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Congestion Reduction Benefits of New Power Flow Control Technologies used for Electricity Market Operations

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SUMMARY

As part of the ARPA-e Green Electricity Network Integration (GENI) program, a new set of power flow control technologies has been under development. These new technologies offer advantages of providing fast, flexible, and reliable control of power flow on the transmission network to ensure reliability while also maximizing efficiency. A study was performed to evaluate these new technologies to understand their characteristics, their technical and economic benefits to system operation, and how they may be able to defer transmission capacity expansion needs [1]. The work described in this paper focuses on the benefits that these technologies can provide to reduce power system congestion on a practical, large-scale power system, and thus reduce system production costs and payments by wholesale consumers. We present several annual simulation results to provide greater understanding of these benefits and how they differ based on the characteristics of the system and technologies.

KEYWORDS

Power flow control, electricity market operation, congestion management, FACTS.

I INTRODUCTION

A new generation of power flow control (PFC) technologies are under development. These technologies have various characteristics which provide potential benefits to various power system applications (See Table 1). Some common characteristics include fast response times and flexible operation and control. Some of these technologies are also modular, and can be moved from one location of the grid to another in a relatively straightforward way. These technologies in addition to traditional technologies like phase angle regulators (PAR), high

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voltage direct current (HVDC) lines, and flexible AC Transmission Systems (FACTS), can provide control of the amount of power flowing on different paths on the transmission grid.

In the United States, as well as most other regions in the world, bulk power system operations are managed in a least-operational-cost manner. The system operator will determine the set of units to turn on (commit) and schedule energy levels (dispatch) based on finding the cheapest selection of those resources based on their fuel and any other operating costs, to meet the load demand subject to various individual generating unit constraints (minimum and maximum capability, ramping rates, minimum online times, etc.), system reserve requirements (e.g., spinning reserve, regulation reserve), and the transmission network security constraints (e.g., normal and contingency line limits). When the transmission system is constrained, the output of economic resources must be reduced, while more expensive units, those that are not limited by the transmission constraints, are used to make up that power. This transmission congestion can lead to increased operational costs on the system. As an example, on the PJM system, these costs have been estimated to be as high as almost $2 Billion USD ($1.932B) in a single year [2]. Although these costs can vary from year to year, it can be seen how the cost of congestion can add up to be several billion dollars per year in the United States alone. Thus, any reduction in congestion costs can lead to substantial cost savings to electricity consumers.

Table 1. New power flow technologies and characteristics.

Device	Developer	Characteristics
Distributed Series Reactors (DSR)	Smart Wires Inc.	• Increases line impedance on demand by injecting the magnetizing inductance of the Single-Turn Transformer. • Functions as a current limiter to divert current from the overloaded lines to underutilized ones • Local or centralized control are possible • Various device models and types
Compact Dynamic Phase Angle Regulators (CD-PAR)	Varentec Inc.	• Power converter integrated with a transformer • Special modulation technique allows for control of angle a module of the injected voltage, thus providing smooth and continuous control of P and Q flows over the line.
Transformer-less Unified Power Flow Controller (UPFC)	Michigan State University	• Cascaded multi-level inverters (CMIs) to eliminate transformers • Fractional MVA rating (10-20%) for >1p.u. (raise/lower/reverse) power swing on typical line • Modular scalable design
Magnetic Amplifier (MA)	Oak Ridge National Lab SPX Waukesha	• Inserts a controlled variable inductance in the line • Power electronics isolated from the HV line • Low power dc source controls the high voltage ac inductance • Smooth reactance regulation, acceptable harmonics • Uses standard transformer manufacturing methods

This paper provides an overview of a study to evaluate the benefits that these new power flow control technologies can have on reducing production costs and payments made by load due to the congestion that they can alleviate. We use ABB's GridView program, which is a commercial production cost simulation tool which incorporates a security constrained unit commitment and economic dispatch model and reflects the same models that are used for market operations at most Independent System Operators (ISO) in practice. The study is performed on the PJM system with appropriate consideration of neighboring balancing areas to ensure realistic interchange scheduling is captured. This paper is structured as follows. Section II provides an overview of the case and the technologies studied. Section III provides the results of benefits as a function of increased penetration of power flow technologies. Section IV provides some further results on key sensitivities. Finally, Section V concludes.

II System and Technology Overview

The PJM system was chosen for this case study to ensure that a large, realistic power system, was studied which also had significant congestion reduction benefit potential. This system was benchmarked using existing congestion impacts and locational marginal prices (LMP) from historical data. The system used for simulation includes 16,883 buses, 1,503 generating units, 21,900 lines, 24 existing PARs, 160 monitored contingencies, with a total peak load of 168,000 MW. GridView utilizes a DC power flow when studying the network impacts, assuming 1 p.u. voltage magnitudes, ignoring reactive power flows, and utilizing a linearized marginal electrical losses calculation.

