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A Guide to Case Studies of **Grid Enhancing Technologies**

Idaho National Laboratory

Introduction

This document has been developed as a resource for the electric power industry to rapidly understand the scale and history with which certain new technologies have been installed on or otherwise simulated to impact the transmission system. This document attempts to address the findings of the 2022 U.S. Department of Energy (DOE) Report *Grid Enhancing Technologies: A Case Study on Ratepayer Impact*[1], which identified the need for workforce development and training materials to transition new technologies from a state of "pilots" and "case studies" to "business-as-usual." The authors go beyond typical survey-style literature reviews in that the key details and notes about each project are identified. Still, as will become evident, there is a need for more work to be done to increase the industry's public knowledge on important topics related to the implementation of grid enhancing technology on the transmission system.

In recent years, the industry has built a growing awareness of grid enhancing technologies (GETs), but an introduction to their primary use case is still helpful. In an ideal world, the most affordable generation would be dispatched first, and increasingly more expensive generation would be ramped up to meet customer demand. Unfortunately, generation merit order based solely on economics is unrealistic because of physical constraints on the transmission system. The generation portfolio is thus usually sub-optimally dispatched, often constrained by non-economic factors including lacking the transmission and distribution infrastructure required to move electricity from generators to load centers. When the transmission system limits generation dispatch economics, this is known as "congestion." Transmission congestion is defined by the DOE as the economic impact on the users of electricity that results from physical transmission constraints that limit the amount of power flow to ensure safe and reliable operation[2]. For example, the flow of power may be restricted by the maximum transmission line safe operating limit or the thermal limit of a transformer or transmission line conductor, or voltage limitations for long transmission lines. Therefore, operators are forced to reroute power through less optimal paths and rely on more expensive power generation, like conventional fossil fuels, while curtailing renewable wind or solar to safely meet the demand of their customers. The result is that congestion causes customers to pay more money for the electrical energy they use. The grid of the future will need to facilitate end use electrification, and increased use of renewable energy sources (RES) that will stress the aging infrastructure in the system. The transition to that future will require a grid with new capabilities, potentially leveraging the intelligent features of a new class of GETs to help mitigate congestion and improve economic performance of electrical energy delivery.

Although new technology has been developed, piloted, and shown to be successful at mitigating congestion under the right conditions, there is still a reluctance (or questions, or hesitance) from industry to adopt GETs across the power systems. Many organizations feel they need to validate the technologies on their own system because there are not references publicly available on performance, integration, and deployment. Recognizing this need, the authors have developed this summary and reference document that is meant to make the volumes of literature on GETs more readily available. This document Includes case studies for two primary forms of GETs:

Dynamic Line Rating (DLR) – Hardware and/or software used to appropriately update the calculated thermal limits of existing transmission lines based on real-time and forecasted weather conditions and measurements of other conditions of the line. Often, these schemes establish new limits that safely allow more energy transfer across existing infrastructure.

Power Flow Controllers (PFC) – Hardware and software used to push or pull power, shifting the flow of power across a mesh network, helping to balance overloaded lines and underutilized corridors within the transmission network.

How to read this document:

Each page of this document describes a case study about the deployment or simulation of GETs by the given investigator. The information included is from primary sources and includes as much publicly available information as possible for each case study. The case studies included are across several continents, though most studies found occur in North America and Europe. Each page includes the following information:

Project Name[#]

[#]corresponding to full reference

Technology (DLR, PFC)

Investigator (Author's Organization)

Type (⬢ Installation, ⬡ Simulation)

Approximate Study Year

Architecture

Type of lines, length, voltages, generation sources, etc.

Outcomes

Benefits from study

Costs

Project costs and/or avoided costs as reported

[Adjusted: Provides Costs as January 2022 $USD][1]

Region of the world

[1] *Bureau of Labor Statistics CPI inflation adjustment (https://bls.gov/data/inflation_calculator.htm) and Department of Treasury historical exchange rates (https://fiscaldata.treasury.gov/datasets/treasury-reporting-rates-exchange/treasury-reporting-rates-of-exchange.) Q1 of study year was used to convert currency (unless otherwise mentioned), then January of study year to January 2022 used for inflation (unless otherwise mentioned).*

