Increasing the Effectiveness of Interface MW Limits for Maintaining Voltage Security

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***Abstract*—Interface MW limits are commonly used as surrogates for voltage constraints in DC power flow models. This work proposes a simple improvement to accepted practice so that the interface MW limits better represent actual voltage vulnerability. Weights are assigned to the individual lines in the interface so that the weighted interface MW flows have the same sensitivity to real power injections as the underlying voltage constraints. Calculation of the weights requires the solution of a small dimensional linear regression equation and is of slight computational burden. The weighted interface MW limit is demonstrated to be an accurate proxy for low voltage limits to inter-area transfers using the Nordic test system.**

***Index Terms*—Interface MW flow, sensitivities, low voltage conditions, power transfer distribution factors.**

I. INTRODUCTION

In the operation of electric power systems, it is common practice to establish maximum limits to power flows across sets of transmission lines in order to safeguard against low voltages and voltage instability [1]–[3]. The sets of transmission lines sometimes represent an interface between two zones, a load pocket, tie lines between areas or some other collection of lines with commercial or operational significance. For the purposes of this paper we refer to any of these situations as *interface MW limits*.

Typically, transmission operators conduct exhaustive off-line simulations to identify the power flow limits on these sets of transmission lines that are associated with low voltages [4]–[7]. Then, in operation of the system, generation dispatch is controlled to observe those power flow limits as a proxy for avoiding low voltage events.

The use of interface MW limits is widespread because it can be implemented with DC power flow [8], can readily be observed as a market constraint, and has less dependency on telemetry and computation than AC power flow approaches [4], [9].

The interface MW flow limits are often used as surrogates for stability (transient angle and voltage) or voltage constraints.

This work proposes the use of **weighted** interface MW limits in order to better represent actual underlying voltage vulnerability where interface MW limits are used as surrogates for voltage constraints.

This paper is organized as follows. The proposed method is presented in Section II while Section III demonstrates proof of concept using the Nordic test system. A discussion and future works are given in Section IV while Section V offers some conclusions.

II. THE PROPOSED METHOD

Given a set of transmission lines that define an interface, the interface MW flow is the sum of the MW flows on each line in the interface.The interface MW limit is the maximum MW flow on the interface that can be securely accommodated.

A *weighted* interface MW flow is the sum of the products of weights and the MW flow for each line in the interface. One can consider the interface MW flow as being a special case of the weighted interface MW flow when all the weights are one.

We propose that the weights for each line be determined so that the vector equal to the weighted sum of the shift factors of the lines in the interface most closely reflects the sensitivity of the limiting voltage constraints to changes in real power injections.

The weighted interface MW limit is the maximum weighted interface MW flow that can be securely allowed in practice.

The procedure to determine the weights and interface MW limit involves the following steps:

1) As in current practice, comprehensive off-line simulations are conducted for a range of transfer, loading, and outage scenarios to determine the total (un-weighted) interface MW flow limited by low voltages.
   For each scenario, the sensitivity of the low voltage with respect to real power injections, $\mathbf{S}_{V_{low}\mathbf{P}} = \partial V_{low}/\partial \mathbf{P}$, is calculated for the limiting bus voltage. This vector has a component corresponding to each node in the network and can be computed as a by-product of the AC power flow simulations [1], [3].
   Note that for different outage and transfer scenarios it is likely that low voltages at different buses will limit transfer. After all simulations and bus voltage sensitivity vectors $\mathbf{S}_{V_{low}\mathbf{P}}$ are computed, the simple average of all the bus voltage sensitivity vectors obtained is calculated and normalized,

$$\mathbf{S}_{V_{low}\mathbf{P},av,n} = \mathbf{S}_{V_{low}\mathbf{P},av} / \left\| \mathbf{S}_{V_{low}\mathbf{P},av} \right\| \quad (1)$$

This vector has practical value since it indicates which generators, on average, are advantageous to dispatch in order to resolve voltage limits. Additionally, this vector is necessary for the calculation of weights to define the weighted interface flow and limit.

2) The shift factor vectors for all the lines in the interface are calculated. Let $\mathbf{PTDF}$ represent the matrix of shift factors where each column corresponds to one of the lines in the interface and each row corresponds to a bus in the network and each component is the sensitivity $\partial MW/\partial \mathbf{P}$ of the real power flow on the line corresponding to that column with respect to injection at the bus corresponding to that row.
3) A multi-linear regression is solved to determine the weighting of each line in the interface,

$$\mathbf{PTDF} * \mathbf{W} = \mathbf{S}_{V_{low}\mathbf{P},av,n} + \epsilon \quad (2)$$

where $\mathbf{W}$ represents the column vector of weights corresponding to each line in the interface and ϵ is the error vector. This can be thought of as determining the linear combination of line flow sensitivities that best aligns with the voltage sensitivity.
4) In operations the weighted sum of MW flows on the interface is monitored and generation is dispatched to maintain the weighted MW flow less than a threshold plus a suitable safety margin, the weighted interface MW limit.

