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

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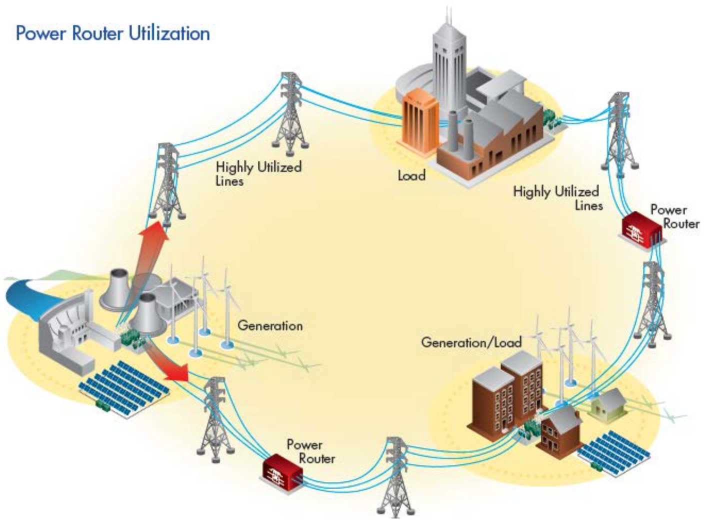
Benefits and Value of New Power Flow Controllers
DOE ARPA-e Project

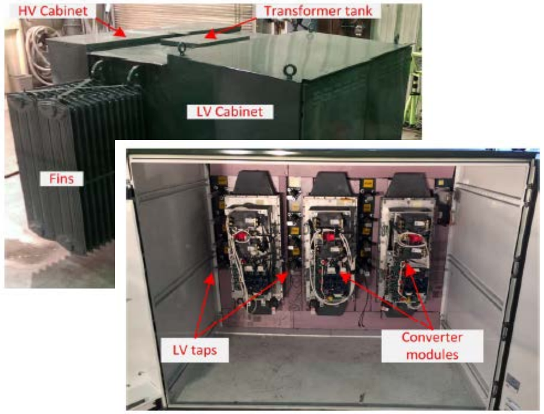
- Goal: Assessment of the types of benefits that can be realized through the use of new power flow control technologies
- Value: Understanding of how these technologies can support reliability and economic efficiency
- Scope:
  - ***Technical analysis and modeling:***
    - Understanding the different technology and their characteristics
  - ***Improvement to power system operations***:
    - How power flow technologies can reduce congestion to improve system costs
  - ***Use for transmission expansion capacity:***
    - How power flow technologies can defer transmission expansion

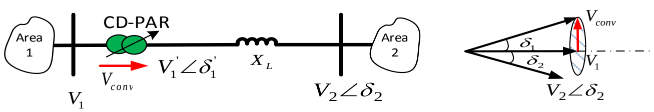


Accelerating Adoption of Power Router Technology Through Assessment and Demonstration of Value Proposition

New Power Flow Controllers

13 kV prototype – Installed on Southern Company Feeder



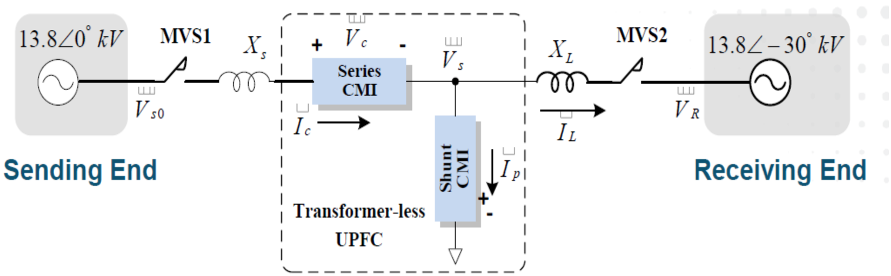


Compact Dynamic Phase Angle Regulator

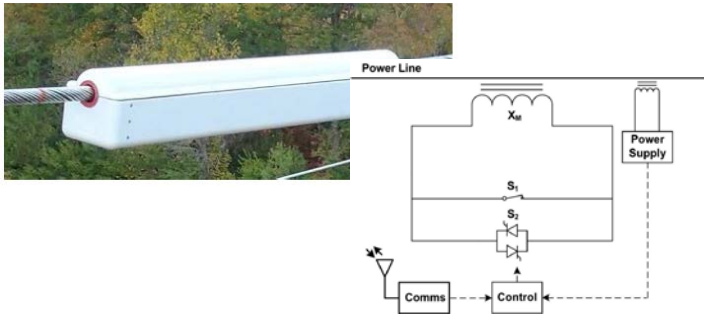
1Phase CVSR 115kV, 1500A

Magnetic Amplifier (MA) or Continuous Variable Series Reactor (CVSR)

13.8 kV prototype - Michigan State University



Transformer-less Unified Power Flow Controller



Distributed Series Reactor by Smart Wires Inc.

