CIGRE-US National Committee
2023 Next Generation Network Paper Competition

Optimized Power Flow Control Device Siting with Coupled Production Cost / AC Powerflow Modeling

Leonard Kapiloff, Andrew Siler
620230339, 620230347
Senior Power Systems Analyst, Senior Power Systems Engineer
Telos Energy, Inc.
Indicate as undergraduate student, graduate student, or professional with 10 years or less experience
leonard.kapiloff@telos.energy, andrew.siler@telos.energy

SUMMARY

The United States power system is currently experiencing a transformation due to the integration of new renewable generation sources, often located far from load centers. This situation has strained the existing transmission system, necessitating the construction of new transmission lines to enhance reliability, reduce congestion, and achieve renewable energy goals. However, building new transmission infrastructure entails significant capital investment and lengthy timelines. To address these challenges, Grid Enhancing Technologies (GETs) such as power flow control devices (PFCs) and dynamic line ratings (DLRs) have emerged as potentially cost-effective and readily deployable solutions. This paper presents a novel method for optimally siting PFCs to address congestion challenges and evaluate their impacts on congestion and system reliability.

The study focused on the ISO-NE system, considering future scenarios with substantial offshore wind generation. To assess the value of PFCs, a coupled approach using production cost modeling in Energy Exemplar's PLEXOS software and AC power flow analysis in PowerGEM's Transmission Adequacy & Reliability Assessment (TARA) software was employed [1,2]. The developed method accounts for the complexity introduced by multiple variables, including PFC location, size, contingencies, and variable dispatch conditions such as PFC angle, renewables generation, and load.

The evaluation process begins by identifying a high priority area based on initial congestion costs in PLEXOS, followed by selecting representative hours for analysis in TARA. AC power flow analysis in TARA is used to apply small disturbances via PFCs to branches within the study area to rank PFC locations based on their ability to avoid overload situations. These PFC locations are then evaluated using PLEXOS production cost simulations to determine their economic impact across all 8760 hours of the year.

The results demonstrate that this novel method effectively captures the essential impacts of PFCs on reliability events, congestion, and identifies economically efficient PFC siting locations. The combined use of AC power flow analysis and production cost modeling provides technical fidelity and confidence in the economic and reliability impacts of PFC siting. The findings indicate that placing a single PFC can yield substantial economic benefits. The study reveals a yearly production cost decrease of $3.1 million to $4.3 million for the ISO-NE system by implementing PFCs, with a payback period of less than a year. These cost savings highlight the potential of PFCs as a valuable tool for complementing transmission line build-out efforts. The research emphasizes the importance of strategic PFC siting to maximize their value, as different locations yield significantly variable benefits.

The proposed PFC siting method using integrated AC power flow and production cost modeling is shown to be a promising approach for assessing the impacts and siting of PFCs. The developed methodology can be further refined and extended for other GETs applications, providing valuable insights into congestion mitigation and system reliability in the context of renewable energy integration.

KEYWORDS

Renewable integration, system reconfiguration, grid-enhancing technologies

BACKGROUND

The United States power system is currently undergoing a significant transformation, as new renewable generation is being brought online, often far from load centers, putting a strain on the existing transmission system. To alleviate these reliability issues, regional transmission planners are constructing new transmission lines, which promise to not only reduce congestion but also increase system resilience and help the country achieve its renewable energy targets. However, the construction of new transmission requires significant capital investment and can take many years.

The large cost and long lead time for building new transmission lines has increased interest in low cost and quick-to-install technologies that can alleviate transmission system congestion. Grid Enhancing Technologies (GETs) such as power flow control devices (PFCs) and dynamic line ratings (DLRs) have emerged as technologies that are both low cost and are quick to install (relative to building a new transmission line).

DLRs refer to the real-time assessment of the maximum power transfer capacity of a transmission line based on live conditions, including ambient temperature, wind speed, and wind direction. Traditional static line ratings are determined based on assumed steady-state conditions but generally tend to be conservative. DLRs could be used to align the operation of the transmission system with its true capabilities.

