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Dynamic Line Rating as a Means to Enhance Transmission Grid Resilience

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SUMMARY

Events that may test transmission grid resilience are varied. Some involve minimal permanent damage and can be recovered from relatively quickly. Other events may require much longer periods of time to recover where extensive damage has occurred. Some events are fast to develop, while other may provide an opportunity to prepare (weather) or not (willful attack).

Resiliency consists of both the ability to resist failure and to rapidly recover from failure. Both sides of grid resiliency as it applies to the transmission grid can possibly be addressed by dynamic line rating (DLR). The purpose of this paper is to present for discussion the use of DLR as a means to improve grid resiliency in a way that is cost effective, quick to deploy, and which provides ongoing operational benefits when not being used for resiliency purposes.

For events involving longer term outages associated with major transmission line fall downs, multiple line outages, or critical substation outages, DLR offers a number of possible advantages. Widespread preemptive installation of DLR can address the problem of determining long term line overload ratings that are necessary when facing the sudden yet long term absence of major assets. DLR can alleviate congestion and other constraints that may appear during recovery. Finally, DLR can provide the added capacity that may be required by lower voltage lines in such events but which would otherwise be difficult to justify economically for normal operation.

Cascading failure events involve the sequential tripping of a number of transmission lines as they become overloaded after a precipitating event. DLR offers the potential to act as a line capacity buffer of sorts to reduce or prevent cascade line tripping.

As a grid resilience technology solution DLR also provides many economic benefits during normal grid operations. This is compared to "insurance policy" type of expenditures that are difficult, or less satisfying, to justify.

KEYWORDS

Dynamic line rating, DLR, resilience, cascading outages, grid collapse

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INTRODUCTION

Grid resiliency is defined as the ability to resist failure and rapidly recover from breakdown. There are any number of causes of power system events that can result in loss in the ability to supply power to loads. A few causes relevant to the topic of this paper are:

- Cascaded transmission line trips resulting in blackouts
- Weather related events that may damage or destroy one or more transmission lines or even entire substations
- Willful attacks on critical transmission lines or substations

Some of these events are fast to develop and may provide an opportunity to prepare (weather) or not (willful attack). Some events involve minimal permanent damage and can be recovered from relatively quickly (blackouts caused mainly from line tripping). Other events may require much longer periods of time to recover where extensive damage has occurred.

Looking at each of these scenarios from the resiliency definition of "resisting failure" and "rapidly recovering" produces many perspectives for examination. But for these scenarios, both sides of resiliency can also be uniquely addressed by dynamic line rating. The purpose of this paper is to present for discussion the benefits that an existing yet widespread deployment of dynamic line rating would provide as a means to improve grid resiliency in a way that is very cost effective, and which provides ongoing operational benefits when not being used for grid resiliency purposes.

DYNAMIC LINE RATING

Every transmission line has a static rating; effectively a nameplate power rating. Static transmission line rating methodologies are dependent on several environmental variables identified in IEEE standard 738 and CIGRE brochures 207 and 324. These variables are related to the amount of heat generated in the line (resistance and current), heat being added to the line (solar radiation), and heat being removed from the line (convective and radiated cooling). The common practice for transmission line rating is to select conservative values for these environmental variables which may be fixed or seasonally varied, and that equate to a low probability that conductor sag will exceed operational or regulatory limits for a very short duration. This methodology directly acknowledges that operational limits of transmission lines are conservative most of the time.

The concept behind dynamic line rating (DLR) is that if the actual real-time status and behavior of the transmission line is known, then it is possible to determine a real-time line capacity, rather than depending upon a capacity based on a set of conservative, fixed, assumptions. This is satisfyingly intuitive as many of the factors that DLR accommodates (ambient temperature, solar radiation, wind, rain, etc.) vary almost continuously. Wind is particular as it is not only transient, but its impact on line cooling is multivariate, with velocity, orientation and spatial context playing roles. This is an important concept as per the US Department of Energy, DLR techniques have been shown to increase a line's static rating by as much as 100%. [1] In all fairness, it must also be noted that it is possible for DLR to occasional reduce a line's rating to below its static rating when conditions are right, for example, when wind speed drops below that normally used for static ratings (0.6m/sec). [2]

In practical application, taking advantage of DLR capacity increases greater than ~25% above static may not be possible unless other potentially limiting line components are also upgraded. This could include items such as switches, CTs and PTs, wave traps, and possible even circuit breakers. Taking advantage of higher levels of DLR capacity may also require examination of relay settings so as not to expose the grid to mis-operations. [3] However, if the cost involved in upgrading the next limiting device or devices is determined, then the economic benefit of releasing this extra capacity through DLR is easily determined. [4]

