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CIGRE US National Committee
2017 Grid of the Future Symposium

Reducing Contingency-based Windfarm Curtailments through use of Transmission Capacity Forecasting

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SUMMARY

The paper examines how dynamic line rating and transmission capacity forecasting can reduce or eliminate windfarm curtailments intended to prevent outlet transmission path overloads.

A 159.1MW windfarm in the southwest United States with two outlet transmission line paths is often curtailed by 30% during certain N-1 system events. These events would result in an overload of one or the other outlet paths if the windfarm was operating above 70% of its rated output. Presently the windfarm is pre-emptively curtailed. In this case, if an overload is foreseen to occur during maximum generation in the event of an N-1 event, the windfarm is immediately curtailed by tripping 30% of its rated production capacity. This produces losses for the windfarm operator and is unnecessary if the contingent event does not occur.

The transmission operator and ISO are considering the implementation of a remedial action scheme (RAS) which would allow the windfarm to operate as usual unless a contingency occurs. In that event 48.7MW of windfarm capacity would be curtailed within cycles of the contingent event. As is common with implementation of an RAS, this is not considered an ideal solution, and has many operational implications to the grid operator.

Deployment of a next generation dynamic line rating (DLR) system incorporating transmission capacity forecasting (TCF) is investigated as an option to both the pre-emptive and reactionary curtailment schemes. This type of TCF system provides hours- to days-ahead forecasts of a transmission line's capacity with up to 99% confidence. This is accomplished by developing numerical forecasts of a transmission line's power handling capacity based on forecast weather data combined with learned and real-time line behavior data and weather conditions.

It is shown that the wind conditions resulting in peak power output from the windfarm also produce significant cooling of the line and a substantial increase in line capacity during those periods. The use of the TCF system to either eliminate the need for the RAS, or to enhance operation of the RAS is presented. In both cases TCF is shown to eliminate the need to curtail, or provide the windfarm operator time to adjust the windfarm's output to an optimal level as means to minimize curtailment.

In an environment where curtailment presents a cost to the windfarm operator, but is caused by overloads in the transmission operator's lines, and where the ISO is responsible for the operation of the bulk electric grid, the issue of who pays for the deployment of the TCF system is possibly complex. The issues around the various options of who pays are also discussed.

KEYWORDS: Curtailment, Windfarm, Dynamic Line Rating, Remedial Action Scheme, Transmission Capacity Forecasting, DLR

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INTRODUCTION

The Southwest Power Pool (SPP) is a Regional Transmission Operator (RTO) in the central United States that oversees operation of the bulk electric grid and wholesale power market in 14 states. [1] Within SPP is located a 159.1MW windfarm, herein referred to as the “Grand” windfarm. The output of Grand windfarm is transmitted through two outlet transmission paths which, under certain contingency situations, would result in one or the other line to be overloaded. To address these situations, up to 48.7 MW (~30%) of Grand’s power production must be curtailed. Costs associated with these curtailments would include:

- Loss of generation revenue for windfarm owner/operator. Assuming a low $0.02/kw-hr bulk rate, this means a loss of approximately $1000/hour at full curtailment. [2]
- The opportunity cost of the loss of production tax credits (PTC) of $0.021/kw-hr (for this project), equalling again, about $1000/hour.
- Wear and tear on equipment from frequent curtailments (circuit breaker operations, etc.)
- The cost of reconductoring the constrained lines to increase their loading capacity. SPP has estimated the cost at $19.5 million.

THE NEED FOR CURTAILMENT

The Grand Windfarm is located near two other windfarms and share two outlets to the SPP system, via lines PCC-H and PCC-N. See Figure 1. Steady state contingency analysis indicates an outage to either outlet would trigger an overload in the other should the windfarms be operating at full capacity. On high production days SPP would order Grand to reduce its output on a pre-emptive basis triggering curtailment of generation from the Windfarm. It should be noted that curtailment resulting from a transmission constraint is the most common reason for wind curtailments in the United States. [3]