PFCs are technologies used to actively manage and control the flow of power on a transmission element and can be used to push or pull power away from overloaded lines and onto underutilized lines/corridors within the existing transmission network. PFCs can be modeled using a dispatch angle to manage the flow of power similar to phase-shifting transformers (PSTs), though companies like SmartWires are developing PFC technologies that make use of power electronics for increased flexibility. Together, DLRs and PFCs offer more flexibility for the transmission network and can be utilized to improve system reliability, resilience, and economics.

GETs can be a valuable interim solution to alleviate transmission system constraints while new transmission lines are being built, thanks to their low cost and rapid installation time. By complementing future transmission line build-out and improving the ability of grid operators to perform **system reconfiguration**, GETs can enhance the flexibility of the transmission system to enable **renewable integration** and a smooth transition towards a more sustainable energy future.

Previous studies of the economic value of GETs and PFCs on real-world power systems sited multiple PFCs to determine if their addition yielded significant cost savings [3,4,5,6,7,8]. EPRI's technical report from 2018 outlined a clear methodology for placing PFCs at specific locations to maximize congestion mitigation but did not account for a PFC's effect on multiple flowgates (contingency-monitored element pairs) [6]. Other studies evaluated optimal PFC siting on smaller test systems [8,10,11,12,13,14]. This study deviates from previous studies by combining the following four crucial aspects. First, one PFC was sited at a time to evaluate the economic benefit of each individual PFC device. Second, a clear methodology for PFC siting was developed that accounted for a PFC's effect on multiple congested flowgates. Third, the economic value of a given PFC location was evaluated using an hourly simulation for an entire year rather than a selection of snapshots. Finally, this methodology was shown to be tractable on a large real-world power system. The primary contribution of this paper is the combination of the four aspects discussed above to develop a novel method to economically site individual PFCs on large power systems.

For the purposes of this study, PFCs are not modeled with the ability to change their dispatch condition post-contingency. This assumption is common for security-constrained assessment of similar technology such as phase-shifting transformers (PSTs). In the future, PFCs could be able to change network flows post-contingency to relieve congestion and improve system stability. However, there are significant operational and protection related hurdles to fully realize this potential which are not within the scope of this study.

METHODOLOGY

This paper focuses on novel methods developed to evaluate the impacts of PFCs in mitigating congestion, and in particular the development and testing of a new method to optimally site PFCs. These methods were developed as part of a larger collaboration with Idaho National Lab to study and quantify the potential benefits of GETs, using ISO-NE as a test system. Two significant challenges are present in determining the optimal PFC location, namely: (1) the complexity introduced by the large number of variables used for modeling PFCs, and (2) the effective coupling of AC power flow with production cost modeling.

This effort was conducted using PowerGEM's Transmission Adequacy & Reliability Assessment (TARA) software for AC power flow analysis and Energy Exemplar's PLEXOS software for production cost modeling. These tools are both widely used in the power systems industry and have the flexibility that allowed them to be used in parallel for the purposes described in this paper.

The PLEXOS production cost simulation uses DC powerflow analysis to assess and solve the power flow network for every hour over the course of a year. While necessary to keep this process computationally feasible, DC power flow analysis relies on simplifying assumptions about the power system (i.e., voltage at all buses is ~1.0 pu) that reduce the accuracy of the network solution. For that reason, AC power flow analysis is widely used in the power systems industry for study applications that require a highly accurate network solution.

Coupling DC power flow based economic production cost modeling with AC power flow analysis allows for a wide variety of PFC locations to be evaluated using AC power flow, while considering the economic impact of each PFC over the course of the entire simulation year. There are many variables to consider when determining the characteristics of an optimally sited PFC, such as the location, size, and dispatch angle of the PFC. Accounting for changes in the hourly angle set point of PFCs over the course of an entire year under both normal and N-1 conditions quickly makes the problem of evaluating all PFC placement options and sizes intractable.

To narrow the scope of PFC siting, production cost modeling is used to initially screen the study area based on yearly congestion costs and key snapshots from a yearly simulation. The initial screening limits the size of the optimal siting problem in terms of locations (identifying a high priority area) and number of dispatch scenarios (identifying key snapshots). Evaluation of key snapshots was performed in TARA to leverage the fidelity of AC power flow analysis and rank a wide range of potential PFC locations using generation and load dispatch information received from PLEXOS.

