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CALCULATING VARIABLE TRANSFER LIMITS FOR DYNAMIC TRANSFERS

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SUMMARY

System Operation Limits (SOL) are traditionally computed using cases with well-adjusted voltage levels and with reactive devices set to ensure that system studies show acceptable post-contingency performance. When Variable Energy Resources produce frequent, large variations in power transfer, the actual operating conditions can be significantly different than what was assumed when calculating the SOL. This leaves the system at risk of unacceptable dynamic or post-transient response to critical contingencies. The Variable Transfer Limit (VTL) is the amount of frequent variability in power transfer that can be accommodated while ensuring reliable system operation. Determining VTL using conventional study methods is inefficient. This paper presents a novel methodology to address this problem.

Scheduling variable transfer on a path will restrict the amount of static transfer capacity available to be scheduled concurrently. Initial studies suggest that the exchange of static capability with variable capability will typically be less than one for one (i.e. less than one MW of variable transfer for one MW of static transfer) on paths with limited or no automatic voltage control: for some paths tested the maximum ratio between static and variable transfer capability was six to one. Dynamic transfer is an emerging issue that has reliability and financial implications for some paths / flowgates and as a result further study is needed.

KEYWORDS

Variable Transfer – Static Transfer — System Operating Limit – Variable Resource – Limit Computation Methodology – Dynamic Transfer - Power System Reliability - Power Transmission - Voltage Fluctuation - Wind Power Generation.

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INTRODUCTION

With the integration of increasing amounts of Variable Energy Resources ("VERs") much of the attention of power system engineers has been focused on how to balance the increased variability on a wide-area basis. An assumption behind many of the proposals for managing generation/load imbalances with remote resources is that the transmission system will be able to accommodate all dispatched intra-hour schedules provided System Operation Limits (SOLs) are respected. In practice, there are multiple transfer paths that can be impacted simultaneously by the change in generation levels of VERs and their associated balancing resources. This paper proposes a methodology for calculating Variable Transfer Limits, including when there are interactions between multiple paths, and discusses how Static and Variable Transfers relate.

BACKGROUND

In August 2005, Bonneville Power Administration (BPA) observed significant voltage variations near the BC-Washington border and unusually frequent switching of local reactive equipment. The unusual system behavior began after a new dynamic transfer service was commissioned between British Columbia (BC) and California, and was due, in large part, to the dynamic transfer ramping from 0 MW to 428 MW and back down, on top of hourly static transfers that were in excess of 2000 MW. The system operators managed the issue by imposing a 300 MW limit on the magnitude of the Dynamic Transfer and requesting a reduction in the frequency of change. They also asked the system planners to determine appropriate limits for dynamic transfers and between 2008 and 2011 four studies were conducted to determine dynamic transfer limits, also known as Variable Transfer Limits [1, 2, 3 and 4].

Dynamic transfers traditionally are schedules between Balancing Authority Areas ("BAA") that can be adjusted mid-hour through automated processes. Because in some cases variability may only apply to a portion of the dynamic transfer and because variability can occur on transfers within a BAA, the authors believe it is most appropriate to use the generic term Variable Transfer Limits and will do so throughout the remainder of this paper.

VARIABILITY

Power flows and voltages vary over time across synchronous AC power systems. Historically, these changes, with the exception of those associated with contingency events, have been relatively slow and reasonably predictable responses to load or generation re-dispatch. Variable resources and the balancing services that will necessarily be associated with them will impose new sources of variability and unpredictability on transmission system operation. The fundamental question to be answered is: "How much and how frequently can transfer across a flow gate and bus voltages vary without causing any adverse impacts?"

Ultimately, individual Transmission Providers will need to calculate the maximum variations that could be accommodated on the transmission paths (e.g. Variable Transfer Limits) for their system, however, to aid the process the DTC Task Force recommended a three part methodology for calculating the limits by quantifying the adverse impacts from three perspectives: 1) Impact on customers; 2) impact on system equipment and 3) impact on reliability.

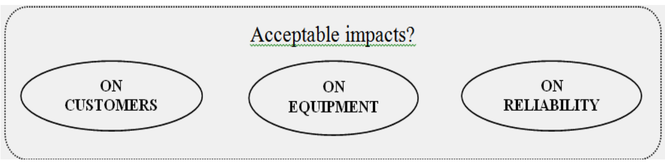

Figure 1: Three part methodology for calculating Variable Transfer Limits

The customer impacts due to voltage fluctuations resulting from transfer variations could be significant depending on the nature of the load and customer equipment. An acceptable increase in equipment impacts would be closely related to the equipment maintenance program and practices of the respective transmission provider. Reliability impacts due to variability would still need to be managed.