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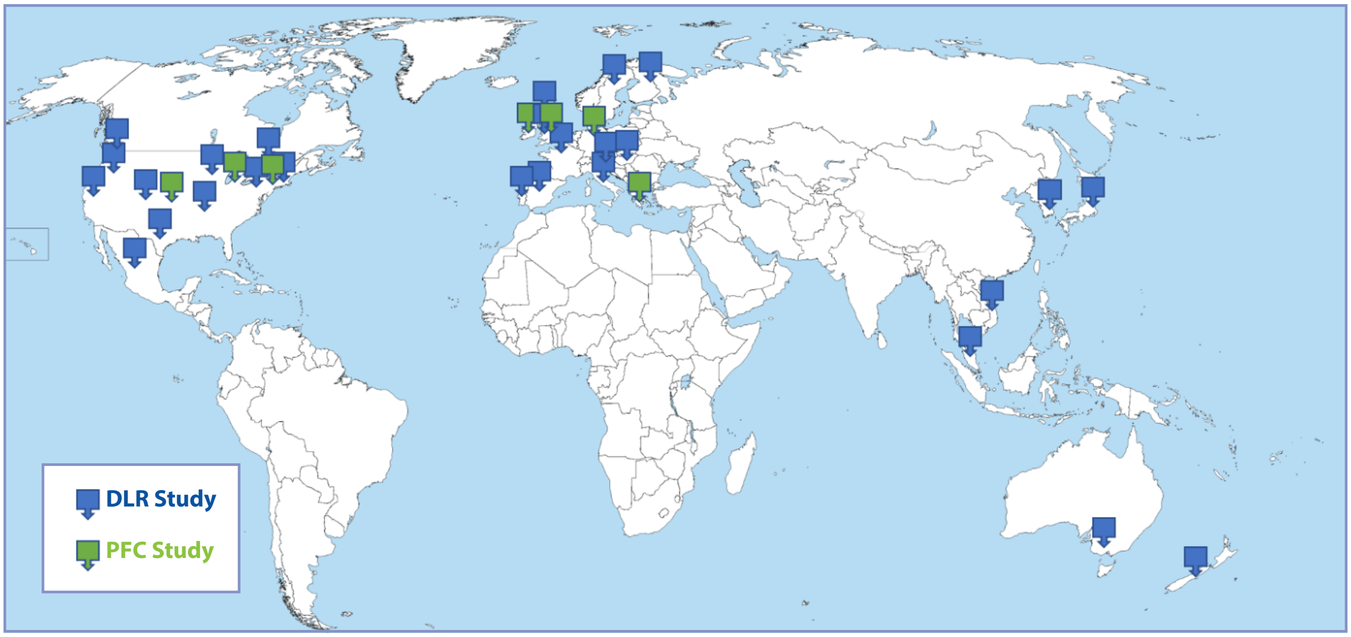

DLR Study
PFC Study

Acronyms

AAR Ambient Adjusted Ratings

ACSR Aluminum-core Steel-reinforced

ACSS Aluminum-core Steel-supported

BPA Bonneville Power Authority

DOE Department of Energy

DLR Dynamic Line Rating

DTR Dynamic Thermal Rating (often interchangeable with DLR)

ECMWF European Centre for Medium-Range Weather Forecasts

EPRI Electric Power Research Institute

EMF Electromagnetic Field Sensor

ERCOT Electric Reliability Council of Texas

FACTS Flexible Alternating Current Transmission System

GET Grid Enhancing Technology

INL Idaho National Laboratory

m-SSSC Modular Static Synchronous Series Compensator

MPFC Modular Power Flow Controller

ORNL Oak Ridge National Laboratory

PFC Power Flow Controller

PJM Pennsylvania-New Jersey-Maryland Interconnection

PPL Pennsylvania Power and Light

RES Renewable Energy Sources

RT-TLMS Real-Time Transmission Line Monitoring System

RTTR Real-Time Thermal Rating (often interchangeable with DLR)

SSSC Static Synchronous Series Compensator

SPP Southwest Power Pool

TSO Transmission System Operator

TVA Tennessee Valley Authority

Grid Enhancing Technologies: A Case Study on Ratepayer Impact[1]

DLR and PFC

U.S. Department of Energy

⬡ Simulation

2022

Architecture

Focused in on a county in the NYISO grid with 230 kV and 115kV lines. Multiple GETs and traditional grid upgrade scenarios were run through a hourly chronological production simulation with different resource mixes to understand how grid enhancing technologies altered generation dispatch across a calendar year.

Outcomes

Certain values created by GETs were quantified, including reduced congestion, asset deferral, and new generation (renewables) integration. Other values are more qualitative in nature but assist the grid operator to operate an increasingly dynamic and complex power grid. The case study provided proves that GETs can be considered alongside traditional upgrades to optimize infrastructure investments in support of customer and policy interests.

