NETSS

Operating beyond PV curves

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Main messages

- Impact of optimal voltage dispatch in today's practice:

  -PV curves better with voltage dispatch since maximum power transfer always higher

  -DC OPF accounts for voltage with PV curve limits; more efficient with voltage dispatch

  -Region-to-region PV curves in large systems "similar" to point-to-point PV curves

- Recommended future practice—Beyond PV curves *(***the issue: selection of interface limits***)*

  -Use AC OPF for the entire system without observing net interface limits; much more efficient with voltage dispatch

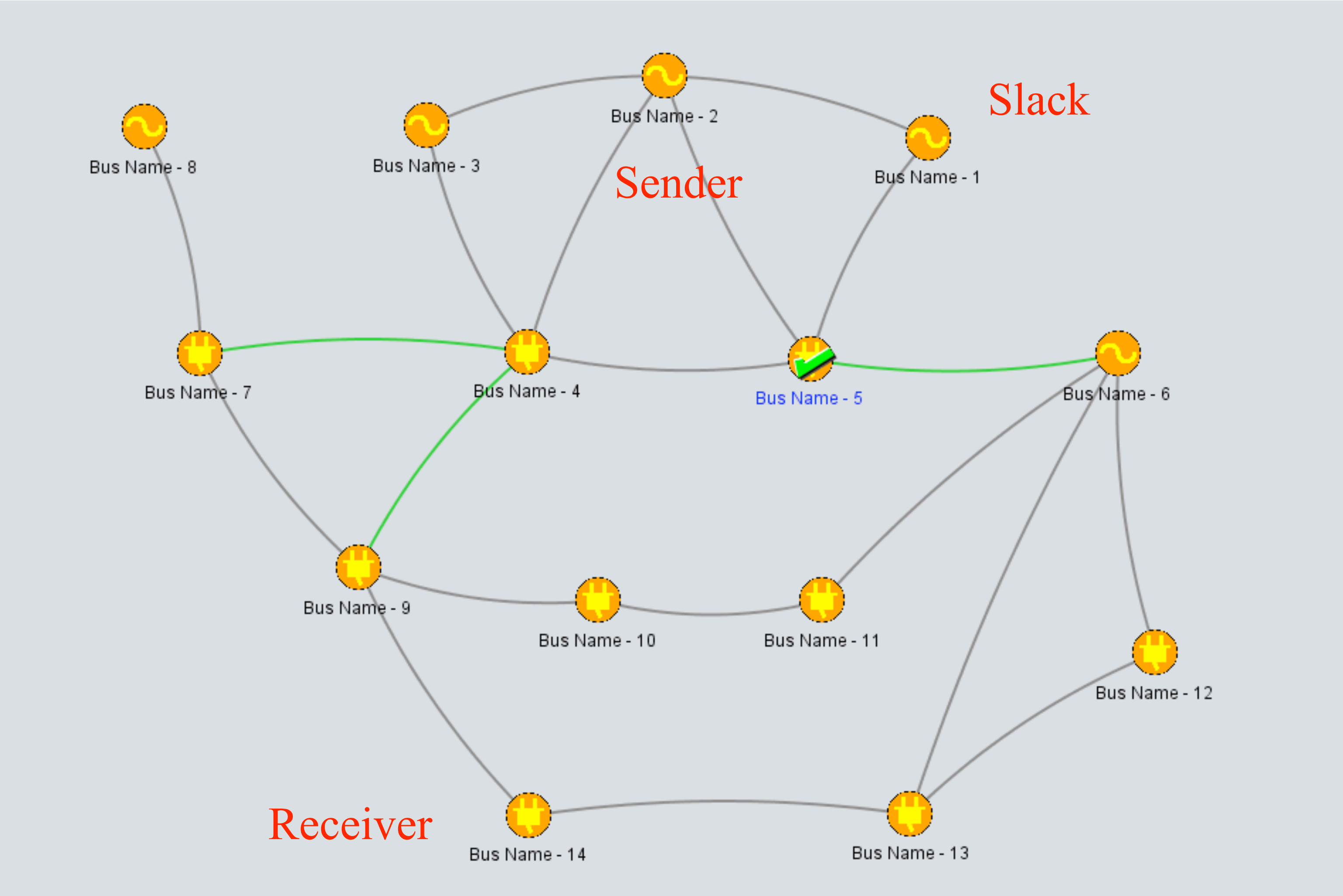
  -AC OPF enables both economic and physical efficiency

- Demonstration of extended AC OPF with voltage dispatch for systems up to 30,000 buses

