



A Guide to Case Studies of Grid Enhancing Technologies

December 2022

Changing the World's Energy Future

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



Summary



The growing complexity of the modern grid requires:

- Better utilization of models and sensors,
- Development and deployment of power flow control devices & analytical tools, and
- Novel protection and control mechanisms that would maximize transmission of electricity and improve grid resilience while maintaining reliability.

These are all features provided by Grid Enhancing Technologies (GETs). However, many obstacles must be overcome to fully adopt and integrate GETs, including U.S. industry education. GETs can enable integration of oncoming renewable energy sources at lower costs, as well as decrease consumer costs by extending the lifetime of current grid infrastructure. This document is an attempt at improving the GETs knowledge of the industry by providing a resource that effectively summarizes the available literature on case studies and, where possible, provides cost savings to document the utilities' benefits from GETs.

GETs adoption throughout the US has seen many small pilot-scale cases ranging from voltages as low as 63 kV up to 745 kV transmission lines. However, the public information on GETs implementation costs and monetary gains against traditional upgrades is limited. For the cases that do include this information, the costs of GETs are substantially less than traditional upgrades, with a return-on-investment timeframe typically under 2 years, with some cases substantially faster. Public information on pilot studies have typically not included the information necessary for actual system integration, such as the information technology, telecommunications, and security needs of each installation, which likely vary from utility-to-utility. Many of the successful documented GETs implementations have been done by European transmission system operators; perhaps the US deployments can learn from these European deployments, many of which have expanded past pilots and case studies to include daily use of GETs on their transmission grids. With 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.

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 operation². 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. GETs provide the potential to increase RES penetration at lower costs, as well provide opportunities to delay traditional infrastructure upgrades, thus extending its life and decreasing costs.

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:

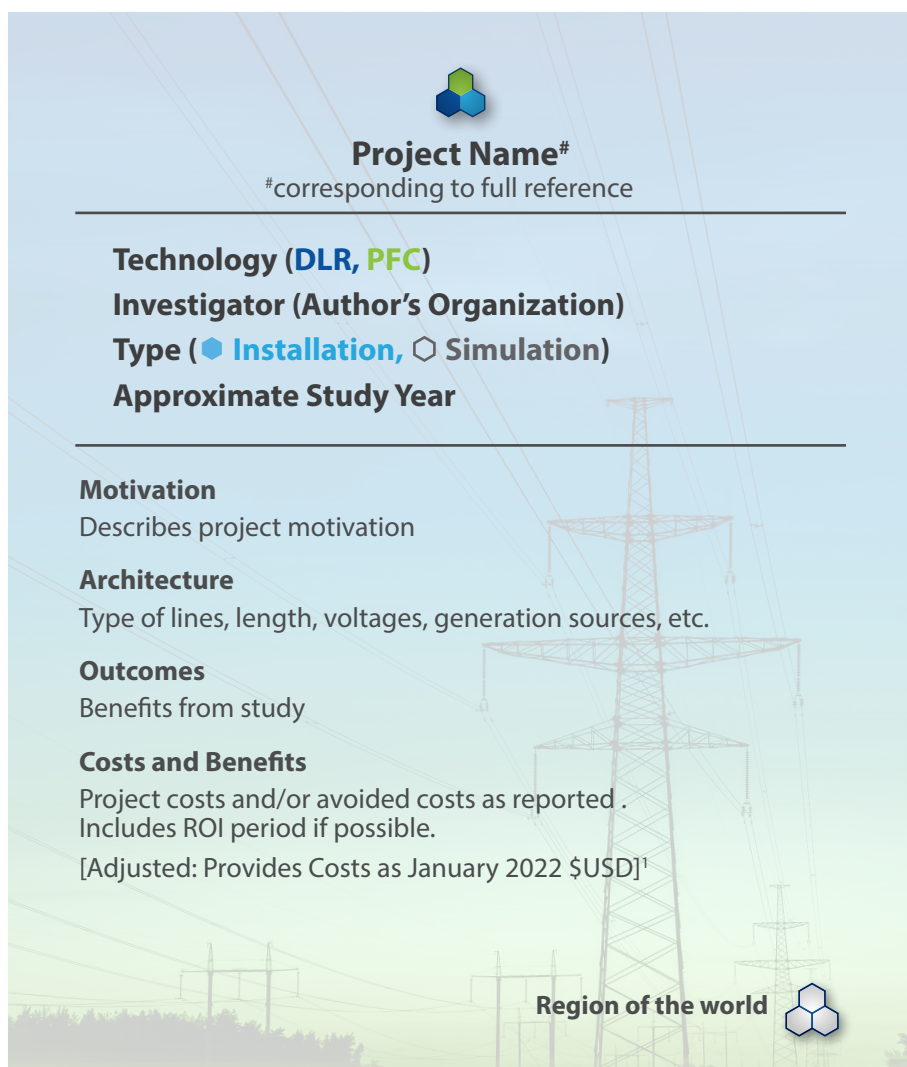
Dynamic Line Rating (DLR) – Hardware and/or software used to appropriately update the calculated thermal limits of existing transmission lines based on real-time and forecasted weather conditions and measurements of other conditions of the line. Often, these schemes establish new limits that safely allow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