TECHNICAL APPROACH

This project used an iterative approach to couple DC power flow based production cost modeling in PLEXOS and steady-state AC power flow analysis in TARA. Production cost modeling and AC powerflow analysis are quite different processes, and it is common for production cost models to simplify certain electrical parameters relative to AC powerflow models so that system can be modeled across many periods, rather than just for one snapshot. However, for this project it was important that the models were reasonably similar, so that their results could be adequately compared and information could be passed between them.

The coupling process was done carefully, to ensure that both models clearly represented the study area and every generator, transmission branch, and load could be mapped between PLEXOS and TARA. This process was validated by comparing the power flows on every line within the study area for several dispatch conditions and ensuring they matched within a reasonable tolerance. Figure 1 displays an example of that comparison, filtered to show the peak observed mismatch on a single line, of approximately 10% of the line's base thermal rating. A correlation was observed between lines with low reactance and high mismatch. This is likely due to differences between the AC and DC powerflow solvers used by TARA and PLEXOS, respectively. From Equation 1, we see that for smaller reactance values (X), any difference in voltage (V) or phase angle difference (δ) will have a greater impact on power flow between two nodes (P_{12}). In the case of our two models, the simplifying assumptions used in DC powerflow analysis likely led to the slight mismatches in power flows that were observed. Despite these differences in solution method, the peak mismatch of only 10% indicated that the AC powerflow model and the production cost model were in reasonable agreement and successfully coupled for the purposes of the study.

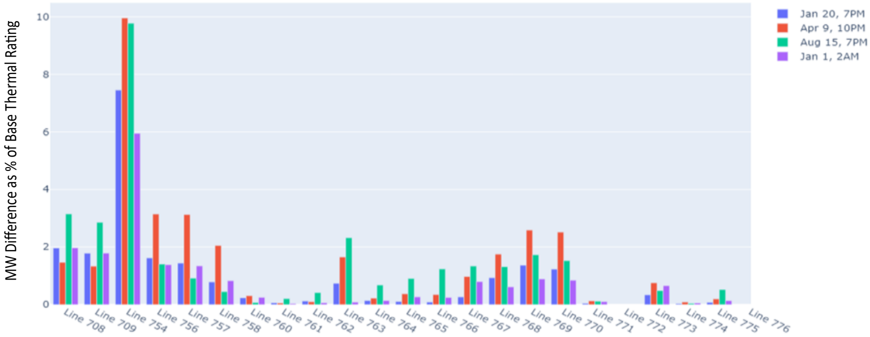

Figure 1: Line Flow Comparison Between PLEXOS and TARA

Equation 1: Network Equation for Power Flow Between Two Nodes [15]

$$P_{12} = \frac{V_1 V_2}{X} \sin \delta$$

Once they were successfully coupled and validated, the PLEXOS and TARA models were used to optimize PFC placement to mitigate congestion on the ISO-NE system. After completing the model coupling calibration, the first step in determining the optimal location for a PFC is to determine what congestion (on a single transmission element or set of transmission elements) should be mitigated. Choosing which element(s) or regions' congestion to mitigate is done by identifying a high priority area based on PLEXOS case congestion costs.

For this project, significant congestion was identified around the Brayton Point 345 kV substation within the ISO-NE study area. The observed congestion was due to the large amount of offshore wind that was planned to be built in the future year case. With this in mind, the area around Brayton Point, shown in Figure 2, was chosen as the high priority area for potential PFC locations to be assessed.