System Operating Limits are normally determined with a well-adjusted voltage profile across the system which is based on the condition of adequate reactive & dynamic support and whether sufficient time is available for the dispatchers to affect the necessary switching operations to accommodate the changing operating conditions. However with increased variable power injections, certain parts of the system could more frequently experience low voltage conditions and/or significant voltage deviations due to sudden large flow increases and also can cause reliability issues. As a result the actual operating point and corresponding system conditions would be different from what was assumed when calculating the SOL. Until a dispatcher is able to readjust the system back to a normal operation range – in particular restoring the voltage profile and an adequate reactive margin - the system could be at a risk of unacceptable dynamic and/or post-transient response if a critical contingency occurred.

VARIABLE TRANSFER LIMIT (VTL):

The Variable Transfer Limit (VTL) is the amount of frequently anticipated variability in the power transfer across a Flow gate that can be accommodated over a specified intra-hourly timeframe, while ensuring the reliable operation of the system and the avoidance of unacceptable adverse impacts on equipment and customers.

The VTL for a flowgate would be the lowest of the Customer, Equipment and Reliability limits:

VTL = MINIMUM of {Customer Limit, Equipment Limit, Reliability Limit}

Acceptable variability is also limited by the resources' ramp rate and operator response time, which is the assumed to be the length of time that the power system would be operating on auto-pilot because the system operators are busy.

Variability (MW) = Ramp Rate (MW/min) x Time (min)

In order to manage variability on the transmission system, the transmission providers must make an assumption on how long transfers could vary before system operators would readjust the system to restore the appropriate voltage profile and update RAS arming levels. In order to calculate the variability associated with a given variable resource it is necessary to analyze performance data for the variable resource and quantify its variability.

The need for a Variable Transfer Limit (VTL) to supplement the Static Transfer Limit (STL) for critical transmission paths has been identified. Figure 2 illustrates a Variable vs. Static transfer nomogram for power flows in the same direction on a path and it indicates that the safe operating region is below the nomogram line, rather than a single SOL value. For a given system condition there is a corresponding Static Transfer Limit as well as a Variable Transfer Limit. Changes of the operating condition will result in the need to recalculate a new set of limits.

There is a relationship between a flowgate's Static Transfer (ST) and Variable Transfer (VT) that defines the safe operating region. The maximum ST equals the SOL when VT is zero. Similarly the maximum VT equals the Transfer Variability Limit (TVL) when ST is zero. In between these end-points, the ST and VT on a flowgate will need to be managed to ensure that both the operating and the net scheduling points stay within the perimeter of the calculated nomogram. The TVL is the maximum VTL. The TVL cannot be greater than the SOL. The TVL could be less than the SOL which has traditionally been calculated using constant, non-varying flows. In addition, the sum of the scheduled ST and VT must never exceed the SOL.

ST + VT < = SOL

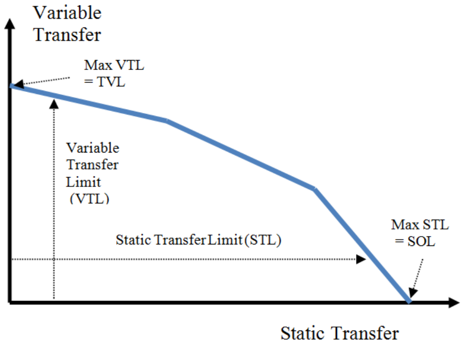

Figure 2: Nomogram relating Variable and Static Transfers on a Path

The scheduled amount of VT could restrict the available amount of ST capacity. Initial studies suggest that the exchange of ST capability with VT capability will typically be less than one for one (i.e. less than 1 MW of VT for 1 MW of ST) on flowgates. To ensure consistent and reproducible study results, a standard methodology is necessary. This paper presents a novel methodology to address this problem.

OPTIMIZATION FORMULATION

VTLs can be computed easily if there is only one transfer path or if interactions between the transfer paths are very minimal. The problem becomes quite complicated when there are multiple interdependent paths. The complexities of the problem increases due to the very large number of state and control variables, the interlinked impacts of multiple transfers, the direction of the variable transfers, the operating conditions and the location of the balancing resources and variable energy resources.