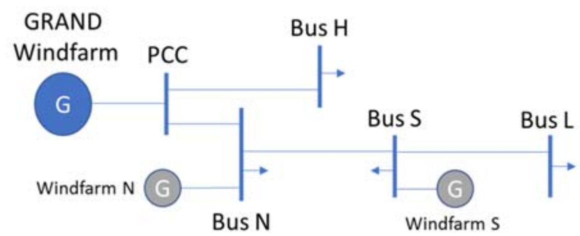

Figure 1: Interconnection of Grand Windfarm to SPP system

Under normal operating conditions and controlling to N-1 limits, the wind farm would be required to operate at only 69.4% of its total available capacity. Generation is tripped by the opening of any required combination of the various feeders at Grand. This is the default, pre-emptive, curtailment process. [4]

FAST REACTIONARY REMEDIAL ACTION SCHEME

To reduce the number of curtailment events, at the behest of the connection transmission operator, SPP investigated the implementation of a remedial action scheme (RAS) which would trip generation at Grand only when one of the outlet line segments (PCC-to-H, PCC-to-N, or N-to-S) actually tripped off-line. This reactionary curtailment process would involve monitoring the two outlets and, upon the occurrence of a line open status, immediately and automatically trip sufficient generation. The RAS would therefore mitigate the identified contingency overloads within a few cycles and allow for maximum output without precautionary curtailment.

While the RAS could reduce the number of curtailments by taking action only during actual contingency conditions, like all RASs the design and deployment of the scheme requires detailed studies to be performed to ensure that the RAS, 1) meets all performance requirements, 2) has minimal likelihood of false operation, and, 3) will not have any unintended impacts. A long term reconductoring plan ensures the RAS is not to be considered a permanent solution.

Both the pre-emptive and reactionary solutions to the contingency line overload situation involve curtailment as a means of addressing fixed line capacity ratings during periods of high windfarm power output during windy conditions. The balance of this paper looks at addressing these contingencies using the actual power handling capacity of the transmission lines experiencing those same windy conditions.

CONSIDERATION OF DLR AND TRANSMISSION CAPACITY FORECASTING

Transmission line rating is dependent on several environmental variables, including heat generated in the line (I^2R losses), heat added to the line (solar radiation), and heat being removed from the line (convective and radiated cooling) due to wind and precipitation. This latter point is of relevance to windfarm curtailment as the same high wind levels that produce maximum windfarm output also produce significant conductor cooling.

Traditional operational limits of a transmission line are established through "static" transmission line rating methodologies which, while ensuring a very low probability that conductor sag will exceed operational or regulatory limits of even short duration, results in very conservative line ratings and often unnecessary curtailment events.

Seasonally adjusted ratings (SAR) and ambient adjusted ratings (AAR) are commonly used today to increase a line's static rating by acknowledging different environmental conditions exist at different times of the year. [5] Dynamic Line Rating, or DLR, is a transmission line's actual, real-time, power carrying capacity based on the conductor's actual operating temperature using real-time line behavior data and weather conditions. DLR is the natural and logical extension of seasonal and ambient adjusted ratings. DLR techniques have been shown to increase a line's static rating by as much as 100%, though going above 25% may require addressing the next limiting element in the line. [6]

Some next generation DLR systems also provide transmission capacity forecasting (TCF) capabilities where the forecasts are based upon learned conductor behaviour correlated to past and forecast weather conditions. Forecasts are available for hours or days ahead windows with 98% confidence factors. [7]

With the cost of a modern dynamic line rating system being about 1% the cost of line reconductoring, TCF provides a cost effective possible alternate solution to curtailment and the RAS. [6] For this system, basing the TCF system cost as 1% of SPP's estimated reconductoring cost, the cost of a TCF system is equal to roughly 100 hours of the cost of curtailment at Grand (at about $2000/hr for the cost of lost generation revenue and production tax credit value).

TCF AS AN ALTERNATIVE TO PRE-EMPTIVE CURTAILMENT

Numerical weather prediction (NWP) models that utilize weather data are commonly used for wind energy forecasting and are used to develop the forecast day ahead power output of Grand. [8] Curtailment of Grand is typically ordered on a day ahead basis after determining that an overload condition would exist that day in the event of a contingency situation and the forecast power output.