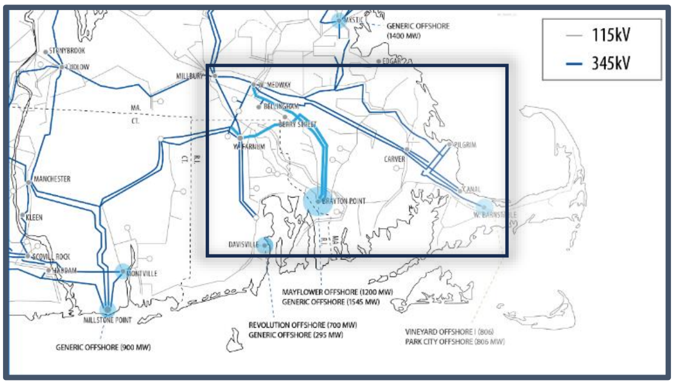

Figure 2: High Priority Area for Optimized PFC Siting

The hours that were most representative of case congestion in the high priority area were identified and passed to TARA for analysis. The most representative hours were determined based on the unique combinations of flowgates that accrued the highest congestion costs in the PLEXOS production cost model.

The most representative hours were determined according to the following method: Each period of the simulation where congestion occurs in the high priority area is attributed a distinct ID based on the unique combination of congested contingency-monitored element pairs (including the direction that the monitored element is congested). Each unique ID thus represents a unique congestion scenario. Table 1 below shows an example of how the flowgates are grouped into unique identifiers based on the combination of congested flowgates that occurred in the simulation.

For the example shown in Table 1, three flowgates within the high priority area were congested in the production cost simulation. Each flowgate can be congested in the forward direction, reverse direction or not congested in either direction. Thus, each additional flowgate included in the analysis increases the number of potential congestion scenarios by a factor of three. For a large system, this means that each additional congested flowgate significantly increases the problem complexity. Although there are many combinations of flowgate congestion that could occur during the year, only four of these unique combinations of congested flowgates appeared in this example. Each of the four combinations is designated by a unique Flowgate ID in Table 1.

Table 1: Example of Unique Flowgate Combinations

Unique Flowgate ID	Flowgate 1- Direction To-> From	Flowgate 1- Direction From -> To	Flowgate 2- Direction To-> From	Flowgate 2- Direction From -> To	Flowgate 3- Direction A To-> From	Flowgate 3- Direction From -> To
A	✓	x	x	x	x	x
B	✓	x	✓	x	✓	x
C	✓	x	x	✓	x	✓
D	x	✓	✓	x	✓	x

The congestion costs associated with each unique Flowgate ID are subsequently summed for the entire simulation. The below figure shows the Flowgate IDs and their relative congestion costs in the ISO-NE case.

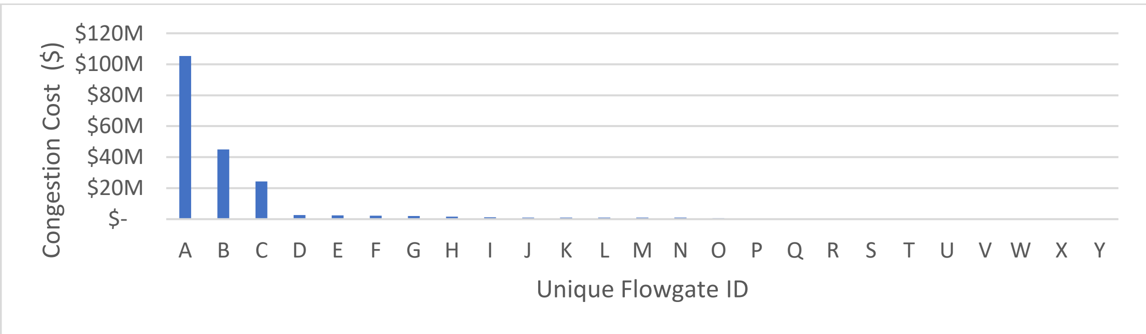

Figure 3: ISO-NE system congestion costs by unique combination of congested flowgates within the high priority area.

A single hour for each of the unique IDs with the largest congestion costs are subsequently passed to TARA. Of the many possible flowgate combinations, only 25 different combinations of congestion occurred. The unique Flowgate IDs with the 3 largest congestion costs (A, B, and C) accounted for approximately ninety percent of the congestion costs accumulated in the chosen area during the simulation. Thus, only hours with a congestion pattern from unique IDs A, B, and C were chosen as hours representative of congestion in the case. Choosing hours from these three unique Flowgate IDs ensured that TARA captured a significant portion of the congestion in the simulation while also improving the tractability of the PFC optimization siting in TARA. If the congestion pattern in the simulation was spread out over more unique IDs, more representative hours would be passed to TARA for evaluation.