Costs

Varied based on solution deployment scenario, DLR roughly $2M for the study region, and PFC deployments varying from $7M-$28M depending on the quantity as compared with $205.5M for traditional Upgrades.

[Adjusted: Already in 2022 dollars.]

North America

Enabling Renewable Energy with LineVision[3]

DLR

National Grid w/LineVision Inc.

Installation

2021

Architecture

Pilot case in Massachusetts on a single line.

Outcomes

Conductor monitors tested were easy to install, reliable, and effective at reporting periods of either excess or limited capacity. Results showed and average of 13% increase in lines' current capacity.

Costs

No costs mentioned.

North America

Unlocking the Queue with Grid- Enhancing Technologies[24, 25]

DLR and PFC

Brattle Group w/SPP

⬡ Simulation

2021

Architecture

SPP grid, focused on Kansas and Oklahoma. DLR was simulated on 56 lines with each DLR line requiring 15-30 sensors. PFCs were selected in 8 locations with 204 unique topology optimization reconfiguration options. The locations were selected based on transmission constraints and significant generation resource changes.

Outcomes

The combined GETs allow for an increase of 2,670 MW of integrated RES without additional transmission upgrades. GETs lowered curtailment of existing wind generation by 76,000 MWh/yr. Annual production costs savings estimated at $175 million. Additional RES reduced carbon emissions by 3 million tons. Other economic benefits include: 650 long term jobs & 11,300 short term jobs, and local benefits of $15M land lease and $32M in tax revenues per year.

[Adjusted: $188M, $16M, $34M]

Costs

Estimated to be $90M initial investment with ongoing costs of $10M per year. Pay-back investment is about one-half year. Cost savings of $20/MWh.

[Adjusted: $97M, $11M, $22/MWh]

North America

Demonstration of Advanced Monitoring and Data Analytics of Power Transmission Lines[6,7]

DLR

ORNL w/LineVision and Xcel Energy

⬢ Installation

2021

Architecture

Install non-contact EMF sensors to monitor three transmission lines for 12 months to determine market efficiency gains with DLR and planning with conductor health monitoring. Sensor installation on lines across Minnesota, Wisconsin and Colorado. Ongoing analysis with power flow simulations coupled with MISO region.

Outcomes

Average DLR exceeded static reference ratings by 9-33% in winter months and 26-36% for the summer months. DLR exceeded static ratings over 85% of the time. Conductor health monitors show no significant annealing or loss of tensile strength over time span.

Costs

$350K out of $500K DOE proposal awarded to subcontract LineVision – unknown install cost versus personnel cost.

[Adjusted: $376K]

North America

Dynamic Line Rating - Installation on Three PPL Circuits[11]

DLR

Ampacimon w/PPL

⬢ Installation and ⬡ Simulation

2021

Architecture

Deployed 18 sensors across 3 circuits of 230 kV line. One circuit is ACSR, the other two are ACSS in Pennsylvania. The ACSS circuits represents ~50 km of line. Sensors deployed using live-line installation via helicopter with select spans installed from ground.

Outcomes

Simulation results prior to the installation show that DLR should provide a 25-29% average gain relative to normal static rating. DLR Sensors successfully installed with a mounting procedure that takes 5-10 minutes per sensor.

Costs

The projected 2025 congested costs on the lines are $23 million. Reconductor costs were estimated at $0.5 million/mile, double circuit costs were estimated at $2-3 million/mile. The DLR installation is under $1million in total cost.

[Adjusted: $0.54M/mile, $2.2-3.2M/mile, $1.1M]

North America

Renewable Integration in France[39, 40]

DLR

RTE w/Ampacimon

Installation

2021

Architecture

63 kV network associated with northern wind power.

Outcomes

50% increased annual wind power generation.

Costs

Avoid replacement of line with a traditional cost of 24M €.
[Adjusted: $30.1M]

Europe

Overhead Transmission Line Monitoring Incubating Energy Labs 2020 Pilot Project Report[4]

DLR

EPRI w/LineVision and TVA

⬢ Installation

2020

Architecture

One span was between dead ends at Raccoon Mountain, and two spans were at Chickamauga. TVA collected line loads at multiple locations to compare against loads calculated by the LineVision V3 system. EPRI collected weather information to compare against the system's weather model data and calculated parameters such as wind cooling of conductors.

Outcomes

Summary includes a comparison of the line loading values as reported by LineVision's EMF sensors and TVA's substation current transformers. This comparison showed that while line load >300A the average error of the LineVision load sensing vs the CT was between 2.0%-6.6% meaning the DLR system can accurately determine load with only external sensors.

Costs

No costs mentioned.