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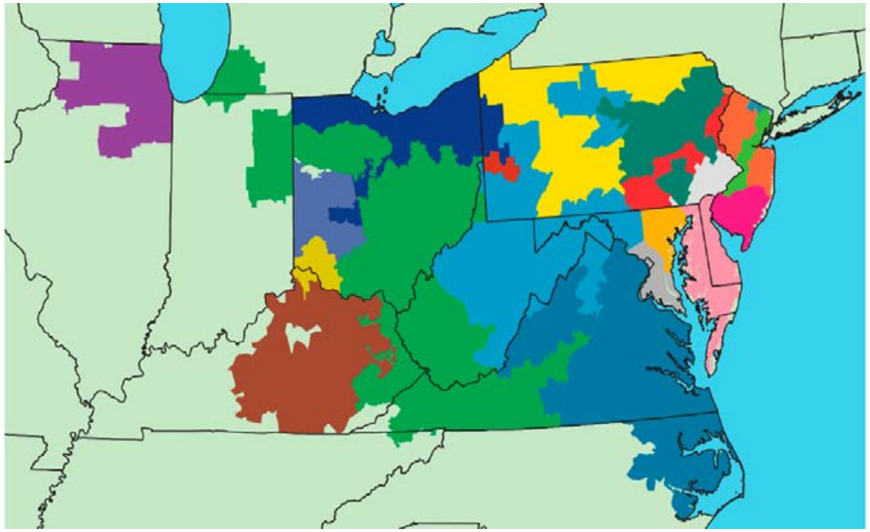
Study Objectives (Congestion Benefits Task)

- How can power flow controls provide benefits on practical systems in terms of production cost and energy market savings?
- Is there a point where they reach saturation and no longer provide benefit? What is that point? Can power flow controllers replace transmission expansion?
- How do different technologies compare in terms of congestion benefits?
- How do parameters of the technologies impact the overall benefit?
- Can advanced control provide greater benefit?
- Can power flow controls provide greater benefit on high renewable penetration systems?
- How general are the conclusions we have found? Are they applicable to other scenarios and other regions?
- What other research is required in this area?

System Model

- GridView Production Cost Simulation Tool
- PJM 2016 System
- Annual Simulation at hourly resolution
- Moderate VG penetration in base case
- Sensitivity with high VG penetration
- The latest Ventyx 2016 market simulation ready database (2015 edition)



PJM Data Base:

- 16,883 buses;
- 1,503 gen plants;
- 21,900 lines; 18,233 lines of 161 kV and below
- 24 Phase shifter;
- 2 HVDC
- 160 Contingencies
- 11,617 MW capacity of renewable generation
- Total load: 168,024 MW

Device modeling:

- CD-PAR and UPFC: Represented by Phase angle regulator (**PAC**)
- DSR and MA: Represented by Variable Impedance control (**VIC**)

Power Router Placements

- We use line outage distribution factor (LODF) matrix
- Rank sensitivity of candidate lines on highest congested lines (in terms of costs) that can relieve congestion
- Equivalent to highest price differences
- Method produced 80 candidate locations with LODF greater than 0.5 on lines with greater than $20k in congestion costs
  - 21 lines had a high impact on 3 different highly congested lines
  - Congested lines themselves are high ranking candidates (LODF=1)
  - LODF and congestion cost of the congested line can be used together for ultimate ranking of locations
- Voltage class, line length, other technical characteristics must also determine the validity of locating power routers on branch

