Advanced Sensitivity Analysis for Long-Range Transmission Expansion Planning

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Abstract

Transmission planning should seek to maintain or improve system security over time and facilitate robust wholesale power markets by improving transmission capacity for bulk transfers across wide regions. Uncertainty about the development of future generation resources and regulatory policies complicates the process for long-range transmission planning. Furthermore, the evolution toward regional transmission planning requires that planners analyze and suggest improvements over significantly larger networks than have been studied in the past. Methods are required to screen numerous alternatives to determine those that offer the most cost effective means of security enhancement.

This paper presents a methodology for using linear sensitivity analysis to evaluate potential transmission connections and aid selection of those that provide the most cost-effective improvements to overall system security. The methodology is applied to the planning of an extra high-voltage (EHV) overlay for the Southwest Power Pool (SPP) regional transmission system.

1. Introduction

It is common today for electric power transmission system planning horizons to be 10 years or less. These short horizons typically result only in incremental improvements to the system to maintain minimal reliability standards rather than development of a comprehensive blueprint for the future of the North American electric system. This incremental approach to system improvements is further reinforced when one considers the difficulty of transmission siting, which is often a time-consuming and contentious issue. Obtaining approvals to expand existing rights-of-way is often easier than acquiring new rights-of-way, especially in the short-term As a result, common remedies for transmission congestion involve reconductoring or adding lines in parallel to existing lines to improve capacity or reduce the frequency and severity of overloading. This approach has its merits since it uses a well-defined deterministic planning process and is relatively fast to implement.

However, the incremental approach is limited in that it can only address a few specific security problems at a time. It is difficult to address security across a wide area or the whole interconnected system. It is biased by the existing transmission topology and ownership boundaries, designed many years ago for the vertically integrated utility industry. Long-range planning, such as that being performed by the Southwest Power Pool ("SPP") Regional Transmission Organization (RTO) and other regional planning entities, requires a process that can address wide-area security weaknesses and consider alternative topologies beyond the existing ownership boundaries to facilitate future needs of improving reliability and transporting power across large regional markets. Increasingly, entities such as SPP want to develop long range plans that serve as a true blue print for the future. Proactive long range planning processes are developing that look 15 to 20 years into the future.

Coupled with this emerging regional planning activity, the Energy Policy Act of 2005 gives FERC statutory backstop authority to site interstate transmission lines and provides financial incentives for transmission investment. Proposed transmission facilities that impact national interest electric transmission corridors (NIETC) and provide a demonstrated improvement to system security have an improved chance of gaining approval in this new regulatory environment. As a result of these changes, planners can thus consider a broad spectrum of improvements for long-range transmission system development going far beyond the traditional ownership boundaries of the local utility.

However, the option to consider a very large number of new transmission connections adds complexity to the planning and selection process. Suppose n substations are candidates for new transmission connections. The number of possible new transmission lines is given by:

$$\frac{n!}{(n-2)!2!} \tag{1}$$

Evaluating the impacts of such a large number of transmission connections requires tools for screening the list to determine which transmission upgrades would provide the most cost-effective benefits. This paper presents

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such a screening tool, developed for SPP's long range EHV study, which uses weighted transmission loading relief (TLR) analysis and other linear techniques to quickly estimate the impacts of a large number of potential transmission lines on transmission system security. This method was based upon previous work on locating new generation sources in an optimal location to reduce congestion. This method presented in this paper is not limited to on-peak cases, but can be adapted to all loading levels of interest to the planner.

2. Evaluating Transmission Security

Steady-state system security typically requires no loss of load, bus voltages within power quality bands, transmission flows within thermal limits, and system operation at a safe margin from static voltage collapse [1-4]. Contingency analysis during periods of high demand drives the long-term design of system expansion, as other considerations are typically addressed over shorter planning horizons. Contingency analysis enables determination of quasi-optimal transmission topologies. NERC requires that systems be designed and operated to withstand N–1 and certain critical N–2 or greater contingencies. [5]

2.1. Aggregate Contingency Overload

One measure of system security is the amount of thermal overloading that occurs during a set of simulated contingencies or forced outages. The level of contingent overloading may be expressed as the sum of MVA overloads across all monitored transmission elements and simulated contingencies, or the Aggregate MVA Contingency Overload (AMVACO), defined as follows [6]:

$$AMVACO = \sum_{c\in CONT}\sum_{ij\in BRANCH}\left(\mathrm{MVA}_{ij,c} - \mathrm{Rating}_{ij}\right)\Big|_{\mathrm{MVA}_{ij,c}>\mathrm{Rating}_{ij}} \quad (2)$$

Thus for a given line ij and contingency c, the contribution to the AMVACO would be the amount of MVA that the flow on line ij exceeded its emergency limit or contingency rating. If the line operates within its limits for all contingencies, then its contribution to AMVACO is zero. A desirable goal of any transmission upgrade or expansion would be to improve the system security as measured by the AMVACO.