TCF systems can similarly develop numerical forecasts of a transmission line's power handling capacity based on forecast weather data. Figure 2 shows output from one commercially available TCF system showing both 24-hour ahead and 2-hour ahead forecasts of a line's capacity. The 24-hour forecast means the line may be operated at the forecast level for the next 24-hours. The 2-hour forecast means the line may be operated at the forecast level for the next four hours. Note that the 24-hour forecast is more conservative than the 2-hour forecast. This reflects the greater uncertainty associated with longer term weather forecasts. Conversely, a 1-hour forecast would be higher than the 2-hour forecast shown as the uncertainty of the forecast weather data is less in the shorter term.

Application of TCF to address day ahead pre-emptive curtailment would use a 36-hour ahead forecast to allow for both the next day's operation and the time required during the prior day for the required market setting and clearing activities.

Figure 2: Transmission Capacity Forecast System Output showing 2- and 24-hour ahead forecasts

Forecasted windfarm output would be used to determine the power flow on the outlet lines during N-1 contingencies. The loading would then be compared to the line's forecasted capacity. Only if the loading exceeded the forecasted capacity would the windfarm be ordered to curtail.

System analysis shows that:

- For an outage of the PCC-H line, under full output from Grand, the worse-case overload is on the S-L line which would be loaded at 115% of its 4-hour rating, or 147.4% of static;
- Outage of the PCC-N or N-S lines would result in the PCC-H becoming the line of concern. The PCC-H line normally has a 239MVA rating, and with this rating, never becomes overloaded even under these conditions. However, in the past PCC-H has been required to be de-rated to 120MVA. Under that derating the line would be overloaded to 148.7%.
- Therefore, for both lines there is a need to carry approximately 150% of static during contingency to avoid curtailment. See Table 1.

Table 1: Worse case line overload summary

Contingent Element	Monitored Element	% Static Rating	% 120MVA derating
PCC-H	S-L	147.4%	N/A
N-S	PCC-H	74.6%	148.7%

With windfarm output forecasts being based on numerical weather predication models, TCF ratings based on the same forecast weather predictions are logical to consider. Maximum windfarm output will occur during times when wind is high. This will also produce the greatest amount of line cooling and additional DLR capacity. Both the static and 4-hour line ratings are based on 0.6m/sec (2ft/sec) wind speed (per SPP Planning Criteria [9]). For the outlet lines connecting Grand, evaluation using the thermal balance equations in IEEE Std. 738 shows that a wind speed of 3.0 m/sec is required to produce 152% of static rating. [10]

The wind turbines used at Grand require a windspeed at the nacelle of at least 14m/sec to produce maximum power. The turbines can be used with nacelle heights ranging from 60-80m. Wind speed compared to ground increases with height. We use the highest nacelle height (i.e., greatest de-rating of ground wind speed) and the more conservative Danish Wind Industry Association curve of wind speed versus height (Figure 3). [11] From this a 6m/sec windspeed at ground (10m) equates to about 8.7m/sec for an 80m nacelle. This ratios to a 9.6 m/sec ground speed for a 14 m/sec minimum nacelle wind speed for rated turbine output. This is more than the 3.0 m/sec needed for achieving 150% of static rating.

Note that for the location of Grand, the average annual windspeed is 6.8m/sec, with the lowest average monthly speed (August) being 3.3 m/sec. Both levels are also above the wind speed needed for 150% static. [12] Further, the orientation of all the lines of interest are roughly perpendicular to the prevailing wind patterns, maximizing the wind's cooling effect.

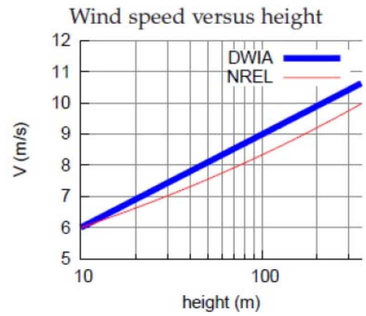

Figure 3:Wind Speed versus Height

TCF AS AN ENHANCEMENT TO RAS-based FAST REACTIVE CURTAILMENT

As a second analysis, it was assumed that TCF was used in conjunction with the RAS solution. Recall the purpose of the RAS was to curtail generation within cycles of a contingency event. The assumption here is that the overloaded line's actual capacity was again limited to its emergency rating.

