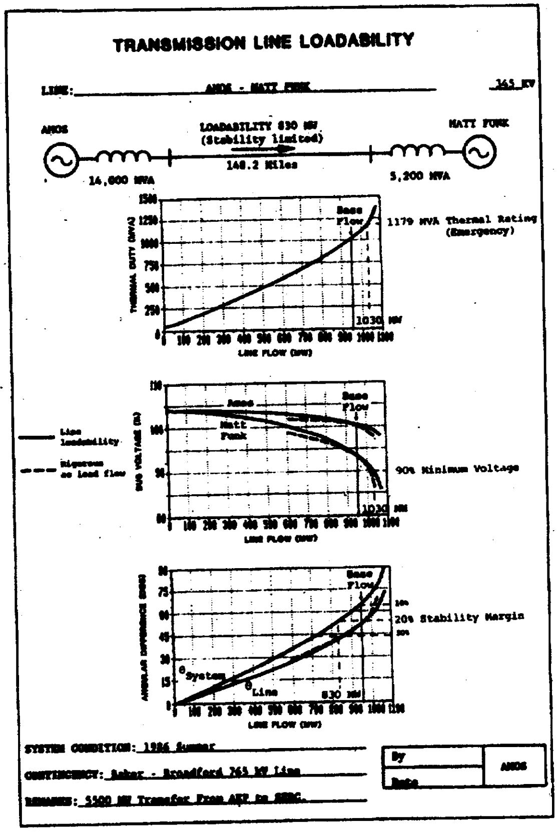


Figure 10. Line loadability analysis vs. rigorous ac load flow analysis.

In general, the line loadability analysis will produce somewhat more optimistic results (i.e., higher line loadability) than the rigorous ac load flow analysis. This is because the Thevenin equivalents used in the loadability model are assumed static over a wide range of line loading levels. While yielding accurate results close to the base flow level, this assumption may not be acceptable at higher or lower line loadings. In such situations, it may be desirable to establish two or more base flow levels to improve the accuracy of the line loadability analysis. It should be kept in mind, however, that getting the additional base flow levels will require more ac load flow solutions of the interconnected network that may pose difficult convergence problems, particularly at heavy line loading conditions.

APPLICATION TO OPERATING STUDIES

Loadability Enhancement Studies

Line loadability concepts can play an important role in operating/planning studies. Loadability analysis is particularly well suited for assessing the effects of system changes and for identifying limiting factors to transmission system operation. Both features are necessary to develop effective plans for increasing transmission loadability.

The initial step in loadability enhancement studies is the identification of the existing transmission limitations. This is facilitated by the operating loadability characteristics, i.e., thermal duty, bus voltage, and system stability curves. From these curves, the existing limitations can be identified and their severity measured in terms of the impact on line loadability. Concentrating any system improvements on the most restrictive limitation will yield the greatest improvement in line loadability. The magnitude of the potential loadability improvement is assessed by comparing the limitations from each of the three curves. If one limitation is significantly more constraining than the other two, the loadability of a line can best be improved by addressing the most constraining limitation. This could entail upgrading the existing transmission facilities to improve thermal capability; or installing reactive correction to increase voltage support; or strengthening the system to improve steady-state stability. If the most constraining limitation is close to the other two limitations, a more complex solution may have to be developed.

When a plan or several alternative plans for improving the loadability of a line have been developed, new operating loadability characteristics can be derived to show the relative effectiveness of each plan. If the number of plans is large, the new characteristics can be used to identify the most promising plans before the rigorous load flow and dynamic stability studies are conducted. Similarly, the loadability analysis provides a means to optimize a particular system improvement plan.

Seasonal System Appraisals

To determine if sufficient levels of reliability are being maintained on the system, extensive studies are conducted to appraise the performance of the system. These studies, which are typically conducted on a seasonal basis using large interregional network models, rely on linear load flow analyses to screen transmission system capabilities and to identify potential thermal limitations during transfer and outage conditions. Guided by these linear load flow analyses, ac load flow studies are carried out to assess the potential problems in detail. In addition to the thermal loading problems, both voltage and steady-state stability conditions are considered in the ac load flow studies.