Motivation
Describes project motivation

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

Outcomes
Benefits from study

Costs and Benefits
Project costs and/or avoided costs as reported .
Includes ROI period if possible.
[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).

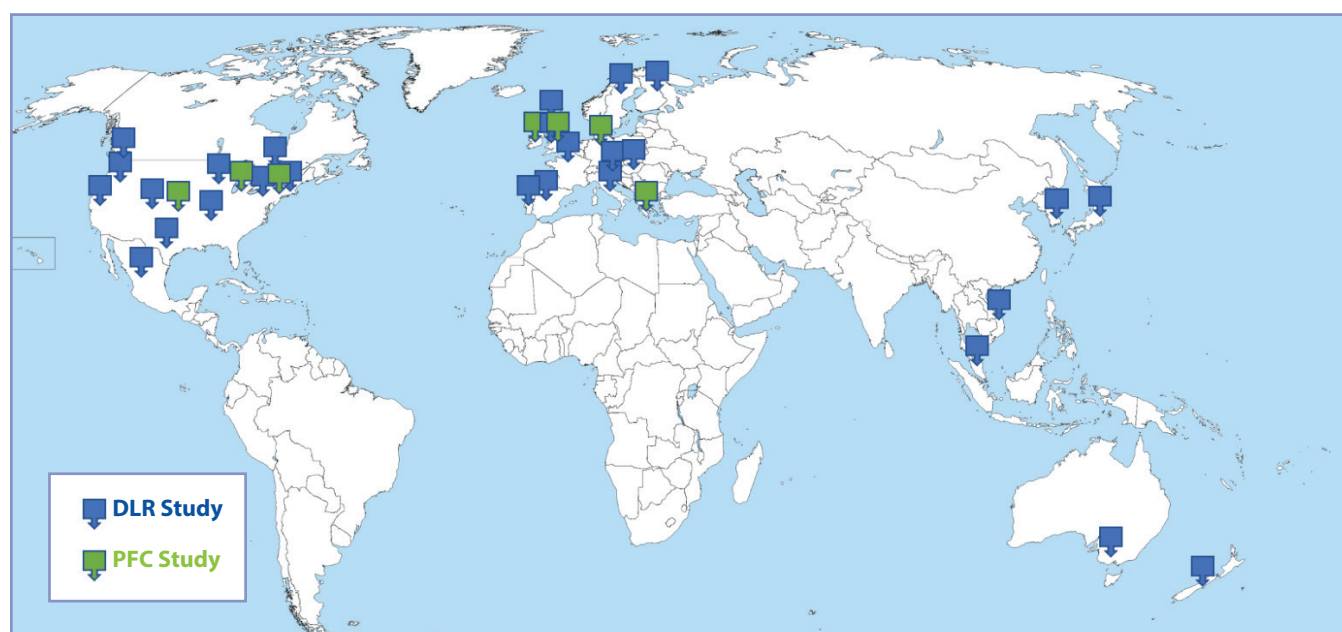
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Project Name	Technology	Type	Traditional and/or Congestion Costs	GETs Costs	GETs Cost Savings	Capacity Gains and/or Curtailment Reduction Quantified	Line Voltage(s)	Page
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Acronyms



AAR	Ambient Adjusted Ratings	m-SSSC	Modular Static Synchronous Series Compensator
ACSR	Aluminum-core Steel-reinforced	MPFC	Modular Power Flow Controller
ACSS	Aluminum-core Steel-supported	ORNL	Oak Ridge National Laboratory
BPA	Bonneville Power Authority	PFC	Power Flow Controller
DOE	Department of Energy	PJM	Pennsylvania-New Jersey-Maryland Interconnection
DLR	Dynamic Line Rating	PPL	Pennsylvania Power and Light
DTR	Dynamic Thermal Rating (often interchangeable with DLR)	RES	Renewable Energy Sources
ECMWF	European Centre for Medium-Range Weather Forecasts	ROI	Return on Investment
EPRI	Electric Power Research Institute	RT-TLMS	Real-Time Transmission Line Monitoring System
EMF	Electromagnetic Field Sensor	RTTR	Real-Time Thermal Rating (often interchangeable with DLR)
ERCOT	Electric Reliability Council of Texas	SSSC	Static Synchronous Series Compensator
FACTS	Flexible Alternating Current Transmission System	SPP	Southwest Power Pool
GET	Grid Enhancing Technology	TSO	Transmission System Operator
INL	Idaho National Laboratory	TVA	Tennessee Valley Authority