2.2. Transmission Relief

The bus Transmission Loading Relief (TLR) describes how an incremental power injection at a given bus k (ΔP_k) impacts power flow (ΔP_{ij}) on a transmission branch between bus i and bus j:

$$TLR_{BUSk,BRANCHij} = \frac{\Delta P_{ij}}{\Delta P_k} \quad (3)$$

ΔP_{ij} is positive if the incremental power flow is positive from bus i to bus j, and negative otherwise. From this, the Weighted Transmission Loading Relief (WTLR) value is defined to represent the impact of an incremental power injection on all contingent overloaded branches. It expresses the expected system AMVACO change of an injection at the corresponding bus, where the impact on each overloaded line is weighted by the total MVA overload on the line [6].

$$WTLR_k = \frac{N_{cont}}{SysAMVACO}\times\sum\begin{pmatrix} CODir_{BRANCHij} \\ \times TLR_{BUSk,BRANCHij} \\ \times AMVACO_{BRANCHij}\end{pmatrix} \quad (4)$$

$CODir_{BRANCHij}$ reflects the direction of the contingent overloading, relative to the branch reference direction (from bus i to bus j). It is equal to +1 if the contingency overloading occurs in the direction of bus i to bus j and -1 if the contingency overloading occurs in the direction of bus j to bus i. Thus the product of $TLR_{BUSk,BRANCHij}$ and $CODir_{BRANCHij}$ is negative if the flow (ΔP_{ij}) imparted by the incremental power injection at bus k (ΔP_k) alleviates the contingency overloading.

The bus WTLR value can thus be applied to each end of a proposed transmission line to linearly estimate the total expected AMVACO change expected from the addition of a new transmission branch.

To enhance system security, new lines should be added to produce counter-flows on lines and transformers that experience contingency overloads as illustrated in Figure 1.

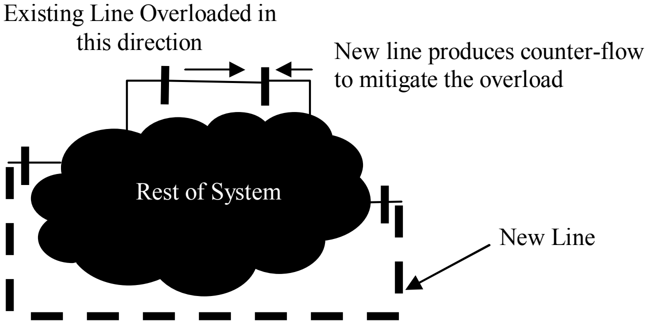

Figure 1. Transmission relief

2.3. Security Enhancement Measure

Assume the flow expected in the direction of bus k toward bus m is P_{km}. If one approximates the system as loss-less and linear within a range defined by the incremental flow on the proposed line, then adding the proposed line is equivalent to placing a generator at bus *k* with output $-P_{km}$ and a generator at bus *m* with output $+P_{km}$, as illustrated in Figure 2. The impedance parameters of the proposed line have a significant effect on the value of P_{km} in that a lower per unit impedance yields a larger P_{km}.

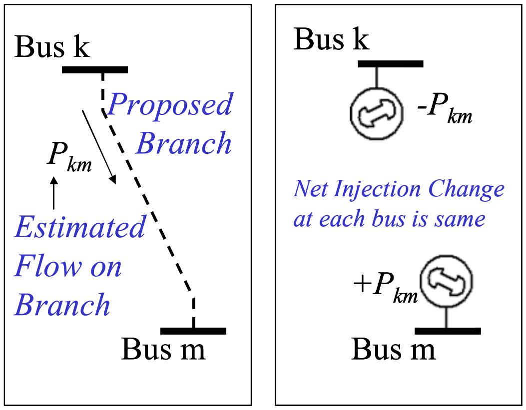

Figure 2. Network equivalents

The bus-based WTLR values may then be applied to estimate the AMVACO impact or Security Enhancement Measure (SEM):

$$\mathrm{SEM} = P_{km}(WTLR_k - WTLR_m) \tag{5}$$

3. Transmission Line Selection Process

The first step is to define a list of candidate transmission branches and assign impedance parameters to each. An implementation involving the study of the SPP high voltage transmission system is described later in this paper.