For each of the hours considered, every transmission line within the chosen area was evaluated for PFC siting. Using Python to set up and run the TARA case for each hour, small disturbances were applied via PFC to each branch within the chosen area for all contingency conditions.

In TARA, each PFC was modeled using a phase-shifting transformer (PST). However, the parameters of the PST were adjusted using Python for each power flow solution to closely represent the characteristics of a modular Static Synchronous Series Compensator (SSSC) such as the SmartValve product developed by SmartWires [16], which work by injecting a voltage in quadrature with line current to effectively modify the reactance and modulate the power flow along a line. The key formulas used to calculate the PST parameters in TARA are shown in Equation 2 and Equation 3, where φ is the dispatch angle of the PFC and *t* is the transformer turns ratio. These formulas are set to ensure that V_{inj}, from the PST will be in quadrature with V_1. The key difference between the modeled quadrature PST and a modular SSSC is that for the PST, the injected voltage is not necessarily in quadrature with line current for all scenarios. However, assuming that the active current on the line is significantly greater than the reactive current as is most often the case (and line voltage is therefore approximately in-phase with line current), the effects of the modular SSSC on network power flows are accurately represented by the quadrature PST model.

Equation 2: Voltage Transformation across PST [15, 17]

$$\frac{\overline{V_1}}{\overline{V_2}} = t \times e^{j\varphi}$$

Equation 3: Quadrature PST Turns Ratio [17]

$$t = sin\left(\frac{\alpha + \varphi}{\alpha}\right);\ \alpha = 90° \text{ (quadrature)}$$

For each dispatch and contingency condition, a perturbation was applied in the TARA model at each potential PFC location by adding a PFC and setting the dispatch angle of the PFC to 0.5 degrees, corresponding to a per-phase V_{inj} of approximately 1.7 kV RMS. From the new AC powerflow solution, the power flow on every branch within the study area was recorded and compared with the pre-disturbance solution. The impact of the perturbation at each PFC location on any observed overloads (power flow above the transmission element limit) was quantified. An example is shown in Table 2, where the impact of each PFC location on the overload of branch 303-309-1 is shown for a specific dispatch condition and contingency. Values of larger magnitude indicate that a PFC at the specified location has a greater ability to influence the flow of power on the monitored element. This example is expanded in Table 3, showing the impact of each PFC location on overloads on every monitored element, for the specified dispatch hour and contingency. Every monitored element must be evaluated because the PFC may shift overloads from one element onto another portion of the network.

Table 2: Example PFC Impact on MW Overloads – One Monitored Element

		MW Overload on 303-309-1
Contingency	**PFC Location**	
301-303-1	**301-302-1**	-0.54
	301-303-1	-0.06
	301-305-1	0.45
	303-309-1	9.82
	304-309-1	-0.93
	308-309-1	-0.93
	315-324-1	9.74

Table 3: Example PFC Impact on MW Overloads

		Monitored Elements - Compare MW Overload with Base Case									
	FromBus	**301**			**303**		**304**	**308**	**309**		**315**
	ToBus	**302**	**303**	**305**	**309**	**324**	**309**	**309**	**311**	**312**	**324**
	ID	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Contingency	**PFC Location**										
301-303-1	**301-302-1**	0.00	0.00	0.00	-0.54	0.00	0.00	0.00	0.00	0.00	0.00
	301-303-1	0.00	0.00	0.00	-0.06	0.00	0.00	0.00	0.00	0.00	0.00
	301-305-1	0.00	0.00	0.00	0.45	0.00	0.00	0.00	0.00	0.00	0.00
	303-309-1	0.00	0.00	0.00	9.82	0.00	0.00	0.00	0.00	0.00	0.00
	304-309-1	0.00	0.00	0.00	-0.93	0.00	0.00	0.00	0.00	0.00	0.00
	308-309-1	0.00	0.00	0.00	-0.93	0.00	0.00	0.00	0.00	0.00	0.00
	315-324-1	0.00	0.00	0.00	9.74	0.00	0.00	-4.87	0.00	0.00	0.00

It is important to note that not all overloads have the same impact on congestion or on the reliability of the system over the course of the year. To assign the proper importance to each flowgate, the measured MW overloads are weighted according to the total congestion rent accumulated by the associated flowgate over the course of a year in the base case production cost model. The previous example is continued in Table 4 and Table 5, showing the results of the cost weighting.