North America

Evaluation of SmartValve™ Devices Installation at Central Hudson[19]

PFC

EPRI

Installation

2020

Architecture

Deployment of three SmartValve m-SSSC devices at a 115 kV line from Sturgeon Pool to Ohioville substation in New York's Hudson valley.

Outcomes

The pilot program focused on installation process, communications and controls, cyber security, protection impact and power system impact. Plan for larger deployment of the 345 kV Leeds-Hurley Avenue transmission line.

Costs

No cost mentioned other than the PFCs are anticipated to be lower costs that traditional series compensation systems.

North America

Modular Power Flow Control Enhancing German Transmission Grid Capacity: An Investigation[33]

PFC

RWTH Aachen University w/Smart Wires Inc.

⬡ Simulation

2020

Architecture

Major Germany grid lines and European interconnects. The m-SSSC are parameterised with an injected voltage per phase at line rating of 96 kV, which is equivalent to a PST with a line voltage of 400 kV, a line rating of 2750 MVA.

Outcomes

Annual reduction of 17% in redispatch and RES curtailment with 4 m-SSSC installations. An additional 18% of gains realized using 12 m-SSSC devices.

Costs

Remedial actions with redispatching and curtailment of renewable generation resulted in a 2019 annual cost of 1.2 billion €.

[Adjusted: $1.5B]

Europe

Grid Optimization Technologies to Build a Greener Europe Project: Modular power flow control technology, multisite deployment, Great Britain[14, 21]

DLR

National Grid Electricity Transmission w/SmartWires

Installation

2019

Architecture

MPFC were installed in 2020 on five 275 kV and 400 kV circuits in the NGET network. Results show an increase in boundary capabilities by 1.5 GW across three boundaries. This totals of 375 MVAr of power flow control capability.

Outcomes

Slowly increase the utilization of PFC to maintain new compliance requirements.

Costs

No costs mentioned.

Europe

Benefits and Value of New Power Flow Controllers[16, 17]

PFC

EPRI w/PJM

⬡ Simulation

2019

Architecture

Simulated the 2016 PJM system with 13 optimally placed PFCs on individual lines and 4 alternative PFC locations. Considered interconnection queue with 3.7 GW solar and 10.7 GW wind. PFCs on 115, 138, 230 and 345 kV lines.

Outcomes

Annual production cost savings of $67 million.

[Adjusted: $79M]

Costs

Initial investment cost of $137 million.

[Adjusted: $162M]

North America

Maximizing Energy Transfer and RES Integration using Dynamic Thermal Rating Italian TSO Experience[38]

DLR

University of Palermo w/Terna Rete Italia S.P.A.

Installation

2019

Architecture

N-1 Calculations for 380/220 kV lines and for managing local congestion with high RES on 160 kV lines for wind power and 132 kV lines for hydro power in Italy. Terna has 90 monitoring systems across 20 grid connections operating with DTR, with 30 monitoring systems across 10 new grid connections planned in the near term.

Outcomes

Saving for the curtailment costs by using DTR are approximately 1 million €/year for each line.

[Adjusted: $1.25M]

Costs

Exact costs not mentioned, but payback periods are stated as a few months to a maximum of two years. [Note: From the stated savings and payback period the maximum cost could be inferred to about 2 million €.]

[Adjusted: $2.5M].

Europe

Field Validation of Various Line Rating Methods in British Columbia[10]

DLR

BC Hydro

Installation

2019

Architecture

Multiple line rating techniques evaluated on a 15 km stretch of 138 kV transmission line with ACSR Merlin conductor. The 15 km stretch has two customer-owned taps spanning 6km and 4km. Three commercially available transmission line monitors were live-line installed that reported raw data to a secure cloud server via satellite network. Raw data and rating results were available from the vendor provided website.

Outcomes

BC Hydro's seasonal static rating method could be improved significantly by using a monthly based, probabilistic rating method. Use of both night-time and day-time ratings may further improve rating accuracy. DLR results show that the 2 ft/sec perpendicular wind speed assumption used in calculating line ratings is sometimes too aggressive, particularly considering vegetation.

Costs

No costs mentioned.

North America

Grid Optimization Technologies to Build a Greener Europe Project: Mobile modular power flow control technology, Greece[22, 23]

DLR

Flexitranstore w/SmartWires

Installation

2019

Architecture

The mobile MPFC device has been installed in Peloponnese region that is served solely by a 150-kV transmission system.

Outcomes

MPFC based on grid planning simulations indicated a 17% reduction of the line's loading for initial installation. Subsequent testing showed the MPFC devices' ability to reduce the line current by approximately 27% when 50% reactance was applied and 43% when injecting 100% of the nominal reactance. An N-1 contingency case was also tested by transferring 29% of the power off the overloaded line to meet the threshold limit on amps.