Here a 4-hour TCF rating can be used. If the 4-hour TCF rating showed the line capable of carrying the resulting power flow, then the operation of the RAS could be inhibited. The 4-hour TCF forecast would be refreshed periodically (for example, every 15-minutes, 30 minutes, or hourly) and either continue to inhibit operation of the RAS or allow it to become active. See Figure 4.

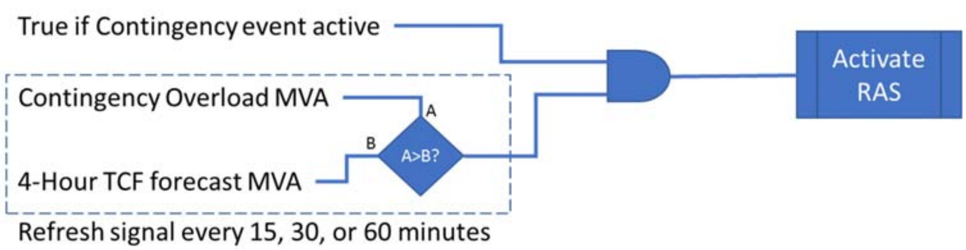

Figure 4: Simplified logic diagram showing supervision of RAS by TCF forecast

An enhancement to this simple go/no-go supervision would be for longer term TCF ratings to be developed and compared against the appropriate operational emergency rating to provide an indicator of possible curtailment. For example, a 6-hour TCF rating is developed. Examination shows it is approaching the amount of power the line would carry during a contingency. There it could be assumed that should a contingency event occur, the RAS will be enabled and the windfarm would be immediately curtailed. In the case of Grand, this would curtail 48.7MW. However, with this advanced knowledge the windfarm operator could take more measured action and taper the output of the windfarm to a level that would allow it to remain in service in the event of a contingency and avoid initiating the RAS and loss of the full 48.7MW.

Deployment of a dynamic line rating system incorporating weather forecast based transmission capacity forecasting can either eliminate the need for an RAS, or enhance the operation of an RAS by minimizing the amount of power which must be curtailed.

WHO PAYS and WHO BENEFITS

Early DLR systems had various technical and installation-related issues that kept them from being widely deployed. Next generation systems have eliminated these concerns. [7] However, a key issue for DLR/TCF system deployment in this application is who benefits, who pays, and how do they recover the cost.

If the transmission asset owner (TO) decides to install the TCF system, they must do so acknowledging they have indirect financial benefit. Cost recovery could be achieved as an enhancement to the transmission asset. If the TO is to be charged with implementing the RAS, then avoidance of this cost would be an additional one-time cost benefit.

The relationship between the generator and the TO will determine if there is any benefit to the TO:

- If the additional transmission capacity is provided as part of a network integration transmission service (NITS), no benefit will accrue to the TO.
- If the transmission capacity provided is point-to-point or off-system, then the TO would share in any incremental revenue resulting from transmitting the incremental capacity.

The use of DLR with TCF to relieve the transmission constraint positively impacts energy costs.

- If excess generation is trapped behind the constrained line, without TCF the LMP local to the windfarm is depressed, which would benefit local consumers. This also has the effect of elevating remote LMPS, increasing the cost to remote consumers.
- Once the constraint is removed, the power can be exported. Remote LMPs will drop and local LMPs will rise (reversing the above scenario). This makes the cost of electricity more equal than before.

The transmission capacity forecast aspect of the system are of particular interest, as it should be to other ISOs and RTOs. Within SPP, transmission system limitations are based on static information. [13] TCF systems replace static capacity ratings with fully operational real-time ratings for any short- to medium-term timeframe required. This would provide enhanced situational awareness allowing for transmission system limits, constraints, and congestion to be continuously evaluated. So equipped, the system essentially becomes alive, rather than a set of fixed assets.

As the amount of wind power generation increases within SPP, it becomes increasingly important to export the power as there is dwindling ability to absorb within SPP's operational area. SPP currently has 17GW of connected wind generation and can absorb wind generation within the system up to about 20GW. Beyond this, any wind generation must be exported. Present transmission limitations restrict wind power export to 600MW. More widespread implementation of TCF would help overcome this limitation and enable the point-to-point transmission transactions needed to export additional wind power.