Table 4: Example Cost Table

Contingency	Monitored Element	Congestion Rent from Initial Case
301-303-1	303-309-1	$3,117,740.00
301-303-1	308-309-1	$38,307,694.61

Table 5: Example PFC Impact on MW Overloads with Cost Weighting Applied

	FromBus	301			303		304	308	309		315
	ToBus	302	303	305	309	324	309	309	311	312	324
	ID	1	1	1	1	1	1	1	1	1	1
Contingency	PFC Location										
301-303-1	301-302-1	0.00	0.00	0.00	-1.68E+06	0.00	0.00	0.00	0.00	0.00	0.00
	301-303-1	0.00	0.00	0.00	-1.87E+05	0.00	0.00	0.00	0.00	0.00	0.00
	301-305-1	0.00	0.00	0.00	1.40E+06	0.00	0.00	0.00	0.00	0.00	0.00
	303-309-1	0.00	0.00	0.00	3.06E+07	0.00	0.00	0.00	0.00	0.00	0.00
	304-309-1	0.00	0.00	0.00	-2.90E+06	0.00	0.00	0.00	0.00	0.00	0.00
	308-309-1	0.00	0.00	0.00	-2.90E+06	0.00	0.00	0.00	0.00	0.00	0.00
	315-324-1	0.00	0.00	0.00	3.04E+07	0.00	0.00	-1.87E+08	0.00	0.00	0.00

In many cases, the PFC adjustment was observed to increase overloads on one element while decreasing overloads on another. This is shown in Table 5, where the adjustment of the PFC at 315-324-1 increases overloads on 303-309-1 and decreases overloads on 308-309-1. To account for this when summarizing the effectiveness of each PFC location, the cost-weighted impact of each PFC location is summed for every monitored element and the absolute value is taken, understanding that PFCs can operate to either push or pull power. This is summarized in Equation 4, where $R_{ctg,hr}$ represents the effectiveness of each PFC location for a given dispatch hour and contingency condition.

Equation 4: PFC Reliability Metric for a Given Dispatch Hour and Contingency Condition

$$R_{ctg,hr} = \left| \sum [\text{cost-weighted impact on every element}] \right|$$

The results of this method, applied to the example case, are shown in Table 6.

Table 6: Weighted Reliability Metric for Each PFC Location, for a Given Dispatch Hour and Contingency

Contingency	PFC Location	Congestion Rent Weighted Reliability
301-303-1	301-302-1	1.68E+06
	301-303-1	1.87E+05
	301-305-1	1.40E+06
	303-309-1	3.06E+07
	304-309-1	2.90E+06
	308-309-1	2.90E+06
	315-324-1	1.56E+08

This method is applied for every contingency condition and every dispatch hour passed from PLEXOS. These results are then summed across every combination of dispatch hour and contingency condition, outputting a final cost-weighted reliability metric for each PFC location. Using this metric, the PFC locations are given their final rankings. Table 7 showcases the final reliability metric results from the example case. PFC location 303-309-1 is shown to have the highest weighted reliability metric score, indicating that it is a favorable location to site a PFC.

Table 7: Final Weighted Reliability Metric for Each PFC Location

PFCLocation	Congestion-Rent Weighted Reliability
303-309-1	1.93E+09
315-324-1	1.07E+09
301-303-1	7.32E+08
301-302-1	6.76E+08
304-309-1	5.90E+08
301-305-1	4.24E+08
308-309-1	3.58E+08
NoPerturbance	0.00E+00

Ultimately, this metric is a measure of the ability of a PFC at a given location to mitigate impactful overloads on the system. When this process was applied to the ISO-NE model, there were three clear front runners for potential PFC sites. These three sites are shown in

Figure 3 and Figure 4. Intuitively, these sites make sense as they are electrically near the point of interconnection (POI) for the large amount of offshore wind resources that are planned for the ISO-NE system.