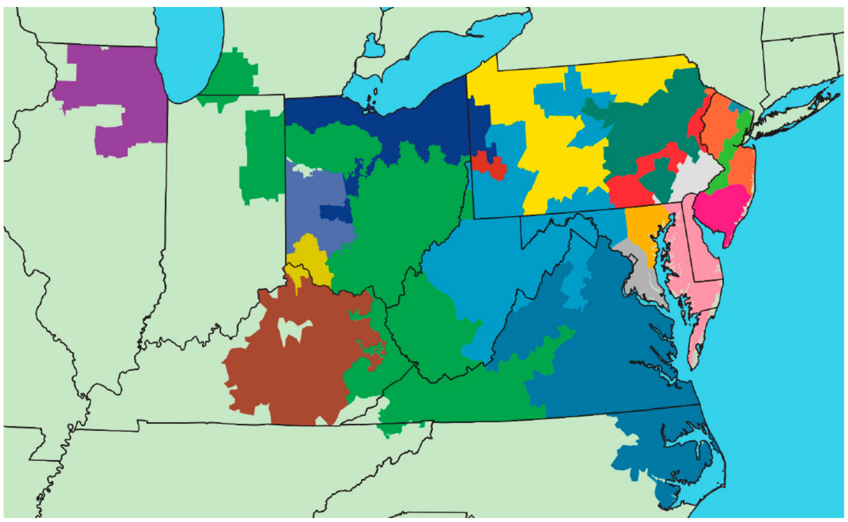

Figure 1. PJM system.

For this study, we evaluate two representations of the four technologies described earlier. CD-PAR and UPFC are represented using the traditional PAR model, where phase angle can be controlled based on the limits of that technology. DSR and MA is modeled using a variable impedance control (VIC) technology. The VIC required enhancements to the traditional production cost simulation tool, since allowance of impedance as a control variable causes the power flow solution to be nonlinear. To overcome this issue, an iterative approach is used to estimate the equivalent angle changes to mimic impedance changes based on the previous iteration flow through the branch until convergence is reached. More direct implementations have been developed [3], but the method proposed here was a more practical utilization of VIC for the existing GridView model and large-scale optimization of a system such as PJM.

III Power Flow Control Technology Benefits

The benefits of various configurations of power flow control technologies will depend on where these end up locating within the transmission system. It is important to place these in the most beneficial locations possible, subject to the limitations of where these technologies can actually be located. We ranked the optimal locations based on the highest line outage distribution factor (LODF) of all lines within the PJM systems to the constraints that had the highest congestion costs after simulating the base case annual run[1]. This would give locations that are able to have the largest ability to change the flow on those lines with high congestion. Other characteristics based on voltage class, line length, overhead/underground, etc., were used to finalize locations for the technologies that represent those that are where they would realistically be placed. Table 2 shows the 6 cases where we study up to 17 placements.

Table 2. Cases of increasing power flow control capacity

Case	Description	MVA
C1	Base Case	0
C2	1 PFC	186
C3	4 PFCs	522
C4	8 PFCs	1065
C5	13 PFCs	1427
C6	17 PFCs	2117

Results and benefits of the power flow control technologies using angle control are shown in Table 3. We evaluate load payments, production costs, adjusted production costs (PJM costs + export sale), congestion costs, congestion hours, and generation revenue. The PJM Energy Market Benefit metric [4] takes the combined equally weighted benefits from Load Payment and Adjusted Production Cost. The Energy Market Benefit results are also shown in Figure 2.

Table 3. Benefits of Power Flow Control Technologies

	C1	C2	Benefit	C3	Benefit	C4	Benefits	C5	Benefit	C6	Benefits
Load payment (M$)	26,959	26,961	(3)	26,893	66	26,791	167	26,770	189	26,787	172
Generation cost (M$)	18,932	18,887		18,875		18,867		18,856		18,849	
Export sale (M$)	609	601		596		606		601		599	
Adjusted production Cost (M$)	18,323	18,287	36	18,280	43	18,262	61	18,255	67	18,250	73
Energy Market benefit (M$) (PJM metric)	N/A		16.67		54.15		114.14		128.17		122.07
Total system production cost (M$)	31,195	31,164	31	31,161	33.9	31,134	61	31,127	68	31,121	74
Transmission Congestion (M$)	589	549	39	454	134	414	175	402	187	393	196
Transmission Congestion (h)	181,058	186,399	(5,341)	204,130	(23,072)	213,690	(32,632)	245,897	(64,839)	260,079	(79,021)
Generation Revenue (M$)	25,814	25,840	26	25,850	35	25,787	(28)	25,772	(43)	25,792	(22)

The benefits of the power flow control technologies increase fairly linearly until about 1500 MVA of capacity (or 13 locations). At this point, the locations were providing the majority of relief for the major thermal congestion on the system for this year of study. The total thermal

[1] In this study, since based on the DC power flow method used in commercial production cost simulation models, we only chose locations that would relieve thermally congested transmission constraints (both normal and contingency constraints). In PJM, several interface constraints exist which represent voltage and stability constraints. The power flow control technologies were not used to relieve these constraints, although in practice, they may be able to do so as well.

congestion costs are about $340M, while the PFC are able to relieve about $200m. It may be that the remaining congestion can only be relieved through expansion of the transmission capacity of the system. Also, it is interesting to note that while the total system production costs are consistently reduced up to the full 17 locations, load payments are not always the case. Finally, while the PFC are able to reduce the total congestion costs on the system substantially, the actual quantity of congested lines and congested hours increases by a relatively high amount.