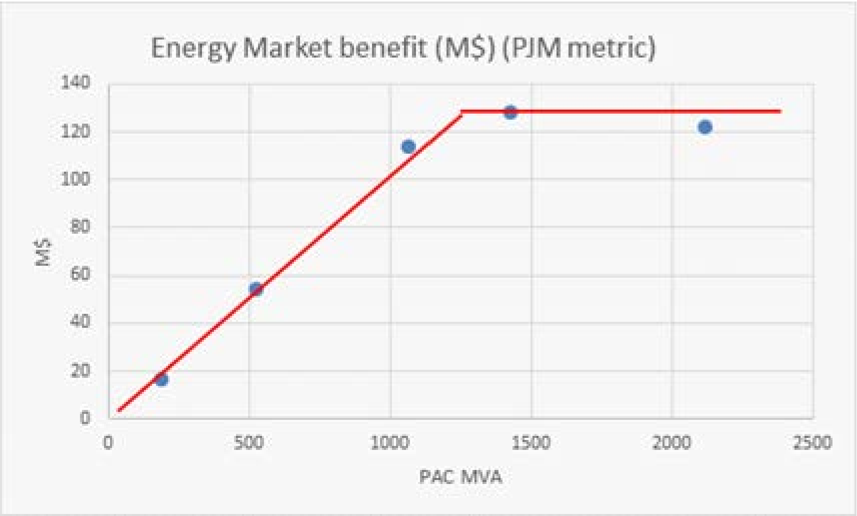
Power Flow Controller Benefits Results

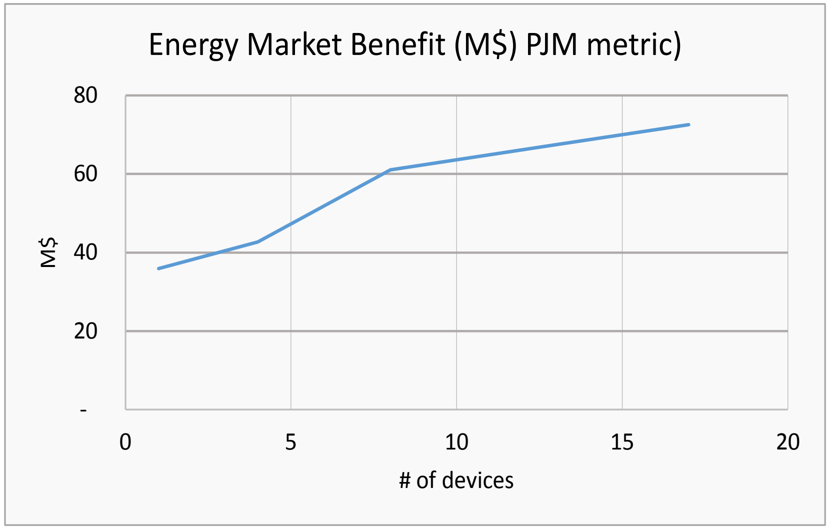
PJM wide Metrics	Case 1	Case 2	Benefits	Case 3	Benefits	Case 4	Benefits	Case 5	Benefits	Case 6	Benefits
Load payment (M$)	26,959	26,961	(3)	26,893	66	26,791	167	26,770	189	26,787	172
Generation cost (M$)	18,932	18,887		18,875		18,867		18,856		18,849	
Export sale (M$)	609	601		596		606		601		599	
Adjusted production Cost (M$)	18,323	18,287	36	18,280	43	18,262	61	18,255	67	18,250	73
Energy Market benefit (M$) (PJM metric)	na		16.67		54.15		114.14		128.17		122.07
Total system production cost (M$)	31,195	31,164	31	31,161	34	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)
SO_2 Amt (M Short Ton)	1.130	1.126	0.004	1.132	(0.001)	1.134	(0.003)	1.133	(0.002)	1.133	(0.002)
NO_x Amt (M Short Ton)	0.378	0.378	0.000	0.378	0.000	0.378	(0.000)	0.378	(0.000)	0.379	(0.000)
CO_2 Amt (M Short Ton)	460.127	458.977	1.150	459.062	1.065	459.086	1.041	458.882	1.246	458.886	1.241
Mercury HG Amt (Short Ton)	2.812	2.810	0.002	2.810	0.002	2.812	(0.000)	2.810	0.002	2.812	(0.000)
NO_x Cost (M$)	9.749	9.739	0.010	9.751	(0.001)	9.764	(0.014)	9.762	(0.012)	9.768	(0.018)
CO_2 Cost (M$)	81.607	73.606	8.000	72.660	8.946	72.445	9.162	72.468	9.139	71.983	9.623