Note that the limits and bus voltage sensitivity vectors are calculated with an AC power flow model but the weighted MW interface flow requires only a DC power flow model.

III. PROOF OF CONCEPT TEST

The Nordic test system [10] is used to illustrate the proposed method. The one-line diagram of the system is shown in Fig. 1. Most of the generation in the system is in the North area while most of the load is in the Central area resulting in large transfers from the North to the Central areas.

The interface includes all four paths (five lines) connecting the North and Central areas (as indicated by red dashed line in Fig. 1).

A. The weights and interface MW limits determination

1000 AC power flow scenarios were executed (Step 1) by increasing loads in the Central area in random proportions and constant power factor until a low voltage limit of 0.95 (pu) was encountered, typically in the Central area near the increased load.

For each scenario the load increase was met by increasing generation from generator g19 in the North. The shift factor vectors for each of the lines in the interface were calculated (Step 2) and the weights corresponding to each of the lines determined (Step 3) to minimize the mean square error between the average voltage sensitivity vector and the weighted combination of the shift factor vectors.

The scatter plot displayed in Fig. 2 illustrates the relation of un-weighted and weighted interface MW. Every dot represents a unique transfer scenario at the point that the transfer is limited by a low bus voltage of 0.95 pu. The red dot represents the minimum transfer observed and the magenta dot represents the minimum weighted transfer observed for the 1000 scenarios. The minimum interface MW flow observed is 3115.0 MW corresponding to a weighted interface MW flow of 452.0 MW (the red dot).

B. Simulation of operational application

The scenario highlighted by the red dot (see Fig. 2) ($P_{w,th} = 452MW$ and $P_{uw} = 3115MW$) is used as a seed to generate 1000 new trials to simulate operational application (Step 4) of the weighted interface MW limit.

A trial consists of a set of four different AC power flow solutions for the same random load increase in the Central area. The four different AC power flow solutions calculated for each trial are as follows:

- The T case corresponds to the un-weighted transfer being held constant for the load increase by increasing the central generator g14 by the amount of the random load increase. Generator g14 was selected because it has the least impact on the weighted transfer of any generator in the Central zone.
- In the WT case, the two generators in the central zone with the least (g14) and greatest (g7) impacts on the weighted transfer are adjusted so that the un-weighted interface flow is still maintained as in T but that the weighted MW transfer is also set to equal the minimum observed weighted interface flow of 452 MW.
- WT-5MW is the same as in WT but the weighted transfer is set to be 5 MW less than the minimum observed, 447 MW.
- WT-10MW is the same as in WT but the weighted transfer is set to be 10 MW less than the minimum observed, 442 MW.

In practice, the weighted MW interface limit could be observed by appending a single constraint to the security constrained economic dispatch program

$$\mathbf{a^T x} \le b \quad (3)$$

where $\mathbf{a^T}$ is a row-vector equal to the weighted sum of the shift factor vectors corresponding to each line in the interface. The scalar b is the desired reduction in the weighted MW interface flow, and the column-vector $\mathbf{x}$ is the resulting changes to the generator dispatch.

In the experiments, for simplicity and pragmatic reasons, we use only two generators for re-dispatch. In order to compute the amounts of dispatch for the three ”WT” cases, a 2x2 set of linear equations is solved for each case