Grid Enhancing Technologies: A Case Study on Ratepayer Impact¹

DLR and **PFC**

U.S. Department of Energy

 **Simulation**

2022

Motivation

The NYISO service area was selected as the regional case study for this analysis because it has existing wind curtailments despite low overall penetration, high congestion costs, and large proposals for new transmission and wind and solar resources to reach a 70% RES goal.

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. Scenarios with a different number of PFC and DLR deployments showed between 9-73% of curtailment could be avoided.

Costs and Benefits

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 LineVision³

DLR

National Grid w/LineVision Inc.

 **Installation**

2021

Motivation

Pilot to assess recent FERC proposals on GETs.

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 an average of 13% increase in lines' current capacity.

Costs and Benefits

No costs mentioned.

North America





Unlocking the Queue with Grid- Enhancing Technologies^{24, 25}

DLR and PFC

Brattle Group w/SPP

 **Simulation**

2021

Motivation

Lines selected for near-term RES integration in 2025 (before new transmission projects could be built).

Architecture

SPP grid, focused on Kansas and Oklahoma. DLR was simulated on 56 lines with each DLR line requiring 15-30 sensors. The breakdown of these monitored lines is 10 345 kV, 3 230 kV, 11 161 kV, 22 138 kV, 3 115 kV, and 7 69 kV. PFCs were selected in 8 locations with 204 unique topology optimization reconfiguration options. The breakdown of these lines are 3 345 kV, 4 161 kV, and 1 138 kV. 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. Additional RES reduced carbon emissions by 3 million tons. Other economic benefits include: 650 long term jobs & 11,300 short term jobs.

Costs and Benefits

Annual production costs savings estimated at \$175 million with local benefits of \$15M land lease and \$32M in tax revenues per year. 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: \$188M, \$16M, \$34M, \$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

Motivation

Lines provide additional capacity for new RES integration.

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 and Benefits

\$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 Circuits¹¹

DLR

Ampacimon w/PPL

◆ Installation and ◻ Simulation

2021

Motivation

The lines were selected due to high costs of predicted future congestion.

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 and Benefits

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

Motivation

RES integration of new wind energy.

Architecture

63 kV network associated with northern wind power.

Outcomes

50% increased annual wind power generation.

Costs and Benefits

Avoid replacement of line with a traditional cost of 24M €.

[Adjusted: \$30.1M]

Europe





Overhead Transmission Line Monitoring Incubating Energy Labs 2020 Pilot Project Report⁴

DLR

EPRI w/LineVision and TVA

Installation

2020

Motivation

Lines were selected to provide a range of conditions of conductors, voltages, and profiles for assessment. One line was selected connected to energy storage and routine heavy loading.

Architecture

One span was between dead ends at Raccoon Mountain, and two spans were at Chickamauga on a 161 kV line. 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 and Benefits

No costs mentioned.

North America





Evaluation of SmartValve™ Devices Installation at Central Hudson¹⁹

PFC

EPRI

Installation

2020

Motivation

Central Hudson reached a System Delivery Upgrade threshold for the UPNY-SENY interface, obligating construction of a new project.

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 and Benefits

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

North America





Modular Power Flow Control Enhancing German Transmission Grid Capacity: An Investigation³³

PFC

RWTH Aachen University w/Smart Wires Inc.

 **Simulation**

2020

Motivation

Examine PFCs on the grid for reducing RES curtailment for scenario in 2023 with phase out of nuclear and coal power.

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 and Benefits

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}

PFC

National Grid Electricity Transmission w/SmartWires

◆ Installation

2019

Motivation

Enable greater volume of RES power to customers.

Architecture

MPFC were installed in 2020 on five 275 kV and 400 kV circuits in the NGET network.

Outcomes

Slowly increase the utilization of PFC to maintain new compliance requirements. Results show an increase in boundary capabilities by 1.5 GW across three boundaries. This totals of 375 MVar of power flow control capability.

Costs and Benefits

No costs mentioned.