DLR makes use of technologies that allow for the real-time measurement and monitoring of the critical parameters of a transmission line. Specifically, conductor clearance-to-ground (or its cousin, sag), conductor temperature and current. Add to this weather information such as wind speed, ambient temperature, etc., and the ability to communicate all of this information, and computer models can then be used to determine both real-time, and even forecasted line capacity ratings. Note that spot readings of conductor temperatures must be tempered and cannot be depended upon directly. For example, the author's company's DLR software learns overtime how the spot temperatures correlate to the average conductor temperatures used in IEEE standard 738 and CIGRE brochures 207 and 324.

Numerous papers have been written detailing the benefits of DLR to a utility. Some of the more commonly cited benefits include [5]:

- Relieving congestion and transmission related constraints
- Increased transmission capacity at minimal investment
- Real time monitoring of thermal state of conductors
- Increased situational awareness for operators
- Improved forecasting
- Deferment of large capital investments
- Enhanced performance of reliability of aging assets
- More efficient integration of renewables such as wind and solar energy
- Potential savings with generation dispatch

This paper will focus on the first five of these listed benefits and their impact on grid resilience.

It should be noted that dynamic line rating systems are very quick to deploy compared to other means of adding incremental line capacity (re-conductoring, constructing parallel circuits, etc.). The assumption is also that the dynamic line rating systems will have been deployed before any system resiliency event occurs.

MAJOR ASSET LOSS MAY REQUIRE LONG TERM RATING INCREASES

Individual transmission towers are regularly damaged by weather or willful events and result in the affected transmission line being removed from service until the tower can be repaired or replaced. Some events result in the collapse of dozens of towers. See Figure 1. One infamous event was the 1998 ice storm in Canada where 300 towers in Quebec and another 50 in Ontario collapsed due to ice loading [6]. Substations are not immune to weather either as witnessed by the loss in 2014 of an entire 500kV substation in Arkansas due to a direct hit by a tornado. [7]

Figure 1: One of 16 cascaded 500kV DC Towers collapsed at the Los Angeles Department of Water and Power (LADWP) in 1988 due to High Winds

The ability to implement any "rapid recovery" type of resilience is gated by the ability to access spare equipment, emergency stores, crews, and the resulting rebuild time. During this time, the grid should be able to resiliently adapt to supply power in the absence of these lines or stations.

Possible Line Capacity Issues

Should one or more substations or transmission lines be lost to natural or man-made calamities, a resilient grid must be able to provide alternate transmission paths around the damaged portion of the grid to ensure power can serve the affected load. This ability is dependent on the capacity of those transmission lines still in service. One concern is that such outages are relatively long-term, where no "emergency rating" equivalent for transmission lines can be used to address any path capacity limitations.

Normal sources of generation used to serve loads may no longer be cost effective from an economic dispatch perspective if the normal transmission paths are sufficiently disrupted. Here, generation mixes that do not exceed allowable ratings may not be possible [8]. Conversely, remaining transmission paths may become so constrained or congested that it may be not be possible to supply power effectively.

While the long term outage of a single 69 – 230kV line may not be cause for too much concern from a resiliency standpoint, the collapse of a major EHV line at 345kV – 765kV, or an HVDC line, or attacks on one or two critical EHV substations likely would be. In these events the lower voltage transmission assets will more likely be depended upon to absorb the additional transmission capacity. Lower voltage lines are more commonly on the cusp when it comes to capital investment upgrade capacity for constraint or contingency events as these investments are much harder to justify economically.

Alleviating line capacity issues with DLR

An existing DLR deployment could be an effective tool to address all of these identified issues.

- DLR can provide both real-time and forecast short- and medium-term "emergency-equivalent" ratings for all remaining in service lines.

- Varying amounts and types of generation offered to the grid, economic dispatch issues, the dynamic topology of a grid during a recovery event, and so forth, all present challenges to operation personnel. DLR can provide a window into an equally dynamic and flexible transmission network where constraints would be more easily mitigated.

- As mentioned, uprating lower voltage lines for marginal contingency scenarios is often difficult to justify economically. Yet in the event of a major outage as described here, this additional capacity may become instantly desired. DLR is a very cost effective means to address line capacity upgrades where the economic case, normally hinging on a 5 - 10% increase in capacity for normal N-1 scenarios, is difficult to make [9]. This can be true at higher voltages, where N-2 or greater scenarios may need be considered. Again, it must be noted that there is a risk additional line capacity may not be available due to certain weather conditions. In such event, grid operations may need adjust dispatch and experience some congestion costs to maintain reliability requirements.