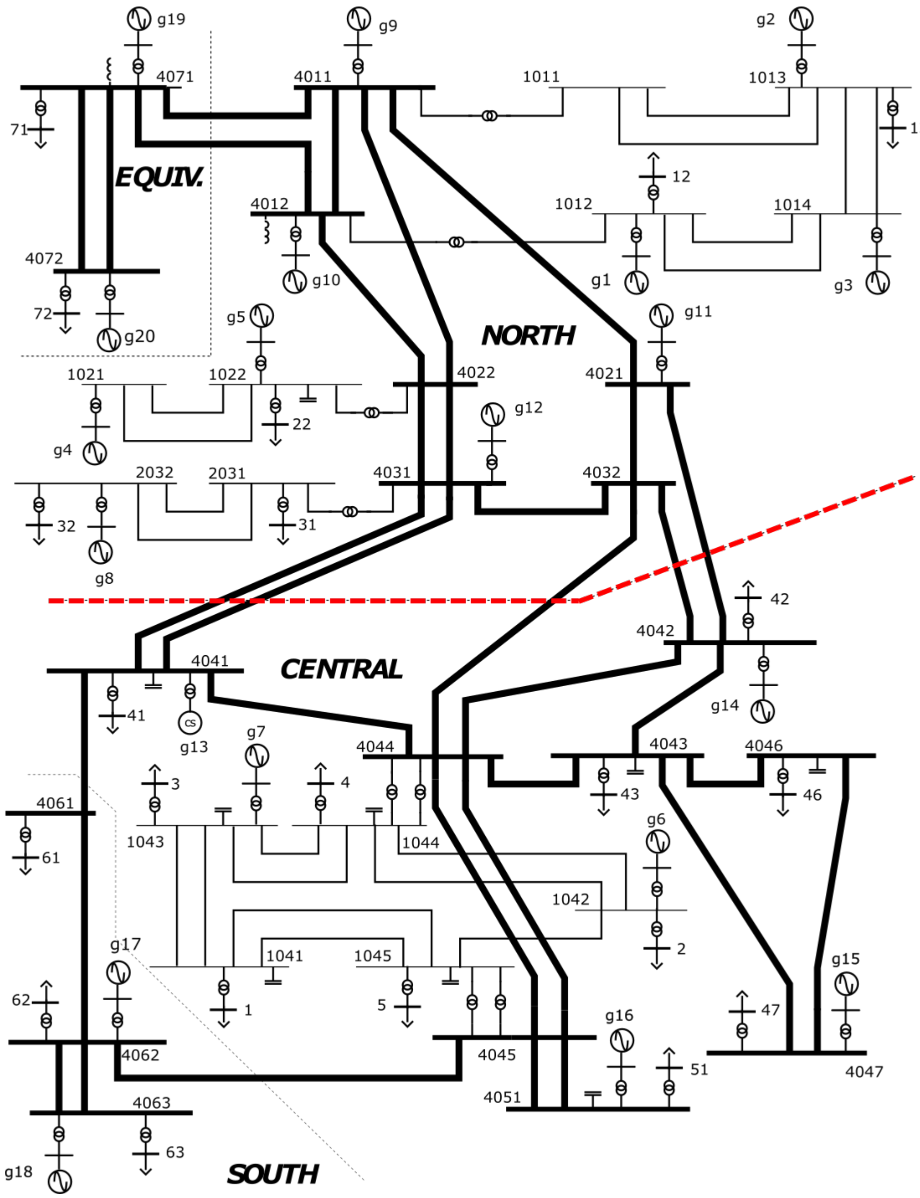

Fig. 1. One-line diagram of the Nordic test system [10].

$$\mathbf{A}_{2\times 2}\mathbf{\Delta P}_{w,2} = \mathbf{b}_2 \qquad (4)$$

where the top row of $\mathbf{b}$ is the desired change in the weighted transfer while the bottom row is power balance and is set to the total amount of the load increase above the load in the seed case.

$\mathbf{A}_{2\times 2}$ is formed by selecting the columns of $\mathbf{A}$ that correspond to the greatest and least effective generators at impacting the weighted interface MW flow. The bottom row of $\mathbf{A}$ is a vector of all ones (ignoring losses) so that the sum of the changes in generation balances the increase in load. The top row of $\mathbf{A}$ is the weighted sum of the $\mathbf{PTDF}s$ corresponding to the interface lines.

In order to solve for the dispatch at various levels of weighted interface MW flow limits, we adjust the top row of $\mathbf{b}_2$ in (4).

Note that for the situation in which the ”T” case resulted in a weighted interface MW flow below the desired interface MW limit for the ”WT” case, the top row component of $\mathbf{b}$ would be set to zero to hold the weighted interface flow constant rather than to increase the interface MW flow up to the limit. However, that situation was not encountered in the experiment reported.

Note also that the existence of identical parallel lines in the interface creates an indeterminate regression problem which can be avoided by requiring the weights of parallel lines to be equal or by calculating the shift factors for the single line equivalent.