Europe





Benefits and Value of New Power Flow Controllers^{16, 17}

PFC

EPRI w/PJM

Simulation

2019

Motivation

The lines were selected from SPP reports on expansion projects due to thermal overload, and how PFC could reduced overloads and defer expansion projects.

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

The analysis in the PJM system shows that PFC solutions to reduce congestion seem to be economically sound, with pay-back periods less than three years. However, specific cost numbers would have to be compared for particular technologies to understand better the true cost/benefit analysis. In general terms, the more devices are placed in the system, the greater the benefit. Nevertheless, the incremental benefits from additional devices placed to alleviate congestion decrease, reaching a saturation point.

Costs and Benefits

Annual production cost savings of \$67 million. Initial investment cost of \$137 million. [Note: ROI in about 2 years]

[Adjusted: \$67M, \$162M]

North America





Maximizing Energy Transfer and RES Integration using Dynamic Thermal Rating Italian TSO Experience³⁸

DLR

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

 **Installation**

2019

Motivation

Two RES cases for wind energy and hydroelectric grid integration are studied.

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

For the wind case DLR are higher than seasonal SLR 98% of the time in summer and 92% in winter. For cases with low DLR, they almost always occur during periods of low load on the line. For the hydroelectric case, current exceeding SLR was possible without any reduction in RES production.

Costs and Benefits

Saving for the curtailment costs by using DTR are approximately 1 million €/year for each line. Exact costs are 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: \$1.25M, \$2.5M].

Europe





Field Validation of Various Line Rating Methods in British Columbia¹⁰

DLR

BC Hydro

 **Installation**

2019

Motivation

The line was selected as the local customer's future demand is greater than the current capacity.

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 and Benefits

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

Motivation

Installation was done at a high voltage substation for examining demonstration of PFC for N-1 contingency.

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 and Benefits

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

Motivation

Academic study of DLR impacts across a variety of terrains and geographic territory. Some lines identified by collaborators as high loading or wind power integration.

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 with 138, 161 and 230 kV lines, a deep river gorge in Hells Canyon connecting hydro power to the grid, several 161 kV gen-tie lines for wind generation as well as large 345 and 500 kV regional transmission lines 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 and Benefits

No costs mentioned.

North America





Potential Analyses for Dynamic Rating Optimization on Basis of Four Years of Operational Experience in Austria⁴²

DLR

Austrian Power Grid AG

◆ **Installation**

2018

Motivation

The lines in the study are included to show changes across terrain types, and show congestion management under N-1 cases.

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 results show that the ampacity possible with dynamic rating is already utilized very well using two weather stations per OHL. The additional ampacity can reach peak values up to some ten percent. Exemplary days with high (n – 1) loads are shown where this additional ampacity could be sufficient to avoid congestion management measures.

Costs and Benefits

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. Average cost of DLR with weather stations 1 million € per 100 km line. [Note: ROI 0.8-1.5 years]

[Adjusted: \$16.8M, \$923K, \$1.79M, \$1.4M]

Europe





Dynamic Line Ratings²⁶

DLR

LineVision w/AEP and PJM

◆ Installation

2018

Motivation

Study included a demonstration, as well as a Target Line selected as one of the most congested in the PJM territory.

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 and Benefits

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. [Note: ROI under 1 month]

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

North America





Understanding the Benefits of Dynamic Line Rating Under Multiple Sources of Uncertainty³⁴

DLR and **PFC**

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

⬡ **Simulation**

2017

Motivation

Assess cost effective integration of high penetration of wind generation using simple models.

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. Two series compensation devices with ± 0.4 degree of compensation capability are modeled at line 2 and line 18. Utilizing FACTs in addition to DLR can reduce the cost of forecasting DLR error by over 60%.

Costs and Benefits

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 Vietnam³⁷

DLR

World Bank Group

 **Simulation**

2016

Motivation

Robust economic growth has led to 14% annual growth in electricity demand, with continued growth expected. Selected lines are high current loads.

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

Ampacity ratings for DLR available 5-25% above SLR.

Costs and Benefits

Net present value of \$44.1 million up to the year 2030 on the system. [Presumably total savings from 2016-2030]. Estimated to be \$1.1 million in capital costs. A DLR sensor costs \$32K while the reductoring costs \$200K/km. Estimated annual operating expenses of \$183K.

[Adjusted: \$53.3M, \$1.3M, \$38K, \$237K, \$217K]

Asia





Smart Valve Pilot Project^{8,9}

PFC

EirGrid Group w/Smart Wires

 **Installation**

2016

Motivation

The case was selected for installation on a newly built, but not yet energized line for a trial installation to assess safe operational conditions.