Costs

No costs mentioned.

Europe

Weather-based Dynamic Line Ratings[27, 28, 29, 30, 31]

DLR

Idaho National Laboratory w/National Oceanic and Atmospheric Administration, Altalink, and Idaho Power Company

⬡ **Simulation and** ⬢ **Installation**

2019

Architecture

Single lines, varying from regional connections to gen-tie lines for concurrent cooling were studied. Sites include a 15,000 km2 span between Boise and Twin Falls, a deep river gorge in Hells Canyon connecting hydro power to the grid, several 161 kV gen-tie lines for wind generation in Columbia Gorge, lines on INL's CITRC site, and lines connecting additional wind generation in Alberta, Canada.

Outcomes

The general line ampacity state solver (GLASS) system was shown to be able to accurately adjust line rating based on weather data for the area. The results show that by using weather-based sensors without considering localized wind conditions, the available ampacity may be over-predicted significantly in regions of complex terrain. For some regions, the DLR simulations show that the line rating is above the static ratings for up to 95.1% of the time, with a mean increase of 72% over static rating with sufficient wind. The benefit of further addition of weather stations diminishes as more stations are added, roughly 6 km spacing is recommended for accuracy.

Costs

No costs mentioned.

North America

Potential Analyses for Dynamic Rating Optimization on Basis of Four Years of Operational Experience in Austria[42]

DLR

Austrian Power Grid AG

Installation

2018

Architecture

The Austrian power grid introduced dynamic rating in 2013, and it currently covers 15% of its transmission grid. The Entire system uses 16 weather stations across 110kV, 220kV and 380 kV lines. Specific analysis is done on two of these lines in mountainous and flat landscapes.

Outcomes

The entire system saved 12 million € in congestion costs in 2016. For the transmission line in the mountainous landscape, the congestion management savings was 660K € per year. For the transmission line in flat landscape, the congestion management savings was 1.28 million € per year.

[Adjusted: $16.8M, $923K, $1.79M]

Costs

Average cost of DLR with weather stations 1 million € per 100 km line.

[Adjusted: $1.4M]

Europe

Dynamic Line Ratings[26]

DLR

LineVision w/AEP

Installation

2018

Architecture

LineVision device was installed under one 2.1 mile line (161kV, double-bundle 397.0 kcmil "Ibis" ACSR, Horizontal Single, wooden H-frames) in SPP's territory. One monitored section provides a full path rating. In PJM's territory, three spans on a 345kV line were monitored in Michigan and Indiana (Nov 2016 - Aug 2017) for a total of 25 miles of line monitored.

Outcomes

Results included an economic analysis for DLR with actual data. Back casting on the data they were able to prove that if they used DLR the line congestion could have been mitigated.

Costs

Estimated savings: $11M savings on the targeted circuit, and $4.2M on additional system congestion reduction throughout overall system. $500K installation costs for the system.

[Adjusted: $13M, $4.9M, $580K]

North America

Understanding the Benefits of Dynamic Line Rating Under Multiple Sources of Uncertainty[34]

DLR

Imperial College London w/Center for Processes, Renewable Energies and Energy Systems (PERSEE), MINES Paris- Tech

⬡ Simulation

2017

Architecture

Uses ECMWF forecasts for determining DLR values for up to 48 hours. simple 2-busbar system, where the line outage is also neglected. There are four conventional generators (G1-G4) located in node 1, two conventional generators (G5-G6) located in node 2 and a wind farm with capacity of 70 MW located in node 2. 70 MW demand is located in the node 1, while a transmission line with DLR of 26 MW links these two nodes. The proposed optimization framework is also applied on a modified 24-bus IEEE RTS system.

Outcomes

The study shows optimal implementation of DLR can achieve high levels of penetration of oncoming wind generation on to the current grid. Utilizing FACTs in addition to DLR can reduce the cost of forecasting DLR error by over 60%.

Costs

For case study real-time DLR reduces the operational cost by 166 K£, and fully optimized DLR operation cost savings of 315 K £. For IEEE 24 bus system operational cost is 42.3k£ vs. 32.3 k£ with DLR.

[Adjusted: $240K, $456K, $61K, $47K]

Europe

Smart Grid to Enhance Power Transmission in Vietnam[37]

DLR

World Bank Group

⬡ Simulation

2016

Architecture

Various smart grid solutions to improve growing infrastructure in Vietnam. The DLR solution proposes 40 sensors on 400 km of transmission lines – 4 lines of about 100 km each. One sensor installed every 10 km.