Since the seasonal system performance appraisals are conducted using large network models, the effectiveness of the screening process in identifying system limitations, regardless of their nature, is an important consideration. By taking into account the voltage and stability constraints under which the transmission lines operate, the effectiveness of the screening process can be enhanced. This added information, in conjunction with the thermal limitation, can serve as a composite line rating for use in the linear load flow analysis. The composite line rating can be determined from the loadability characteristics presented in this paper. Using the loadability ratings in the linear load flow analysis will make it possible to screen out potential voltage and steady-state stability problems prior to the ac load flow analysis. The benefit of this approach would be to enhance both the effectiveness and efficiency of the computer studies conducted as part of the seasonal system performance appraisals.

CONCLUSION

Transmission line loadability has been a useful concept for the planning engineer in assessing the loading limits -- expressed in terms of surge impedance loading -- for transmission lines of various lengths and voltage classes. Although helpful in planning applications, the generalized loadability characteristics introduced by St. Clair are not well suited for use with specific transmission lines which operate under a wide variety of system conditions.

For application to operating studies, where the specific system conditions must be taken into account, line loadability calculations can be customized to provide a set of operating loadability characteristics. These characteristics illustrate the effect of the line flow on the thermal duty, bus voltages, and steady-state stability for the line. Each of these characteristics addresses a possible limiting factor to transmission line loadability. When used in conjunction with a given set of performance criteria, these characteristics can serve to establish line loading limits which fully recognize the inherent system capabilities. While the line loadability analysis presented in this paper cannot be viewed as a substitute for detailed system studies, the results obtained therefrom can be used to enhance the operation of the transmission system while maintaining the desired level of system reliability.

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Richard Gutman (M'77-SM'84) was born July 8, 1948. He received the B.S.E.E. (Magna Cum Laude) and M.S.E.E. degrees from the Polytechnic Institute of New York, New York, and the M.B.A. degree (with Weidler Scholar Distinction) from The Ohio State University, Columbus, Ohio. He also completed a course in Electric Power Systems Engineering by Power Technologies, Inc., Schenectady, New York, and the AEP/OSU Management Development Program at The Ohio State University.

Since 1968, he has been employed by American Electric Power Service Corporation, Columbus, Ohio, where he presently holds the position of Manager, Special Transmission Studies Section in the Bulk Transmission Planning Division. His responsibilities include analytical studies related to the performance of transmission systems, plant/system voltage coordination, application of static var systems, line loadability assessment, ground wire selection, breaker duty evaluation, and three-phase system modeling and unbalance analyses.

Mr. Gutman is a member of Tau Beta Pi, Phi Kappa Phi, and Beta Gamma Sigma honor societies, and is a Registered Professional Engineer in the States of Ohio and New York.

Discussion

Raymond D. Dunlop (New England Power Service Co., Westborough, MA): The author is to be congratulated for taking the concept of line loadability a step closer to practical application. The earlier work by St. Clair (1) was useful at a time when a high voltage (138kV) transmission circuit was used to interconnect two areas that were otherwise weakly coupled (high parallel impedance) and where the line impedance alone dominated voltage regulation and stability limits. The update to St. Clair's work (2) simply recognized that in EHV and UHV circuits of today the effects of the terminating systems and shunt reactors could not be ignored. It was also acknowledged that applications were practically limited to situations where EHV and UHV circuits would be applied in point-to-point transmission associated with remote power plants or interties with very weak parallel paths. The author has taken an important step in recognizing that EHV and UHV transmission circuits are very often part of a strong "network".