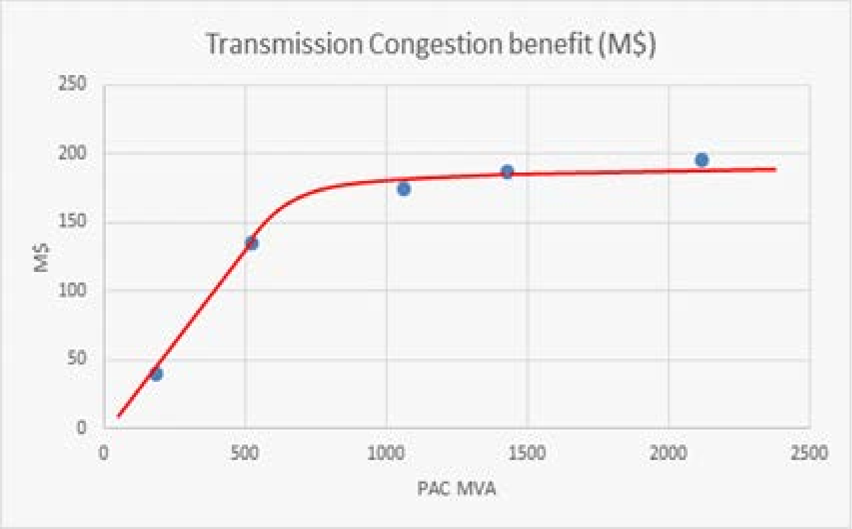
Case	Description	MVA
1	Base case	0
2	1 PARs (#2)	186
3	4 PARs (1-4)	522
4	8 PARs (1-8)	1065
5	13 PARs (1-13)	1426.5
6	17 PARs (1-17)	2116.5

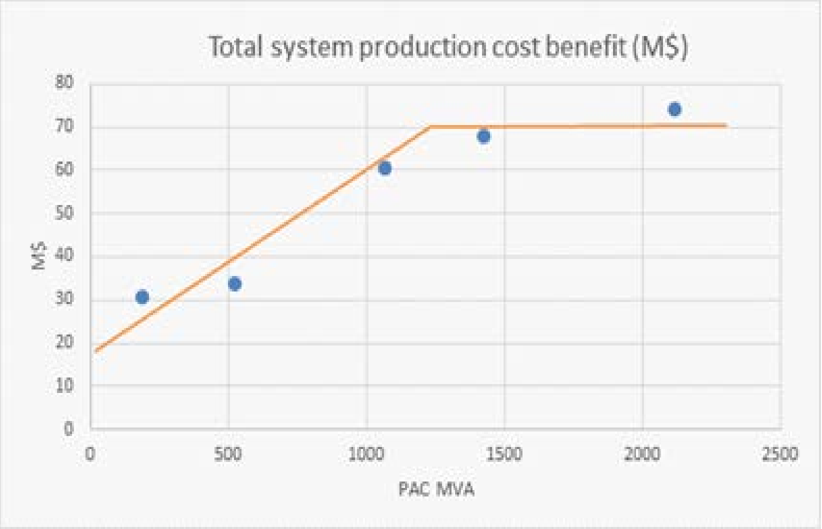
- Power flow controllers do hit a saturation point. Expansion may be required on the congestion that remains
- Voltage, stability, and interface limits are ignored. Only thermal (normal and contingency) constraints are targeted

Benefits Curve









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Impact of Limit Levels

- **Objective**: Gain an understanding of the impact of PAC limits
- **Conclusion**: removing PAC angle limit will move congestion from one place to another, it may have incremental benefits but typically less than additional PFC locations
- Case description:
  - Case 3 - 4 PACs with 15 deg. limit; → Case 11 – 4 PACs with 90 deg. Limit
  - Case 6 - 17 PACs with 15 deg. limit; → Case 7 – 17 PACs with 90 deg. limit

PJM wide Metrics	Case 1	Case 3	Benefits	Case 11	Benefits	Case 6	Benefits	Case 7	Benefits
Load payment (M$)	26,959	26,893	66	26,894	65	26,787	172	26,790	169
Generation cost (M$)	18,932	18,875		18,872		18,849		18,840	
Export sale (M$)	609	596		594		599		602	
Adjusted production Cost (M$)	18,323	18,280	43	18,278	45	18,250	73	18,238	85
Energy Market benefit (M$) (PJM metric)	na		54.15		54.63		122.07		126.71
Total system production cost (M$)	31,195	31,161	33.9	31,158	36.7	31,121	74	31,109	85
Transmission Congestion (M$)	589	454	134	460	128	393	196	409	180
Transmission Congestion (h)	181,058	204,130	(23,072)	204,130	(23,072)	260,079	(79,021)	305,181	(124,123)

Variable Impedance Devices

- **Objective**: Gain an understanding of the benefits of variable impedance control when compared to angle control
- Enhanced modeling to utilize impedance as decision variable for power flow controller branch
- **Conclusion**: Typical VIC Devices have less control capability measured by equivalent phase angle. Bi-directional control improves benefits but not significantly.
- Case description:
  - Case 6 - 17 PACs with 15 deg. limit;
  - Case 8 - 17 VIC with 30% impedance <u>increase</u> limit
  - Case 9 – VIC with 30% impedance <u>increase/decrease</u> limit
  - Case 16 – VICs with 80–150% impedance increase limits