3.1. Estimating Flow

To estimate the SEM and the value of each candidate transmission line in improving system security, the flow P_{km} and bus WTLR pairs must be estimated for each line using fast linear techniques. P_{km} may be estimated with Line Closure Distribution Factors (LCDF):

$$\begin{aligned} LCDF_{BRANCHij,BRANCHkm} &= \Delta P_{BRANCHij}\Big|_{\text{Closure } BRANCHkm} \\ P_{km} &= LCDF_{BRANCHkm,BRANCHkm} \end{aligned} \tag{6}$$

The selected lines can then be added to the system and the actual impact quantified with full non-linear power flow simulations.

3.2. Cost Impact

The SEM by itself does not take into account the feasibility or cost of adding in the potential new transmission line. Also, the SEM may be biased toward capital-intensive higher voltage connections as the corresponding lower impedance yields higher post-closure flow on the branch. Cost considerations, including capital investment and right-of-way acquisition, may be incorporated by dividing capital and other implementation costs by the SEM for each proposed line. A cost-security ratio (CSR) may be defined as follows:

$$\begin{aligned} \mathrm{CSR} &= \frac{\mathrm{Cost}}{\mathrm{SEM}} \\ &= \frac{\mathrm{Cost}}{P_{km}(-WTLR_k + WTLR_m)} \end{aligned} \tag{7}$$

The CSR approximates the investment required per unit reduction in expected AMVACO. Lower CSR represents a greater cost effectiveness of the proposed line in improving system security and relieving contingency overloading.