Outcomes

Based on ampacity ratings 5-25% above static, net present value of $44.1 million up to the year 2030 on the system. [Presumably total savings from 2016-2030].

[Adjusted: $53.3M]

Costs

$1.1 million in capital costs. A DLR sensor costs $32K while the reconductoring costs $200K/km. Estimated annual operating expenses of $183K.

[Adjusted: $1.3M, $38K, $237K, $217K]

Asia

Smart Valve Pilot Project[8,9]

PFC

EirGrid Group w/Smart Wires

Installation

2016

Architecture

3 PFC units on a 110 kV line between Cashla and Ennis in Ireland.

Outcomes

Lessons learned on the installation and time monitoring. The SmartValves in this case required a stepdown transformer which adds to the total weight of the installation. The first installation took 5 hours, but speed increased to 3.5 hours for 2nd and 3rd installations. No structural damage to the Smart Valve or the transmission structures, and remained fully operation through hurricane force winds of 156 km/hr.

Costs

No cost mentioned for initial project. A follow-on project expanded the pilot program at a cost of 300K €.

[Adjusted: $378K]

North America

DNV GL Investigation of PFCs[17, 18]

PFC

DNV GL w/PJM

⬡ Simulation

2016

Architecture

Studied economic benefits in PJM system projected to 2026 with 30% RES on lines higher than 100 kV.

Outcomes

Potential for PJM region-wide savings of $890 million per year, with $267 million reduction in annual transmission savings, and $637 million in production cost savings.

[Adjusted: $1.056B, $317M, $756M]

Costs

Annual operating estimated costs of $81 million per year.

[Adjusted: $96M]

North America

Implementation of RTTR system for Cupar – St Andrews 33kV circuits[41]

DLR

SP Energy Networks

⬢ Installation

2015

Architecture

Two 33kV circuits from Cupar – St Andrews in Scotland monitored with four weather stations installed. A previous installation on 90 km of 132 kV lines was also discussed.

Outcomes

With DLR capped at 20% uprating, an additional 17 GWh of energy can be available per year across the network.

Costs

The traditional cost of rebuilding the line is 1.27 M £. The cost for DLR is estimated at 90K £, with an additional 50K £ for developing automatic network management scheme to avoid exceeding DLR.

[Adjusted: $2.25M, $160K, $89K]

Europe

Estimation method for dynamic line rating potential and economic benefits[36]

PFC

VTT

⬡ Simulation

2015

Architecture

Investigated congestion of power transmission from Sweden to Finland. This consists of the northern connection with two 400 kV lines (2-Finch conductor) and one 220 kV line (1-Condor conductor). The study was based on historical load data and electricity market data for the region.

Outcomes

A set of conservative estimates is made for the economic benefits of DLR. 97% of the time an additional 300 MW of capacity is available. Average price is decreased 4.7 €/MWh (9.7%) for one year. Heavily congested peaks decrease price by 19.3 €/MWh (40.8%).

[Adjusted: $6.1/MWh, $25.0/MWh]

Costs

Consumers could save 21.1 million €.

[Adjusted: $27.3M]

Europe

Implementation of Dynamic Line Rating Technique in a 130 kV regional Network[35]

DLR

KTH Royal Institute of Technology w/Bahria University

⬡ Simulation

2014

Architecture

A 130kV meshed network with a VL3 conductor is investigated for benefits of DLR over SLR in Sweden. The DLR solution is directly compared to traditional upgrades.

Outcomes

The net annual income for the utility of DLR on the line is estimated to be 4.89 million SEK. In net income, the benefit for each solution is 0.29 million SEK/GWh for DLR, 0.14 million SEK/GWh for reconductoring and 0.09 million SEK/GWh for building a new line.

[Adjusted: $710K, $41K, $20K, $13K]

Costs

First time expenditures are estimated to be 1.317 million SEK, compared to the annual capital cost for reconducting at 32.1 million SEK, or the cost of building a new line at 39.3 million SEK.

[Adjusted: $190K, $4.7M, $5.8M]

Europe

Oncor's DLR Demonstration[5]

DLR

Oncor Electric Delivery Company w/Nexans and ERCOT

⬢ Installation

2014

Architecture

Install DLR systems on 8 lines in Texas to reduce line congestion. 27 Nexans CAT-1 units, 5 sagometers, and 2 RT-TLMS installed across five 345kV lines and three 138 kV lines over a 3-year period.