Line reconductoring is a common solution to upgrading lines. This cost can range from $1 million to $8 million per mile or more depending on voltage class [10]. An example clarifies this. An 80km (50 mile) line could cost $50 million to $400 million to reconductor. Depending upon the installation requirements and the DLR system selected, the cost for a DLR implementation would typically range well under $0.5 million, regardless of voltage. DLR can redefine the economics of even marginal line upgrade decisions.

CASCADING OUTAGES

Loss of transmission paths have been the cause of most major blackouts in North America over the past 50 years as losing these paths limit the amount of power generation that can be successfully moved to load centers. Tripping lines when they exceed their operating limits is common to cascading outages and can "potentially widen cascade failures." [11].

In cascading failures, one precipitating event leads to another, and so forth, until an entire system, or a large part of it, collapses. This is true of any type of system, with power systems being but one example of this. The failure event can be the failure of a network node (i.e., substation and/or generation station) or a network connection (transmission line). When a cascade of transmission line trips begins to occur, the network loses its ability to carry the required power flows and the network becomes vulnerable [12]. The common scenario is for one line to trip, rerouting power to another line, causing a real or protective overload, resulting in a second line trip, and so forth. Research shows that the more complex and tightly interconnected the network the more fragile it is, and therefore more likely to suddenly collapse due to cascading events [11]. As power grids are becoming increasingly more meshed to increase their flexibility and reliability, this increases the importance of arresting the possibility of cascading events.

Further, studies have shown that attacks on a small number of nodes (substations) can precipitate cascading line failures. While some military analyses have focused on defending the nodes [13], an alternate solution may be in preventing the node attacks from causing the lines to be overloaded and trip.

DLR as a possible means to limit Cascading Outages

When a line trips from some precipitating event, increased burdens are suddenly placed on the remaining lines in the transmission network. While there may be other reasons to trip further lines, for example grid stability issues, subsequent line trips resulting from overloads may possibly be minimized by an existing DLR system where the true capacity of the line is available in real-time. Preventing cascade tripping can increase the likelihood that even a tightly interconnected system will not experience a sudden collapse.

Effectively integrating DLR into grid operations during a cascading event will not be trivial as it may likely involve interaction with relay settings. For example, unnecessary line tripping occurred during the August 14, 2003 blackout in the U.S. and Canada due to operation of zone-3 distance relays set to prohibit lines from exceeding their static emergency overload ratings. [14] While DLR by itself would not have avoided that, it does identify one example as to how interaction between DLR and relays could be beneficial. In this case, zone-3 settings could be adjusted based on a line's computed DLR. This may be possible considering the highly programmable nature of modern protective relays, in conjunction with high speed inter-relay communications made possible with communication protocols such as IEC 61850.

Here the “resisting failure” aspect of grid resiliency would come into play. DLR eliminates the grid as a set of fixed capacity transmission assets, and replaces it with a living set of transmission pathways whose capacities reflect real-time conditions and the capabilities, above or below static ratings, of those lines. The ability to absorb sudden increases in load without resorting to defensive protective relay based trips could be critical to limiting cascade events. The increased flow capacity and ability to bypass damaged line reduces the risk of cascading failures [15]. Line capacities can act more as elastic bands than taught strings and the grid may become more resilient.

DLR AS AN ECONOMICALLY POSITIVE RESILIENCE SOLUTION

Utilities spend billions of Dollars on improving grid resilience. Many of these costs are defensive in nature; walls, fences, video cameras, spare equipment, redundant systems, etc. A spare transformer is simply a frozen financial asset unless it is someday needed.

Conversely, DLR offers every day economic benefits to a utility that quickly pay for any DLR investments. These benefits include [16]:

- Reduction or elimination of congestion expenses
- Provides the least cost solution for moderate capacity increase projects
- Delivers additional revenue by utilizing the line’s full, real-time, capacity
- Provides a cost effective line clearance compliance tool
- Provides least cost solution to accommodate gradually increasing loads
- Eliminate expensive conductor damage from line overheating
- Improves N-1 Modeling

The resilience aspects of DLR in both allowing the grid to deal with long term major facility outages, and in potentially ameliorating cascading outages, are substantial additional benefits of DLR.

CONCLUSIONS

Dynamic line rating (DLR) is a technology that offers utilities many economic benefits under normal operations. However, DLR may also provide strong grid resilience benefits. During long term substation or transmission line outage scenarios DLR may enhance recovery. DLR may possibly also be part of a system to limit or prevent cascade line outages and the potential system collapse such scenarios present.

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