An automated process for selecting new transmission lines may thus be summarized as follows:

```
Perform contingency analysis and calcu-
  late AMVACO for existing transmission
  lines
Calculate bus-based WTLR
Estimate flow $P_{km}$ on candidate lines
Calculate line-based SEM and CSR
Insert line with highest SEM or lowest
  CSR into the system
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This process may be further automated in a loop that repeats until security criteria are met, such as the reduction of AMVACO to an acceptable level; until a maximum level of capital investment is met; or until a maximum number of lines have been inserted.

4. Application to The Southwest Power Pool

This transmission line selection methodology was applied to a long-range study of the Southwest Power Pool (SPP) extra high voltage (EHV) transmission system. The objective was to develop a plan for a visionary EHV grid overlay for the year 2026. This EHV overlay grid was designed to meet the needs of a variety of possible generation futures as well as simulations of the effects of a possible national renewable portfolio standard. Several generation portfolio scenarios were considered, including a baseline, high renewable energy growth, high nuclear growth, no nuclear growth, and high natural gas growth.

Candidate EHV lines included all pairs that connect 230 kV and higher buses within SPP and 345 kV and higher buses within SPP's immediate neighbors. There were 356 buses in this set. Candidates were initially screened by distance, assuming that EHV lines longer than 500 miles would be impractical for power transmission and lines shorter than 30 miles would not provide enough marginal benefit to justify the investment in EHV terminations. Each remaining pair was considered for 765-kV single-circuit, 500-kV double-circuit, or 500-kV single-circuit connections, yielding approximately 82,000 candidate EHV lines.

EHV line impedances were calculated from fundamental characteristics described in [7], though it was assumed that most line charging capacitance would be compensated with switched shunt inductors if required.

For contingency analysis, the set of monitored lines *ij* included all non-radial lines and transformers in SPP with a maximum nominal voltage of at least 230-KV. The set of contingencies *c* included the following:

1. Loss of single line or transformer (N-1) in SPP with minimum nominal voltage of at least 345 kV.
2. Loss of single largest generator at all plants in SPP with capacity of at least 100 MW.
3. All outages represented in the list of SPP-supplied flowgates, not included in 1 or 2.

Simulations and linear sensitivity calculations were performed on PowerWorld Simulator software.

Figure 3 below shows a color contour of the AMVACO observed on each transmission branch prior to designing the EHV overlay.

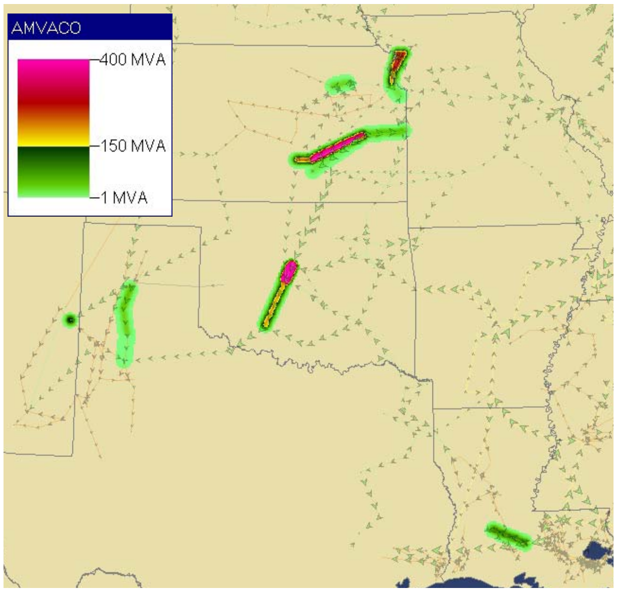

Figure 3. Initial AMVACO, 2026 SPP transmission system

Table 1 shows the results of a sequence of automated TLR-based line selections using the 2026 peak summer model. The initial AMVACO was 5,069. After inserting a sequence of 17 lines, the AMVACO was reduced to 0, resulting in an N-1 secure case.

Table 1. Sequence of sample TLR-based EHV line selections

Line #	AMV-ACO	Connection	WTLR$_k$	WTLR$_m$	P$_{km}$	CSR
0	5,069					
1	4,051	Cimarron-Arcadia	3.12	-1.18	-756	26
2	3,064	Iatan-St. Joseph	-2.12	0.13	1025	31
3	1,589	Swissvale-Wolf Creek	-0.06	-3.22	-1171	27
4	1,078	Lawton-Redbud	2.70	-1.39	-948	65
5	980	Flanders-Wells	0.73	-0.31	-639	94
6	642	Oklaunion-Lawton	1.36	-0.17	-883	108
7	617	Craig-Iatan	0.55	-0.36	-1147	91
8	1,266	Wolf Creek-Tecumseh EC	-0.36	1.18	457	192
9	765	Reno-Tecumseh EC	0.00	-1.18	-832	90
10	521	Summit-E. McPherson	0.12	0.84	315	320
11	204	Brookline-Huben	-0.89	-0.16	380	401

Line #	AMV-ACO	Connection	WTLR$_k$	WTLR$_m$	P$_{km}$	CSR
12	108	Reno-Swissvale	0.30	-0.57	-480	273
13	98	Paola-Plainville	-0.21	-0.02	382	1010
14	64	Wolf Creek-Circle	-0.13	0.29	439	1418
15	97	Arsenal Hill-Sunnyside	-0.44	0.00	185	4199
16	27	Oklaunion-Sunnyside	-0.05	-0.40	-372	2134
17	0	Lawton-Northwest	-0.01	-0.14	-387	4412

Some selections actually worsened the AMVACO security measure by causing new base case or contingent overloads. An increase in AMVACO by itself does not indicate that a proposed line should not be considered. In this example, new overloads were relieved by subsequent connections, which extend the proposed line to the next substation. Where the AMVACO is worsened by a line selection and not restored to a lower level within a few subsequent selections, it may be concluded that the line has an adverse impact on system security.

Figure 4 shows graphically the transmission lines in Table 1 selected by the automated TLR process.

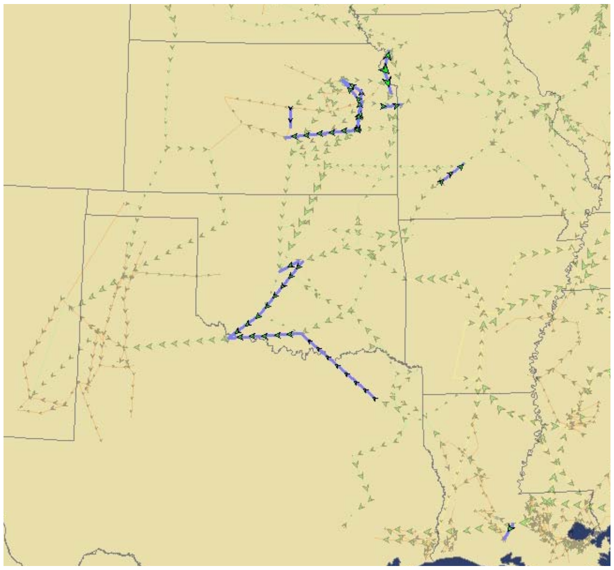

Figure 4. TLR-based transmission plan

The analysis team reviewed these line selections and the best performing lines were considered for inclusion in the team's EHV grid recommendations. Other considerations were factored into the recommendations, including alternate future generation portfolio scenarios such as expansion of the renewable energy portfolio. The final recommendations also linked the EHV substations into a contiguous overlay to enhance flexibility in regional power transfers.

5. Application To Transmission Planning