PFC Location	Ranking
Berry St - Brayton Point	1
Medway - Bellingham	2
Berry St - Bellingham	3

Figure 3: PFC Location Rankings

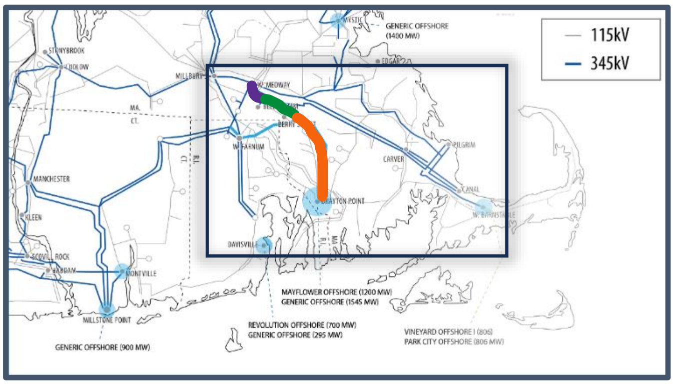

Figure 4: Mapped PFC Locations

These three highest impact PFC locations were then passed to the PLEXOS model for validation. PLEXOS production cost simulations were conducted for each of the new PFC locations individually to determine the economic impact of each PFC location and validate the ranking of the optimized PFC siting process.

RESULTS AND CONCLUSION

Comparing the results of the PLEXOS production cost simulations for each PFC location with the base case allowed for the economic impact of each individual PFC location to be quantified. All three of the top PFC locations were found to reduce congestion, as shown in Table 8, with the top ranked Berry St – Brayton Point PFC found to reduce congestion by $10.4 million annually. Production costs were reduced as well; the top ranked PFC reduced production costs by $4.3 million annually.

Furthermore, the addition of each individual PFC was found to significantly reduce the total annual curtailment of offshore wind resources on the system, as shown in Table 8. The top ranked Berry St – Brayton Point PFC found to reduce wind curtailment by 181.8 GWh annually. These results clearly demonstrate the importance of strategically placing PFCs using a holistic process to find the optimal location, because the benefits of PFCs can vary significantly depending on location.

Table 8: Production Cost Impact of Each PFC Location

PFC Location	Ranking	Congestion Rent Improvement ($M)	Production Cost Improvement ($M)	Total Curtailment Improvement (GWh)
Berry St – Brayton Point	1	10.4	4.3	181.8
Medway – Bellingham	2	8.0	3.1	146.2
Berry St – Bellingham	3	8.7	3.1	143.5

The novel optimal PFC siting process that was developed through this project uses a coupled AC power flow and production cost model to holistically capture the impacts of PFCs on congestion and identify PFC siting in an economically efficient manner. The AC power flow analysis performed provides the technical fidelity that is expected by the power systems industry, and the combined use of AC power flow and production cost modeling provides confidence in the economic and reliability impacts of utilizing PFCs. This coupling of AC power flow and production cost modeling could be further refined in the future and has potential to be used for a wide range of power systems studies.

There is an opportunity for the novel PFC siting process that was developed through this project to be refined and improved in the future. The key challenge in this method is quantifying the benefits to the system provided by PFCs, both in terms of long-term economic benefits as well as reliability benefits, while factoring in the wide range of variables that affect how PFC performance is modeled such as location and dispatch angle. Future work could include consideration of the possible reliability benefits of post-contingent adjustment of PFC angle, reconsideration of the congestion rent weighting process used in this analysis, or possible improvements in the method with which PFCs are modeled in AC powerflow analysis and in production cost modeling.

The results of this study clearly demonstrate that the effective siting and utilization of PFCs can have strong positive benefits for the power system. The top PFC placements identified by the optimal PFC siting process yielded PFC placements with substantial economic benefits. The PFC locations evaluated yielded congestion rent improvement of between $8.0 million - $10.4 million annually and a yearly production cost decrease of between $3.1 million - $4.3 million for the ISO-NE system with a payback period of less than a year. Compared to traditional transmission upgrades, which in addition to greater benefits come with higher capital costs and longer payback periods, there is an opportunity for GETs such as PFCs to be rapidly deployed and alleviate congestion, enabling the continued growth of renewables while new transmission infrastructure is being planned and built.