If there are "n" buses monitored in the system and "m" source/sink pairs (transfers), then the total number of combinations will be large. The problem is even more complicated when multiple source/sink are present in the system, however it can be solved by establishing a goal to maximize the total dynamic transfer across a system with multiple Flowgates so that large quantity of intermittent energy sources (wind) can be integrated at the same time, without violating system operating limits and reliability.

Objective:

$\text{Max} \sum \text{Abs}(\text{Transfer}_i(z))$

for i = 1 to m source / sink pairs

- Subject to
  - $H(z) <= 0$
- Where
  - z = is the vector of decision variables that includes both control and state variables
  - H(z) = is vector of operating conditions that cannot be violated

The change in power transfer between a source at bus k and a sink at bus r, can be written as:

$\Delta T_{kr} = [\partial P_{kr}/\partial V_k]\Delta V_k + [\partial P_{kr}/\partial V_r]\Delta V_r + [\partial P_{kr}/\partial ø_k]\Delta ø_k + [\partial P_{kr}/\partial ø_r]\Delta ø_r$

Where,

ΔT_{kr} = Change in Transfer flow from bus k to r

$[\partial P_{kr}/\partial V_k]$ = Partial derivative of flow change from bus k to bus r by voltage change at bus k

ΔV_k = Change in voltage at bus k

$[\partial P_{kr}/\partial ø_k]$ = Partial derivative of flow change from bus k to bus r by angle change at bus k

$\Delta \o_k$ = Change in bus angle at bus k

In this formulation voltage change and angle change at any bus can be calculated using the injection changes and control variable changes using the Jacobin matrix. The optimization problem can be solved using different optimization techniques. In this work the optimization problem was solved using successive linearization. Similar to the single transfer analysis, bus voltage transfer sensitivities are calculated. Using the optimization approach, delta transfers are calculated such that voltage variation constraints (e.g. +/- 1%) are satisfied within a specified tolerance. They are then applied to power flow and the voltage change constraints are verified. The process is repeated till all voltage constraints are satisfied. Subsequently all credible contingencies must be applied to ensure that post disturbance performance meets the stability and steady state performance requirements and this process repeated until the post disturbance performance requirements are met. Once the transfers between source and sinks are known, the VTLs/TVLs are calculated using Power Transfer Distribution Factors (PTDF) or by power flow. The TVL and VTL calculations are similar. In the TVL calculations static transfer is zero. VTL is calculated for a specified static transfer.

RESULTS

SOLs are traditionally computed with well-adjusted voltage levels using manually controlled reactive devices set to ensure sufficient room for automatic voltage control devices to respond to dynamic changes and produce acceptable system performance after disturbances. Increases in flowgate transfers without any associated manual voltage adjustments would result in depletion of the VAR reserves of automatic devices and lower system voltages. However this presents a limit problem given that the power system must always be operated to survive contingencies and meet the post-disturbance dynamic and steady-state performance requirements.

Allowing VT to increase on a flowgate without the benefit of manual switching of voltage control devices can deplete the dynamic VAR reserves that are required to mitigate the impact of disturbances and help preserve system reliability. Consequently establishing a large VTL could significantly reduce the corresponding STL of a flowgate as less dynamic VAR reserves would be left to respond to disturbances. Transmission systems that have only a few dynamic VAR sources and still permit large VTs to occur in between the regular manual adjustments made by system operators could be at risk if a severe contingency occurred. In addition, systems that depend on manual arming of Remedial Action Schemes (RAS) could be at risk of undesirable control actions if RAS action is initiated after VTs have changed the actual operating point when arming adjustments appropriate to the new operating point have not been implemented.

A. Application of Method for Path 3 (BC to WA Intertie)

STLs and VTLs for the BC to WA intertie (WECC transmission Path 3) for certain system conditions have been assessed to test and illustrate the methodology described above. In addition, some parameters that could affect VTLs have also been noted. Figure 3 presents VTLs verses allowable voltage variation for Path 3 for different static transfer values.

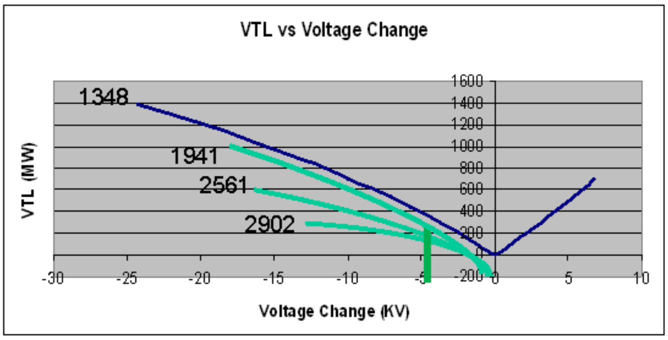

Figure 3: VTL versus voltage variation for 1348 MW, 1941 MW, 2561 MW and 2902 MW STs for Path 3 (BC to NW).