This TLR-based methodology enables an easily automated process for selecting a sequence of new transmission lines. Thus it serves as a fast-screening tool to allow a system planner to evaluate a large number of alternatives beyond those considered in a purely manual process. This fact, in and of itself, demonstrates the importance of the approach. In today's world of limited (and shrinking) transmission planning expertise, the ability to screen a large number of alternatives to determine a subset of promising alternatives for further evaluation (e.g., economic analysis using security-constrained economic dispatch algorithms) is an important advancement.

However, it should be noted that this process is not to be used as the sole consideration in designing transmission system additions. Several important considerations cannot be adequately addressed by an automated TLR-based selection process.

A transmission plan should facilitate multiple transfers of power over the future grid, in addition to improving system security. These objectives typically require multiple projects to concurrently achieve. However, this automated process can only evaluate one dispatch and load pattern at a time. Furthermore, the method only has visibility to the next connection in the sequence. It can estimate which single connection will have the greatest marginal benefit to system security, but it cannot assess multiple connections simultaneously. After each new transmission line selection, the AMVACO and WTLR must be recalculated to assess actual system security changes and incorporate any newly created overloads. Some proposed connections may worsen system security, even following several subsequently proposed connections. Also, the WTLR calculations are sensitive to the set of monitored transmission elements and contingencies. Assumptions have a significant impact on results.

Minimizing the cost and maximizing performance of the entire system often requires consolidating connections in a given locality around as few substations as possible. Because the automated process can only evaluate the cost of the next connection, it may not recognize such opportunities for consolidation. The process may also propose connections with external liabilities, such as those that cross environmentally sensitive areas.

Finally, it may not be feasible or cost effective to relieve all forms of congestion with new transmission lines. For example, if a transformer is slightly overloaded, it may be more cost effective to add another transformer in parallel, rather than redirect flow away from its substation with an EHV line. Similarly, some individual lines that become slightly overloaded may be effectively upgraded with reconductoring. Still other security problems may be averted with special protection schemes, especially those that occur rarely or only under specific circumstances. EHV expansion as an enabler of system security is most effective where several regional issues may be mitigated with a few new EHV connections.

Several other analysis tools may be applied concurrently with the TLR-based selection process to overcome some limitations and design a system that better facilitates economic transfers. A production cost-based unit commitment and dispatch, performed prior to the transmission line selection process and with minimal or no enforcement of existing transmission and security constraints, forces the TLR-based process to alleviate overloading resulting from such purely economic considerations. In addition, the selection process may be repeated with multiple hourly and seasonal system conditions and multiple portfolios of future generation capacity, leading to multiple corresponding transmission line selection sets. A security-constrained unit commitment and economic dispatch may then be performed on the alternative transmission grids determined by the TLR-based process and other planning criteria. The best alternative would yield the lowest cost of system operation with such security constraints.

The TLR-based selection process shows promise for use in other planning situations as well. Examples include:

1. Planners are presented with unfamiliar or unexpected system conditions. In this case this process can be used to highlight problem areas and generate new ideas for further evaluation.
2. Utilities are faced with limited planning resources. In this case engineering managers can employ this method to enhance productivity by increasing the number of project alternatives to be considered for further development.
3. Planners are optimizing project packages. In this case planners can evaluate different project termination points by comparing the AMVACO values for the various terminations.
4. Utilities are faced with limited capital budgets. In this case planning mangers can use this process to evaluate candidate projects to remove by screening and ranking the CSR values of each project being proposed.

6. Conclusions

The automated TLR-based transmission line selection process described herein enables fast screening of many combinations of potential new transmission lines. Despite some limitations, it is very effective at evaluating and screening a greater number of alternatives than could be evaluated manually. When used with prudent engineering judgment, it shows promise as a significant enhancement to the long-range transmission expansion planning process.

7. Acknowledgements

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