ACKNOWLEDGMENT

This research was completed under subcontract to Idaho National Laboratory with funding from the U.S. Department of Energy Office of Electricity (OE) and Wind Energy Technologies Office (WETO). Idaho National Laboratory is operated by Battelle Energy Alliance under contract No. DE AC07-05ID14517 as part of the Transmission Optimization with Grid-Enhancing Technologies (TOGETs) project.

BIBLIOGRAPHY

[1] Energy Exemplar, 2023 [https://www.energyexemplar.com/plexos]

[2] PowerGEM, 2023 [https://www.power-gem.com/TARA.html]

[3] U.S. Department of Energy. Grid Enhancing Technologies: A Case Study on Ratepayer Impact [2022]

[4] T.B. Tsuchida, S. Ross, A. Bigelow Unlocking the Queue with Grid Enhancing Technologies. [Technical Report, The Brattle Group. 2021]

[5] EPRI. Benefits and Value of New Power Flow Controllers. [2018 Technical report, 3002013930. https://www.epri.com/research/products/3002013930. Accessed July 2023]

[6] DNV GL. Assessment of Applicability and Cost Savings of Deploying Smart Wires Power Flow Controls to Integrate Renewable Energy in PJM. [Report No.: 10004216. June 23, 2016.]

[7] A. Moser, A. Klettke, J. Mehlem. Modular Power Flow Control Enhancing German Transmission Grid Capacity: An Investigation. [Technical Report. RWTH Aachen University. June 2020]

[8] X. Zhang, K. Tomsovic, A. Dimitrovski. Security constrained multi-stage transmission expansion planning considering a continuously variable series reactor. [IEEE Transactions on Power Systems 32.6 (2017): 4442-4450.]

[9] H. Pourbabak, T.R Nudell, W. Su. An efficient algorithm for dispatch of modular facts devices in transmission planning. [IEEE Power & Energy Society General Meeting (PESGM), doi:10.1109/PESGM40551.2019.8973921, Atlanta, GA, USA, 08/04/2019, 1-5. IEEE.]

[10] Y. Sang, M. Sahraei-Ardakani. Economic Benefit Comparison of D-FACTS and FACTS in Transmission Networks with Uncertainties. [2018 IEEE Power & Energy Society General Meeting (PESGM), doi: 10.1109/PESGM.2018.8585939, Portland, OR, USA, 08/05/2018, 1-5.]

[11] Zunnurain, Izaz & Sang, Yuanrui. (2021). A Stochastic Optimization Model for Distributed Static Series Compensator Allocation to Mitigate Transmission Congestion. [52nd North American Power Symposium (NAPS), Virtual, 04/11/2021, doi: 10.1109/NAPS50074.2021.9449752, 1-6.]

[12] O. Ziaee, Omid Alizadeh-Mousavi, F. Choobineh. Co-optimization of transmission expansion planning and TCSC placement considering the correlation between wind and demand scenarios. [IEEE Transactions on Power Systems 33.1 (2017): 206-215.]

[13] D. Das, A. Prasai, R. Harley, D. Divan. Optimal placement of distributed FACTS devices in power networks using particle swarm optimization. [IEEE Energy Conversion Congress and Exposition, San Jose, CA, USA, 09/20/2009, doi: 10.1109/ECCE.2009.5316292, 527-534.]

[14] O. Ziaee, F. Choobineh. Optimal location-allocation of TCSC devices on a transmission network. [IEEE Transactions on Power Systems 32.1 (2016): 94-102.]

[15] P. Kundur, Power System Stability and Control. [McGraw-Hill, New York, 1994, 245-249.]

[16] SmartWires, SMARTVALVE™ DIGITAL POWER FLOW CONTROL. [https://www.smartwires.com/smartvalve/. Accessed July 2023.]

[17] Siemens, Program Application Guide Volume 1 PSS®E 34.8.0. [Siemens Industry, Inc., Siemens PTI, Schenectady, NY, USE, 2020, 85-93.]