The BC to WA intertie has well defined transfer limits for various system conditions. An initial assessment was done by BC Hydro under normal conditions and using generation at the G.M. Shrum Generation Station on the Peace River (Northern BC) as a balancing resource for variable wind generation in the Columbia Gorge (Southern Washington) has indicated the need to develop new transfer limits that include a variable component. Figure 4 shows the results for one system operating condition. This nomogram reflects two types of constraints on VTs:

- The maximum pre-contingency voltage variations (which is used as a gauge for assessing customer impact);
- The post-contingency transient stability and power flow results (which are used to determine if the operating point is reliable).

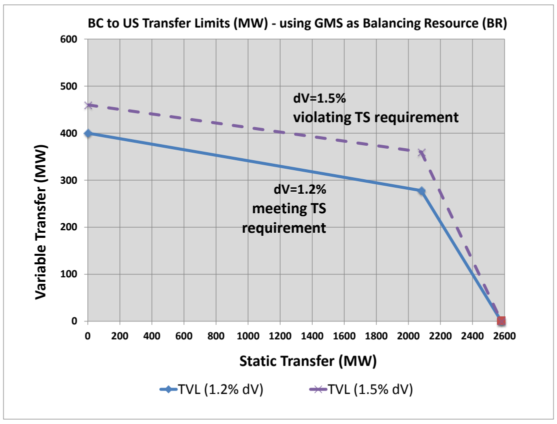

Figure 4: Static vs. Variable Transfer Nomogram for Path 3 (BC to WA Intertie)
North to South Transfer Limits (BC Hydro Perspective)

As expected the VTLs are smaller than the STLs due to increase in stressed flow conditions and reduced pre-outage voltage profiles. The boundary of the safe operating region can be refined with more study points.

VTLs could be affected by various parameters, including selection of balancing resources to respond to wind variations, the availability and capability of automatic voltage regulation in the affected transmission systems, system loading condition, and the ability of impacted system RAS to adjust its required control actions based on the prevailing pre-outage power flows.

OBSERVATIONS

Some of the rules to apply to a Variable vs. Static Transfer nomogram are:

- Sum of Static Transfer (ST) and Variable Transfer (VT) will be less than the SOL;
  - **ST + VT <= SOL**
- Variable transfers will be less than the TVL;
  - **VT <= TVL**
- Maximum static transfer (equal to the SOL) occurs when variable transfer is zero;
  - **SOL = max ST when VT is zero**
- The maximum TVL will occur when the system is the least stressed;
  - **TVL = max VT when ST is zero**
- TVL is less than or equal to the SOL;
  - **TVL <= SOL**
- For any operating transfer level between 0 and the SOL, a maximum variable transfer VTL can be defined using the nomogram;

The maximum Static Transfer equals the SOL when Variable Transfer is zero. Similarly the maximum Variable Transfer equals the TVL when Static Transfer is zero. In between these end-points, the static and variable transfers on a path will need to be managed to ensure that the combined operating point is always within the perimeter of secure operating region.

TVL is less than or equal to the SOL. The reason for this relates the differences in methodology to determine TVLs and SOLs: for TVLs it is assumed that only automatic operations are available to adjust to changes in system flow, whereas for SOLs it is assumed that all the appropriate operator actions will take place to tune the system to the ideal voltage profile based on maximizing transfer levels. SOLs are higher because it is assumed that system operators are not time constrained, and can make as many adjustments as necessary to optimize the performance of the system.

Scheduling variable transfer on a path will restrict the amount of static transfer capacity available to be scheduled concurrently. Initial studies suggest that the exchange of static capability with variable capability will typically be less than one for one (i.e. less than one MW of variable transfer for one MW of static transfer) on paths with limited or no automatic voltage control. Also for the paths tested the ratios were up to 6 times and decrease based on the increase customer impact criteria.

The relationship between Variable and Static Transfers on paths needs to be analyzed. There are some policy questions to be resolved. They are to determine the a) acceptable magnitude/frequency of voltage deviation, b) acceptable levels of incremental cost due to increased variability and c) acceptable levels of equipment operation due to increased variability. Dynamic transfer is an emerging issue that has reliability and financial implications for some paths / flowgates and further study is needed.

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