Outcomes

The 345kV lines experienced an average increase of 6%-14% above AAR and the 138kV lines saw an 8%-12% average above AAR increase of line rating. It was determined that 5% additional capacity through DLR relieves 60% of congestion, and 10% additional capacity through DLR nearly eliminates congestion on target lines. Oncor developed a best practice guide to expedite the future implementation of DLR technologies by other transmission owners throughout the United States.

Costs

Project budget of $7.3M, with $4.8M as installed cost. Associated congestion charges totaled $349M in two years (~$250K/line/day) across the entire Oncor system. [Adjusted: $8.8M, $5.8M, $419M, $300K]

North America

Maximizing Power Line Transmission Capability by Employing Dynamic Line Ratings – Technical Survey and Applicability in Finland[20]

DLR

VTT

Installation

2013

Architecture

CAT-1 measurement unit (2 load cells) installed for a horizontal twin conductor in two phases of a double circuit line.

Outcomes

Configuration matters (changed between 2004 and 2012, significantly changed measurements)

Costs

The price for a single tower CAT-1 instrumentation (2 load cells, one in each direction) is 40,000 €. The fully integrated and operational setup is 2500-3000 € per circuit-km. Though it is noted that wide deployment reduces cost because the control center software is only needed once.

[Adjusted: $66K, $4.1K-5K]

Europe

Introducing the Ampacimon conductor monitor and forecasting systems[12, 13, 14, 15]

DLR

Ampacimon w/ELIA

Installation

2012

Architecture

Deployed sensors across 400 kV conductor in Belgium. Day-ahead forecasting performed on 18 km set of 150 kV lines near the Belgium coast, and a 225 kV line in Britany, France. The project was expanded after initial deployment.

The DLR modules have been deployed on the most critical spans of the respective lines for measuring ambient parameters as well as the physical sag of the conductor. A total of 33 lines are monitored with devices range from 70 kV up to 380 kV. Forecasts are also provided for some of the lines with 48-hour windows.

Outcomes

The technology showed a sag error margin of ±2%. Use of weather forecasts paired with sensor deployments allow for forecasting line ratings one day in advance. Fourteen years of historical DLR data and reliability metrics could be available. This uses a 1-hour ahead ampacity value that almost guarantees the maximum temperature is not exceeded, given a risk value. The pre-defined acceptable increase in risk is currently set at 0.1%, corresponding to roughly 9 hours a year.

Costs

A technical/economic study shows that the investment in an Ampacimon system is justified by deferring the construction of a second circuit of 10 km 380 kV 2*707 AMS, even if the postponement of construction only lasts 2 years.

Europe

Application of Real Time Thermal Ratings[32]

DLR

The Valley Group w/Portland GE

Installation

2000

Architecture

Portland General Electrical installed tension-based devices in 1994, with 5 lines monitored. Two lines send rating data into the EMS system. Transmission lines are 230 kV near interconnects of 230/115 kV bulk power substations.

Outcomes

Utilize DLR to defer two transmission line projects. Deferral of 2003 project until 2010, and deferral of 2005 project until 2012.

Costs

Transmission line projects costs of $2.9 million. Capital savings through 7 years of deferral equate to $1.2 million.

[Adjusted: $4.8, $2M]

North America

Additional Cases

The following cases are included as additional information about other GETs installations or simulations that have been performed world wide. These case studies do not include most of the cost or savings information that the main cases include, and often leave out a fair amount of detail about the grid architecture. Thus, it was deemed these were not warranted for a full-page breakdown of the details. A high-level summary of each of these additional cases and its reference is included here.

DLR | ⬢ Installation[47] | 2021 | North America
LineVision has a pilot project for the V3 monitoring system with the Sacramento Municipal Utility District. Primary focus is on lines from the Upper American River Project hydropower stations.

DLR | ⬢ Installation[49] | 2021 | North America
DLR to be installed by Hydro Quebec on 735 kV lines with 1, 24 and 48-hour look ahead on 1351 kcmil (1.38") ACSR conductors.

DLR | ⬢ Installation[46] | 2020 | North America
Ampacimon has installed DLR line monitors on 5 major American utilities (not specific on number of lines monitored) as of 2020.

DLR | ⬢ Installation[51] | 2020 | Asia
DLR pilot project in Malaysia by TNB operators. Install on 275 kV Segar-Ayer line with two critical spans with Lindsey sensor. DLR higher than static 10-50% for 95% of the time.

DLR | ⬡ Simulation[50] | 2019 | North America
Investigation of implementation of DLR onto the Mexican grid on 115 kV, 230 kV and 400 kV lines. DLR savings range from $2-3/MWh.