I would appreciate the author's comments on some questions related to the application and interpretation of line loadability characteristics with the enhanced model discussed in the paper. First, with regard to voltage regulation effects (Figures 5 and 8), it would seem likely that EHV/UHV transmission circuits (in this case 765kV lines) that do not have generating stations near their terminals could still be strongly influenced by voltage regulation due to the electrical proximity of generating stations connected to the high voltage (765kV) network. Would the author propose to ignore this and accept a conservative result or have you considered running additional load flows around the base condition to provide a more accurate reflection of voltage regulation capability at the terminals of the line being studied?

With regard to stability, the author seems to imply that stability margins and limits (Figure 9) are of the steady-state variety. Since the Thevenin equivalent reactances are derived from short circuit studies where machines are typically represented by their transient and/or subtransient reactances, it would seem that the stability limits and margins are more properly interpreted as "transient" stability based on an assumption that the system behaves dynamically as an equivalent two-machine system. Also, would the author please comment on the validity of a two-machine model for calculating stability performance in a highly integrated multi-machine system such as AEP; i.e., would one expect to achieve conservative results compared with large-scale multi-machine model of thes ystem?

Finally, it would seem that the line loadability methodology would provide a useful screening tool to identify the basis for loadability limitations before conducting more detailed studies related to remedial measures designed to enhance stability or avoid voltage collapse. It would also seem that the model and methodology proposed by the author could be adapted to on-line assessment of line loadability where actual system conditions could be reflected in revised characteristics that would be computed mostly from off-line information.

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RICHARD GUTMAN: The author would like to thank Dr. Dunlop for his comments and interest in the paper. Dr. Dunlop raises an interesting question with regard to voltage regulation effects of generating stations located in the electrical proximity of the line being studied. In the paper, only those stations located at the line terminals are explicitly represented in the loadability model. The effects of other stations are included in the Thevenin equivalents (E_1/X_S and E_2/X_R) derived from load flow and short circuit information. This was a judgemental choice of the author based on the following factors. First, a key objective was the simplicity and ease of use of the loadability technique. Since the technique was designed primarily as a screening tool, accurate modeling of reactive sources located one or more buses away from the line terminals was not considered essential. While it is true that improved modeling would yield better results, the associated complexity appeared difficult to justify for the intended purpose. As an offsetting factor, which also contributes to the simplicity of the proposed technique, the Thevenin equivalent voltages E_1 and E_2 are assumed constant throughout the loadability calculation. The combined effect of these two simplifying assumptions is to yield somewhat optimistic results of line loadability as compared to a more rigorous approach. This comparison is illustrated in Figure 10 in the paper. It is noteworthy that, in addition to its simplicity and reasonable accuracy, the loadability technique provides important insights regarding steady-state stability limit to power transfers; this information is generally difficult to obtain using conventional load flow methods.

In reply to Dr. Dunlop's question regarding the term "steady-state stability margin," the author would like to expand upon a subtle aspect of line loadability determination. As stated in the paper, the Thevenin equivalent reactances X_S and X_R, as well as the equivalent parallel path reactance X_P, are obtained from short circuit analyses which reduce the system surrounding the line to a two-point equivalent to be connected at the line terminals. In these short circuit analyses, the generating units located in the electrical proximity of the line being studied are modeled by their respective synchronous reactances, rather than the usual subtransient reactances. This refinement can be significant keeping in mind the roughly 10:1 ratio of the synchronous-to-subtransient reactances for large generating units connected to an EHV network. The use of the synchronous reactances for generators is considered more consistent with the steady-state nature of the loadability characteristics presented in the paper. Follow-up studies would normally be required to assess the transient and/or dynamic system performance, including the adequacy of the operating margin selected based on steady-state stability considerations.

With regard to on-line adaptation of the loadability technique, it would certainly represent a major new application for this tool. Such an adaptation could be a challenging task, however. In its present form as a two-machine model, the loadability tool is not well suited for on-line applications because it does not capture the limitations (thermal, voltage or stability) that may exist away from the line being studied. A careful study of the tool design and its underlying assumptions would be necessary to extend its use to on-line assessments of line loadability.

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