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. During the injection test on the live trial it achieved an increase in expected performance. The SmartValve achieved a change of ± 0.181 Ohms, or 0.83% of the line's reactance.

Costs and Benefits

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

Motivation

Examine the costs of PFCs against conventional upgrades across entire PJM system for RES integration.

Architecture

Studied economic benefits in PJM system projected to 2026 with 30% RES on lines higher than 100 kV. The long-term plan includes analysis of a large number of candidate lines: 51 345 kV, 26 230 kV, 6 160 kV, 119 138 kV and 10 115 kV.

Outcomes

PFC results show that Smart Wires flow control devices could reduce the investment in transmission system enhancements by 50% or more. The estimated savings are likely conservative, as capacity market savings are not considered.

Costs and Benefits

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. Annual operating estimated costs of \$81 million per year.

[Adjusted: \$1.056B, \$317M, \$756M, \$96M]

North America





Implementation of RTTR system for Cupar – St Andrews 33kV circuits⁴¹

DLR

SP Energy Networks

◆ Installation

2015

Motivation

The line was selected due to predicted load growth in the St. Andrews region.

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. The previous project showed potential for 1.24 to 1.55 times the SLR available in summer.

Costs and Benefits

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 an automatic network management scheme to avoid exceeding DLR.

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

Europe





Estimation method for dynamic line rating potential and economic benefits³⁶

DLR

VTT

 **Simulation**

2015

Motivation

The northern region of the countries have transmission constraints leading to high price areas.

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

97% of the time an additional 300 MW of capacity is available over the 1500 MW available with SLR.

Costs and Benefits

A set of conservative estimates is made for the economic benefits of DLR. Average price is decreased 4.7 €/ MWh (9.7%) for one year. Heavily congested peaks decrease price by 19.3 €/MWh (40.8%). Consumers could save 21.1 million €.

[Adjusted: \$6.1/MWh, \$25.0/MWh, \$27.3M]

Europe





Implementation of Dynamic Line Rating Technique in a 130 kV regional Network³⁵

DLR

KTH Royal Institute of Technology w/Bahria University

Simulation

2014

Motivation

The selected line connects large hydro power in the north to consumption in the east with annual periods of high stress.

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

During winter, both seasonal SLR and DLR are sufficient for significantly increasing load demand. In summer, excessive ambient temperature limits the capacity due to potential sag problems.

Costs and Benefits

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. 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. [Note: ROI about 0.3 years]

[Adjusted: \$710K, \$41K, \$20K, \$13K, \$190K, \$4.7M, \$5.8M]

Europe





Oncor's DLR Demonstration⁵

DLR

Oncor Electric Delivery Company w/Nexans and ERCOT

◆ Installation

2014

Motivation

The study was funded to increase the efficient use of the existing transmission network, mitigate transmission congestion, and develop best practices for applying DLR systems. The selected lines were highly congested during peak loading season.

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 and Benefits

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 Finland²⁰

DLR

VTT

 **Installation**

2013

Motivation

The device was initially installed for monitoring lines in case one was offline for maintenance or contingency. The collected data over the years was used to assess potential for new wind energy integration.

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), showing changes from 1000-3000 N to 500-1500 N for tension measurements of different configurations.

Costs and Benefits

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

Motivation

The pilot lines were selected for integration of new wind energy.

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 Brittany, 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 $\pm 2\%$. 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 and Benefits

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 Ratings³²

DLR

The Valley Group w/Portland GE

Installation

2000

Motivation

Power flow modeling showed requirements to build new projects in 2003 and 2005.

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 and Benefits

This defers two transmission line projects totaling \$2.9 million. Capital savings through 7 years of deferral equate to \$1.2 million.


[Adjusted: \$4.8M, \$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 | ● Installation⁴⁷ | 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 | ● Installation⁴⁹ | 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 | ● Installation⁴⁶ | 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 | ● Installation⁵¹ | 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 | ○ Simulation⁵⁰ | 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 | ● Installation⁴⁸ | 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 | ○ Simulation⁴⁴ | 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 | ● Installation⁴⁵ | 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 | ○ Simulation⁵⁴ | 2018 | Asia 
Simulations are carried out on a modified version of the IEEE 30-bus test system, with DLR ratings set based on Osaka, Japan weather conditions. Power flow ratings are increased by over 40% with DLR, optimal costs are decreased by \$190/hr.

DLR | ● Installation⁵³ | 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 | ○ Simulation⁵⁵ | 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 | ● Installation⁵² | 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 | ● Installation⁴³ | 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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