PFC | ⬢ Installation[48] | 2019 | Europe
SmartValve shown to be a stopgap measure during reconductoring and theorized to address emerging issues such as harmonic injection, transient stability and controller interaction. A case study for an unnamed European TSO showed the PFC could be used to increase transfer capacity across one corridor by 400 MW.

PFC | ⬡ Simulation[44] | 2019 | North America
University of Michigan investigate deployable PFCs simulated on an IEEE 39 bus system. This provides a methodology for power system planning engineers to easily consider the flexibility of GETs during line outages in the test system.

DLR | ⬢ Installation[45] | 2019 | North America
Bonneville Power Administration monitors one mile of the 230kV Ross-Lexington Line and is upgrading from Gen 2 to Gen 3 non-contact EMF installation for LineVision. System will also provide hourly, 2-hour, 4-hour and 24-hour forecasting.

DLR | ⬡ Simulation[54] | 2018 | Asia
Simulations are carried out on a modified version of the IEEE 30-bus test system, with DLR ratings set based on Osako, Japan weather conditions. Power flow ratings are increased by over 40% with DLR, optimal costs are decreased by $190/hr.

DLR | ⬢ Installation[53] | 2017 | Europe
SSEN installed pilot of CAT-1 tension devices on 130 kV line in Scotland. Data shows 50% gain over static 30% of the time and DLR above SLR 85% of the time.

DLR | ⬡ Simulation[55] | 2013 | Asia
A comparison of DLR against actual load for a single line in South Korea shows how the maximum allowable load can be increased.

DLR | ⬢ Installation[52] | 2009 | Australia
Transend maintains 15 weather stations and has 19 transmission line conductor tension monitors on 12 transmission circuits in Tasmania region of Australia on double circuit 110 kV lines for N-1 contingencies. Transpower in New Zealand planned to set up a DLR pilot in 2012.

DLR | ⬢ Installation[43] | 1998 | Europe
DLR implementation by Red Electrica de España (REE) and Iberdrola on a 400 kV transmission line in the feeding ring of Madrid (about 12% of total load in Spain). Monitoring done in real time with four weather stations.

Conclusions

As noted in the February 2022 report Grid-Enhancing Technologies: A Case Study on Ratepayer Impact[1], methods exist that improve the utilization of the existing electricity delivery system by enabling grid modernization techniques, dynamically controlling the flow of electricity, and optimizing electricity delivery system topology. Addressing the challenges of the growing complexity of the modern grid requires better utilization of sensors, development of power flow control devices and analytical tools, and novel control mechanisms that would allow maximized transmission of electricity and improvement of grid resilience. These are all features provided by GETs; however, many obstacles must be overcome to fully adopt and integrate GETs, including U.S. industry edification. This document is an attempt at improving the GETs knowledge of the industry by providing more than a survey resource – rather this document hopefully provides a resource that effectively summarizes the available literature.

GETs adoption throughout the industry has seen many small pilot cases for which each individual utility has typically chosen not to release much, if any, information regarding the specifics of implementation. Roughly half of the included studies provide public information of the implementation costs and monetary gains from the implementation of GETs, but only a quarter provide comparison of GETs with traditional cost upgrades. For those that do, the cost of GETs are substantially less than traditional upgrades. While both DLR and PFC studies include costs at a similar ratio, cost benefit analysis are more often included in DLR studies than in PFC studies. The case studies that do provide cost and benefit economics analysis typically show a rapid payoff. The technologies have been deployed on a wide variety of systems with effectiveness on transmission corridors associated with voltage as low as 63 kV up to larger 745 kV transmission lines.

To be clear, the authors do not believe that the information presented here (and contained within the primary sources) is sufficient in terms of integration of GETs into a utility's system. For example, the "Architecture" section of each case study is primarily focused on the electrical parameters rather than the information technology, telecommunications, and security needs of each installation. This type of information has typically been excluded from the primary sources, and a summary of publicly available data is unable to include such specifics. Specific implementation will also vary as each utility can have different EMS architecture, deployment and dispatching plans, SCADA systems, etc.

As stated above, this document helps highlight that GETs validation and evaluation has been performed across the globe. Much of the recent US literature on the topic is informed by European efforts in the 2010's; perhaps the US deployments can similarly learn from European deployments, many of which have expanded past pilots and case studies to include daily use of GETs on their transmission grids. Still, there appears to be a need for an outside entity capable of deploying, testing, documenting, and publishing the results of these technologies. Once there is general acceptance of the technology and incentives in place to encourage GETs deployments, widespread usage of GETs can help lessen the burden on the increasingly strained grid.

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