If the ISO (SPP) wanted to install the system, there is no actual direct mechanism that would allow them to pay for the installation and implementation. As the role of both ISOs and RTOs is to model, evaluate and approve submitted projects, they cannot compel a TO to build or complete a project.

However, should the ISO take the lead in pressing for the installation of the TCF system as a transmission upgrade, the cost of the system would need to be socialized across the member utilities per existing processes. This cost allocation process can be complicated given the "complex and highly interconnected nature of the bulk power system and existing regulatory frameworks, not considering merchant transmission developments and opportunities which can transcend regions." [14]

Logically, the windfarm operator could take the lead in requesting the system as they would immediately enjoy the financial benefits of avoiding (or reducing) curtailments. However, the windfarm operator would have to convince the TO to install the equipment and to allow their asset to be rated as per the recommendation of the TCF system. The generator and TO would also need to involve the ISO to request the collected data become operational within the ISO's daily activities.

CONCLUSIONS AND NEXT STEPS

Next generation dynamic line rating systems which incorporate transmission capacity forecasting can be used to address transmission constraints that result in curtailment of wind power plant generation levels. These systems can enhance the operation of other means of addressing curtailment, such as implementing complex remedial action schemes.

Allocating the costs of deploying and integrating TCF systems on a transmission asset and within an ISO/RTO's operations is not well defined. This is particularly true if a prime beneficiary is a third entity, such as a wind plant operator.

On a broader basis, TCF systems can be used to maximize the value and utilization of currently existing transmission assets in regions with high levels of renewable penetration. The full benefit of what TCF system deployment can provide requires a systematic assessment of the application including deeper analysis of the potential economic value to the generator, the transmission owner, and the overall system participants.

BIBLIOGRAPHY

[1] "Electric Power Markets: Southwest Power Pool (SPP)," Federal Energy Regulatory Commission, 11 July 2017. [Online]. Available: https://www.ferc.gov/market-oversight/mkt-electric/spp.asp. [Accessed 7 August 2017].

[2] J. S. Hill, "US Wind Energy Prices At “Rock-Bottom Levels,” Says Berkeley Lab," Clean Technica, 18 August 2016. [Online]. Available: US Wind Energy Prices At “Rock-Bottom Levels,” Says Berkeley Lab. [Accessed 2017 7 August].

[3] NREL, "Wind and Solar Energy Curtailment: Experience and Practices in the United States," U. S. Department of Energy, 2010.

[4] Southwest Power Pool, "TRANSMISSION WORKING GROUP MEETING December 7, 2016," Little Rock, AR, 2016.

[5] NREL, "Effective Grid Utilizaation: A Technical Assessment and Application Guide," U. S. Department of Energy, 2012.

[6] J. C. McCall and T. Goodwin, "Dynamic Line Rating as a Means to Enhance Transmission Grid Resilience," in *2015 CIGRE Grid of the Future Symposium*, Chicago, IL, 2015.

[7] J. McCall and B. Servatius, "Enhanced Economic and Operational Advantages of Next Generation Dynamic," in *2016 Grid of the Future Symposium*, Philadelphia, PA, 2016.

[8] National Renewable Energy Laboratory, "FORECASTING WIND AND SOLAR GENERATION: Improviding System Operations," Greening the Grid.org, 2016.

[9] Southwest Power Pool, "SPP Planning Criteria Ver 1.0," 2015.

[10] IEEE Power Engineering Society, "IEEE 738-2006, IEEE Standard for Calculating the Current-Temperature of Bare Overhead," Institute of Electrical and Electronics Engineers, 2006.

[11] D. J. MacCay, Sustainable Energy - Without the Hot Air, Cambridge, England: UIT Cambridge Ltd, 2009, p. 266.

[12] "http://www.usa.com/panhandle-tx-weather.htm," World Media Group LLC, [Online]. Available: http://www.usa.com/panhandle-tx-weather.htm. [Accessed 24 August 2017].

[13] S. Ellis, "Market Efficiency Challenges and Opportunities in SPP," Southwest Power Pool, 2016.

[14] J. Caspary, "Electric Transmission 101: Markets, ISO/RTOs, and Grid Planning Operations," Environmental and Energy Sudy Institute, 2013.