In all the ”WT” cases above, the dispatch is effectuated

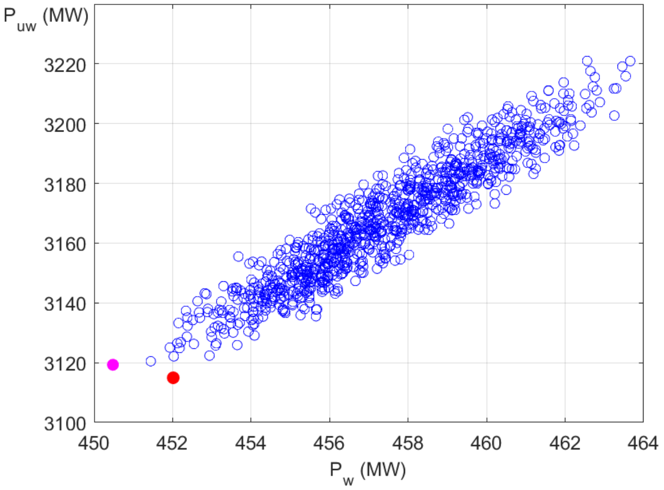

Fig. 2. Un-weighted versus weighted interface MW limit and critical case.

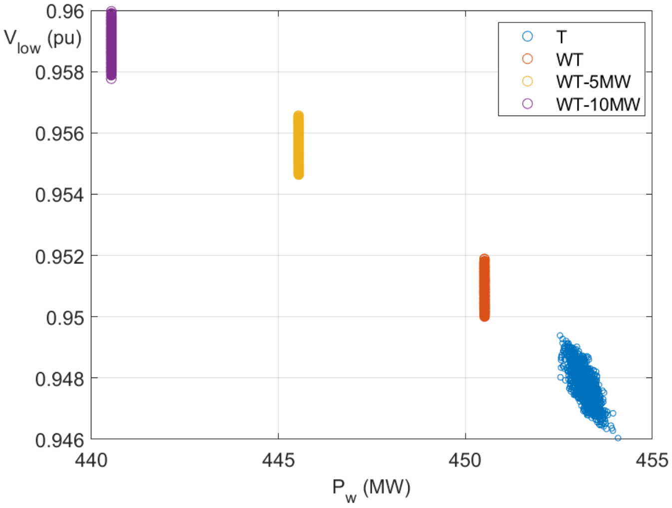

Fig. 3. The minimum voltage versus weighted interface MW for four different dispatch constraints.

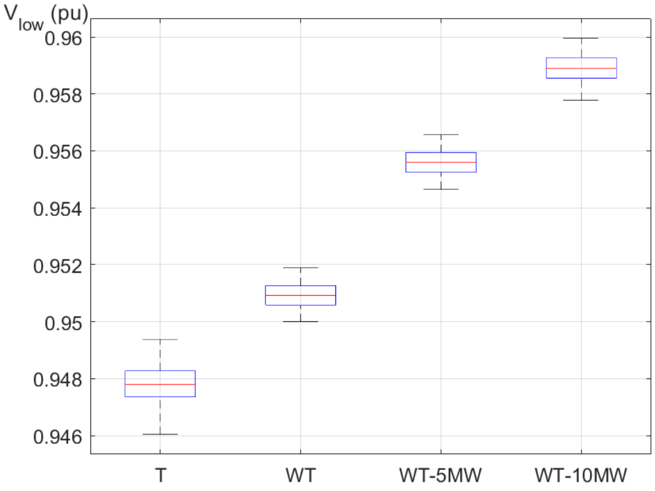

Fig. 4. Box plots of minimum voltage for four different dispatch constraints.

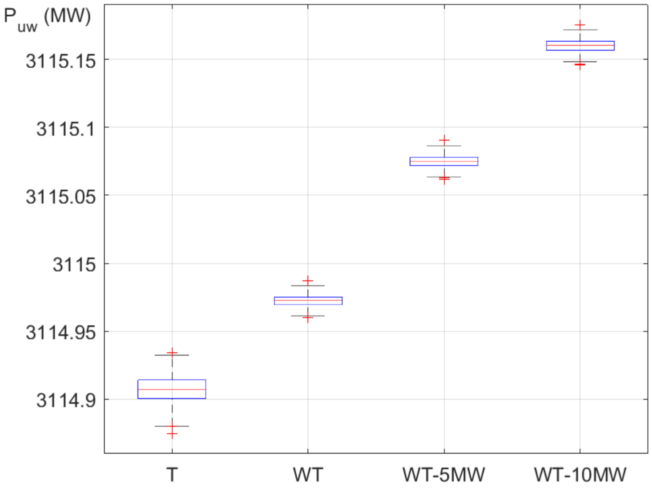

Fig. 5. Un-weighted interface MW flow for four cases

for the most effective pair of generators in the Central area. Note that other dispatches are also possible (for instance the cheapest and sufficient dispatch proposed in [11]). The results are displayed in Figs. 3 , 4 , and Fig. 5.