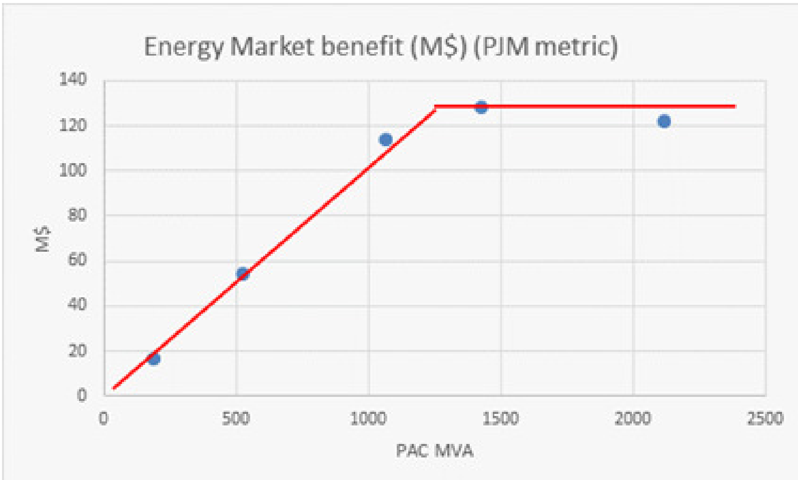

Figure 2. Energy Market Benefit of Power Flow Control Technologies as function of capacity.

IV Sensitivity Study Results

Several additional simulations were performed to get a better understanding of the benefits of PFC technologies. First, we study the benefits of VIC technologies by using the new methodology described in Section II (more details in [1]). Results are shown in Table 4. Most VIC based technologies are shown to provide about 10-30% of impedance change, and mostly in the upward direction only. Case 7 shows upward limit of 30% impedance whereas Case 8 shows a bi-directional adjustment of 30% impedance (both with 17 PFC locations). The equivalent phase angle change of a 30% impedance change on most of the locations within this study are only a few degrees, and thus, the benefits are not as significant as those from the phase angle control technologies (Case 6). However, these technologies may have other benefits or different costs.

Table 4. Benefits for power flow control technologies with variable impedance control.

	Case 1	Case 6	Benefits	Case 7	Benefits	Case 8	Benefits
Load payment (M$)	26,959	26,787	172	26,864	94	26,860	99
Generation cost (M$)	18,932	18,849		18,915		18,909	
Export sale (M$)	609	599		608		605	
Adjusted production Cost (M$)	18,323	18,250	73	18,308	15	18,304	18
Energy Market benefit (M$)	N/A		122.07		54.62		58.66
Total system production cost (M$)	31,195	31,121	74	31,178	16	31,174	21

In addition, installing PFC technologies on systems with increased levels of variable and uncertain renewable generation may have different benefits. Congestion patterns may change and the flexibility that PFC technologies have can have a benefit on the variability of renewable resources. Table 5 shows the results of Case 9 (base case with high renewable penetration) and Case 10 (High renewable case with 17 PFCs). Total production costs were reduced with the addition of PFC in the renewable case. The main benefit however, was the greater reduction in renewable curtailment.

Table 5. Benefits of Power Floc Control Technologies on higher variable renewable generation.

	Case 1	Case 6	Benefits		Case 9	Case 10	Benefits
Load payment (M$)	26,959	26,787	172		26,000	25,887	112
Generation cost (M$)	18,932	18,849			17,994	17,902	
Export sale (M$)	609	599			938	915	
Adjusted production Cost (M$)	18,323	18,250	73		17,056	16,987	69
Energy Market benefit (M$) (PJM metric)	N/A		122.07		N/A		90.84
Total system production cost (M$)	31,195	31,121	74		29,926	29,844	82
Renewable Curtailment (GWh)	83.72	25.10	58.62		230.74	40.80	189.94

Additional sensitivities showed increased benefits from larger control limits (angle or impedance) but not at significant levels. In addition, corrective control during contingencies showed very low incremental benefits based on the contingencies that the locations were able to assist with within the PJM system. Finally, benefits on a system with higher fuel prices showed greater benefits of reducing production costs, while it did not have as high benefits for reducing load payments.

V Conclusions

In this paper, we have explored the benefits of power flow controllers in reducing production costs, load payments, and renewable resource curtailment through enhanced congestion management. Many intuitive conclusions were confirmed with this study. The more devices placed, the greater the benefit. However, as the additional devices are placed on lines with less congestion costs, the incremental benefits decrease such that a saturation point is reached. In addition, the greater the control range and the higher the limits of control, the greater benefits. These increases have diminishing returns as well. Finally, it was observed that generally, systems with higher renewable resources and higher fuel prices both have higher benefits. More specifically however, it may depend on which benefits are being evaluated.

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