Study systems

- IEEE 14 bus
- ERCOT planning case from August 2013 (6,355 buses)
- PJM operations case from November 2012 (13,940 buses)
- PJM planning case (34,171 buses obtained by truncating half of PJM FERC 715)

IEEE 14 bus system



Slack

Sender

Receiver

Set up for PV curve –IEEE 14 bus system

- Maximizing transfer from
  - Generator at bus 2 to load at bus 14
  - Bus 1 is slack
- PV curve is generated
  - Through incremental increase of load at bus 14 by 10% at each step (both P and Q of the load are scaled)
  - While real power output of generator at bus 2 is increased by the same amount (10% of Pl at bus 14) at each time step
- Voltage collapse happens when no feasible AC power flow solution is found

Constraints

- Thermal AC line limits are ignored
- Thermal transformer limits are ignored
- Generation Q limits are both ignored or observed in different scenarios
- No limits on real and reactive power of the slack generator

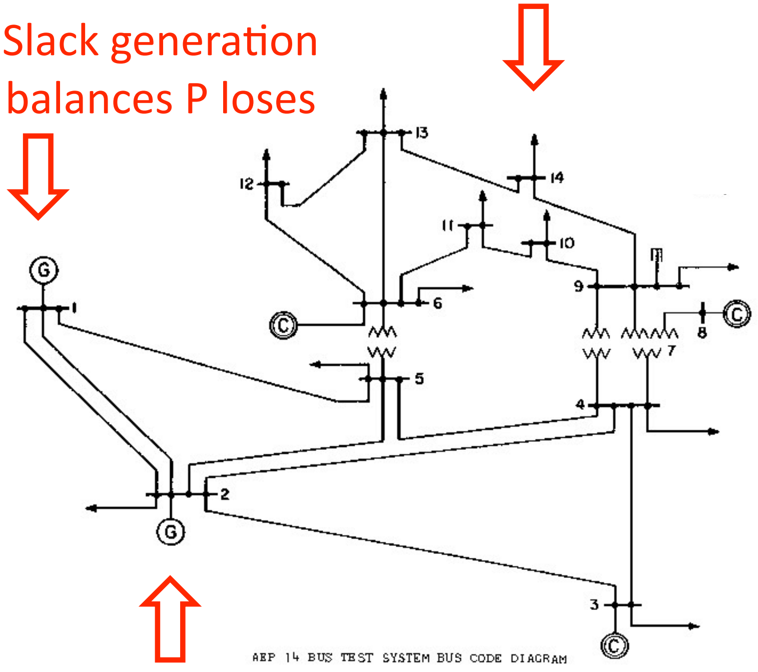
Types of PV curves

- Power flow PV curve
  - All set points of generators are fixed (P and V) *(current practice)*
- PV curve with voltage optimization
  - Voltage set points of generators are optimized
- PV curve with optimization of real power
  - Real power outputs of generators are optimized
- PV curve with optimization of both voltage and real power
  - Real power outputs and voltage set points of generators are optimized

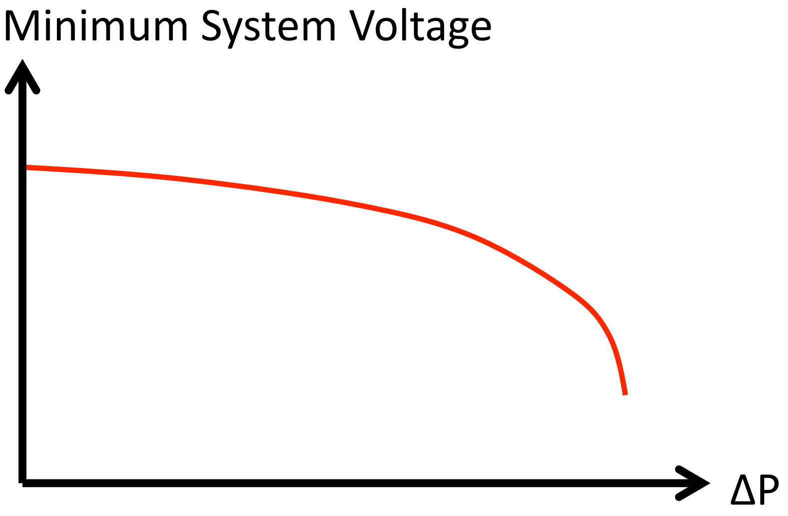
Creating PV Curve With Fixed Generator Voltages