In Figure 3, each power flow solution corresponds to a single hollow circle of a different color. The color indicates which generation dispatch case was applied. The horizontal coordinate of each circle equals the weighted MW flow of the case and the vertical coordinate represents the minimum bus voltage for that case. There are 1000 circles for each dispatch case.

Although the weighted MW interface flow is different for each set, the un-weighted interface MW flow is held constant but for slight variation in losses. We also observe that the ”T” cases all have minimum voltages below 0.95 pu and that generation re-dispatch of those cases to the ”WT” cases corrects the minimum voltage.

Further re-dispatch to more restrictive weighted interface MW limits results in an increase of the minimum voltages (above 0.95pu) across all the scenarios.

Figure 4 presents the same voltages as graphed in Fig. 3, with the red centerline for each dispatch case indicating the median minimum voltage of the set. The top and bottom of the box represent the 25-th and 75-th percentiles of each set and the whiskers extend to the minimum and maximum voltages in each set.

From Fig. 4 it is observed that the dispatches that maintain weighted interface MW limits increase minimum voltage and decrease dispersion of the minimum voltage.

Figure 5 displays box plots for the un-weighted interface MW flow for each dispatch case set. We observe that the weighted interface MW limit constraints have a minor but consistent impact on the un-weighted interface MW flows. We believe that this is due to a reduction in losses.

TABLE I
MINIMUM VOLTAGE AND UN-WEIGHTED INTERFACE MW FLOW FOR THE FOUR CASES

Case	$\mathbf{V}_{low}(\mathbf{pu})$			$\mathbf{P}_{uw}(\mathbf{MW})$		
	Median	***Max***	***Min***	***Median***	***Max***	***Min***
WT-10	0.959	0.960	0.958	3115.16	3115.18	3115.15
WT-5	0.956	0.957	0.955	3115.08	3115.09	3115.06
WT	0.951	0.952	0.950	3114.97	3114.99	3114.96
T	0.948	0.949	0.946	3114.91	3114.93	3114.87

The maximum un-weighted interface flow observed over all cases was 3115.2 MW and the minimum un-weighted interface MW flow was 3114.9 MW.

Table I summarizes the minimum voltages and un-weighted interface MW flows for each dispatch case set. The key point reinforced by Fig. 5 and Table I is that by dispatching to limits in weighted interface MW flow the system is able to achieve constant or slight increases in transfer.

IV. DISCUSSION AND FUTURE WORK

A. Discussion

The proposed method exploits the computations typically completed to determine and update voltage constrained transfer limits [6], [7]. Typical studies require off-line AC power flow contingency analysis for a range of outage and load scenarios. The additional computations to determine the weights and weighted interface MW limit are trivial by comparison. The PTDFs for the lines in the interface are readily available from commercial power flow packages and frequently would be utilized for other analysis as part of determining the transfer limits.

While transmission engineers are generally familiar with obtaining the power flow sensitivities (PTDFs) for post-process manipulations, the voltage sensitivity vectors are less frequently utilized but can also be readily exported from packages such as Powerworld$^{\copyright}$ and Siemens PSSE$^{\copyright}$.

Finally, the linear regression equations have a column for each line in the interface and a row for each generator available to affect the transfer. They are expected to be smaller than two-hundred-by-twenty and could be solved in a basic spreadsheet program deployed on an inexpensive tablet or laptop.

The objective for this study was to demonstrate how transfer limits intended to safeguard against voltage problems can be made more accurate and useful by incorporating weights that tune the limit to the sensitivity of the troublesome voltages. The sensitivity of the low voltage to power injections was used to determine the weights.

B. Future work

In future work, we plan to use a similar procedure but investigate the use of voltage collapse sensitivity or the sensitivity of reactive power margins [2], [3] in place of the voltage sensitivity.

This study also assumed that the lines in defining the interface were already determined. Future work will look at identifying the set of lines or load pockets that would make up the best interfaces to monitor for voltage security.

V. CONCLUSION

This paper proposes the use of **weighted** interface MW limits where un-weighted interface MW limits are used as a proxy for low voltage constraints in power systems. The additional computational burden above what is required to determine un-weighted interface MW limits is numerical solution of a small dimensional regression equation with dimensions equal to the number of lines in the interface and the number of generator buses available to dispatch.

The solution of the multi-linear regression problem finds the best approximation of a low-voltage sensitivity vector as a linear combination of DC power flow sensitivities.

The weighted interface MW limit can be applied to real-time control, incorporated into security constrained economic dispatch, or used in conjunction with machine learning approaches [12].

Proof of concept using the Nordic test system illustrates that dispatch constrained to the weighted interface MW limit results in better voltage profiles than for the dispatch constrained to the un-weighted interface MW limit.

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