PJM-Wide Metrics	Case 1	Case 6	Benefits	Case 8	Benefits	Case 9	Benefits	Case 16	Benefits
Load payment (M$)	26,959	26,787	172	26,864	94	26,860	99	26,808	150
Generation cost (M$)	18,932	18,849		18,915		18,909		18,890	
Export sale (M$)	609	599		608		605		604	
Adjusted production cost (M$)	18,323	18,250	73	18,308	15	18,304	18	18,286	36
Energy Market benefit (M$) (PJM metric)	N/A		**122.07**		**54.62**		**58.66**		**93.31**
Total system production cost (M$)	31,195	31,121	74	31,178	16	31,174	21	31,161	33.60
Transmission congestion (M$)	589	393	196	468	121	462	127	431	158
Transmission congestion (h)	181,058	260,079	(79,021)	181,819	(761)	185,763	(4,705)	187,970	(6,912)

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Cost-Benefit Analysis

- Cost-benefit PACs:
  - Investment: $**137M** (13 locations):
    - Control limit ±15º
    - Investment cost range: $70/kVA - $110/kVA – fractionally rated
  - PJM Metric: **$128 M/yr**
  - Adjusted production cost saving: $67 M/yr
  - Payback period: 2-3 years
- Cost-benefit VICs:
  - Investment: $94M (17 locations):
    - Magnetic Amplifier: $10/kVA – on throughput power
    - DSR: based on tool provided by Smart Wires Inc.
  - PJM Metric: **$93 M/yr**
  - Adjusted production cost saving: **$36M/yr**
  - Payback period: 3-4 years

Renewable Scenario

- **Objective**: Gain an understanding of the benefits in renewable scenario
- **Observations**:
  - Benefit on higher renewable system using PJM metric became less due to lower prices
  - Production cost savings similar – total production costs (all regions) increased
  - Power routers likely helping wind more than solar due to location
  - Curtailment reduced by **189 GWH/yr**

Base Case:

- 556 MW Solar
- 9,483 MW Wind

High renewable case:

- Solar capacity increased seven-fold (3.7 GW) at 115 locations.
- Wind capacity was doubled (10.7 GW) at 60 locations

	RPS	RPS Power Router			Base	Power Router	
PJM wide Metrics	**Case 13**	**Case 14**	**Benefits**		**Case 1**	**Case 6**	**Benefits**
Load payment (M$)	26,000	25,887	112		26,959	26,787	172
Generation cost (M$)	17,994	17,902			18,932	18,849	
Export sale (M$)	938	915			609	599	
Adjusted production Cost (M$)	17,056	16,987	69		18,323	18,250	73
Energy Market benefit (M$) (PJM metric)	na		90.84		na		122.07
Total system production cost (M$)	29,926	29,844	82		31,195	31,121	74
Transmission Congestion (M$)	590	387	203		589	393	196
Transmission Congestion (h)	180,513	256,611	(76,098)		181,058	260,079	(79,021)
Generation Revenue (M$)	25,175	25,205	30		25,814	25,792	(22)
SO2 Amt (M Short Ton)	1.062	1.060	0.003		1.130	1.133	(0.002)
NOx Amt (M Short Ton)	0.359	0.359	0.000		0.378	0.379	(0.000)
CO2 Amt (M Short Ton)	434.097	432.225	1.872		460.127	458.886	1.241
Mercury HG Amt (Short Ton)	2.656	2.650	0.006		2.812	2.812	(0.000)
NOx Cost (M$)	9.232	9.219	0.013		9.749	9.768	(0.018)
CO2 Cost (M$)	73.382	65.463	7.920		81.607	71.983	9.623
Renewable Spillage (GWh)	230.74	40.80	189.94		83.72	82.78	0.93

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Conclusions and Summary

- Tremendous benefits, but saturation point occurs at relatively low penetration
- Locational benefits may change each year depending on many factors
  - Mobility a unique advantage to certain technologies
- Variable impedance have lower equivalent control range, but lower investment cost
- Higher renewable scenarios can lead to great improvements to curtailment mitigation
- Future Research Topics:
  - Improved commitment and dispatch modeling with detailed technology characteristics (e.g., variable impedance technology)
  - Use of technologies for relieving of voltage and transient stability constraints
  - Improved dynamics modeling with detailed technology characteristics
  - Scenario Development
  - Market design for independent entities with power flow control technologies
  - Usage of technologies for corrective control
  - Comparison with other technologies (e.g., topology control, HVDC)

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