Increase load by ΔP

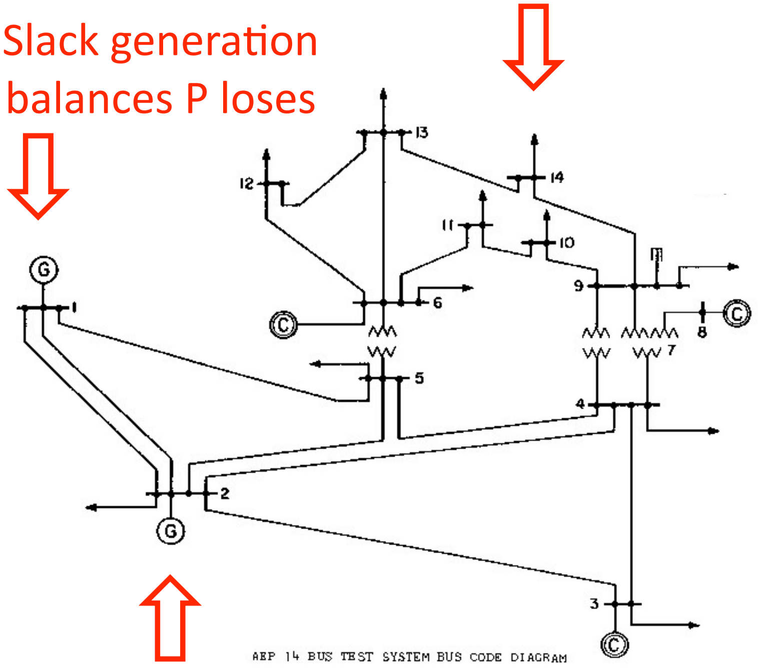
Slack generation balances P loses



Increase generation by ΔP



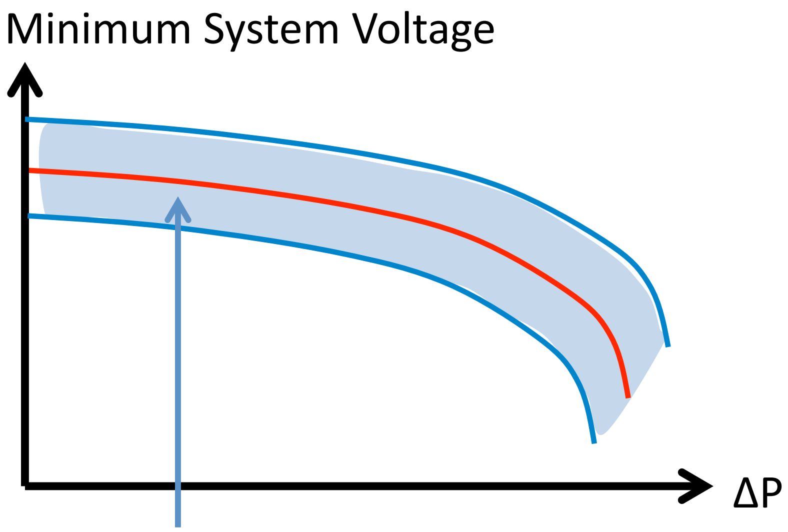
Creating PV Curve With Variable Generator Voltages



Increase load by ΔP

Slack generation balances P loses

Increase generation by ΔP



Varying V_G over $V_{GMin} \leq V_G \leq V_{GMax}$ yields a feasible band.

Select the V_G for each ΔP via optimization. For example, loss minimization will also tend to push the minimum system voltage higher and permit greater transfer.

Optimization Setup: All Fixed—Similar to current practice

- Optimization objective:
  - Loss minimization (feasible space is a single point)
  - Cost of all generators is $100/MWh
- Constraints:
  - Voltage magnitude limits are equal to
    - Generator set points at generator regulated buses
    - Vmin= 0.3pu, Vmax=2pu at all other buses
  - Real power generation limits are equal to
    - Real power generated (except for slack)
  - Reactive power generation limits are
    - Observed/Ignored in two different scenarios
  - All AC and transformer thermal limits are ignored
- For each point on PV curve this optimization is executed after increasing source generation by *X* MW and the sink load by *X* MW

Optimization Setup: Vg variable

- Optimization objective:
  - Loss minimization (tends to raise receiving voltages)
  - Cost of all generators is \$100/MWh
- Constraints:
  - Voltage magnitude limits are equal to
    - Vmin=0.9pu and Vmax=1.1pu at generator regulated buses
    - Vmin= 0.3pu, Vmax=2pu at all other buses
  - Real power generation limits are equal to
    - Real power generated (except for slack)
  - Reactive power generation limits are
    - Observed/Ignored in two different scenarios
  - All AC and transformer thermal limits are ignored
- For each point on PV curve this optimization is executed after increasing source generation by *X* MW and the sink load by *X* MW

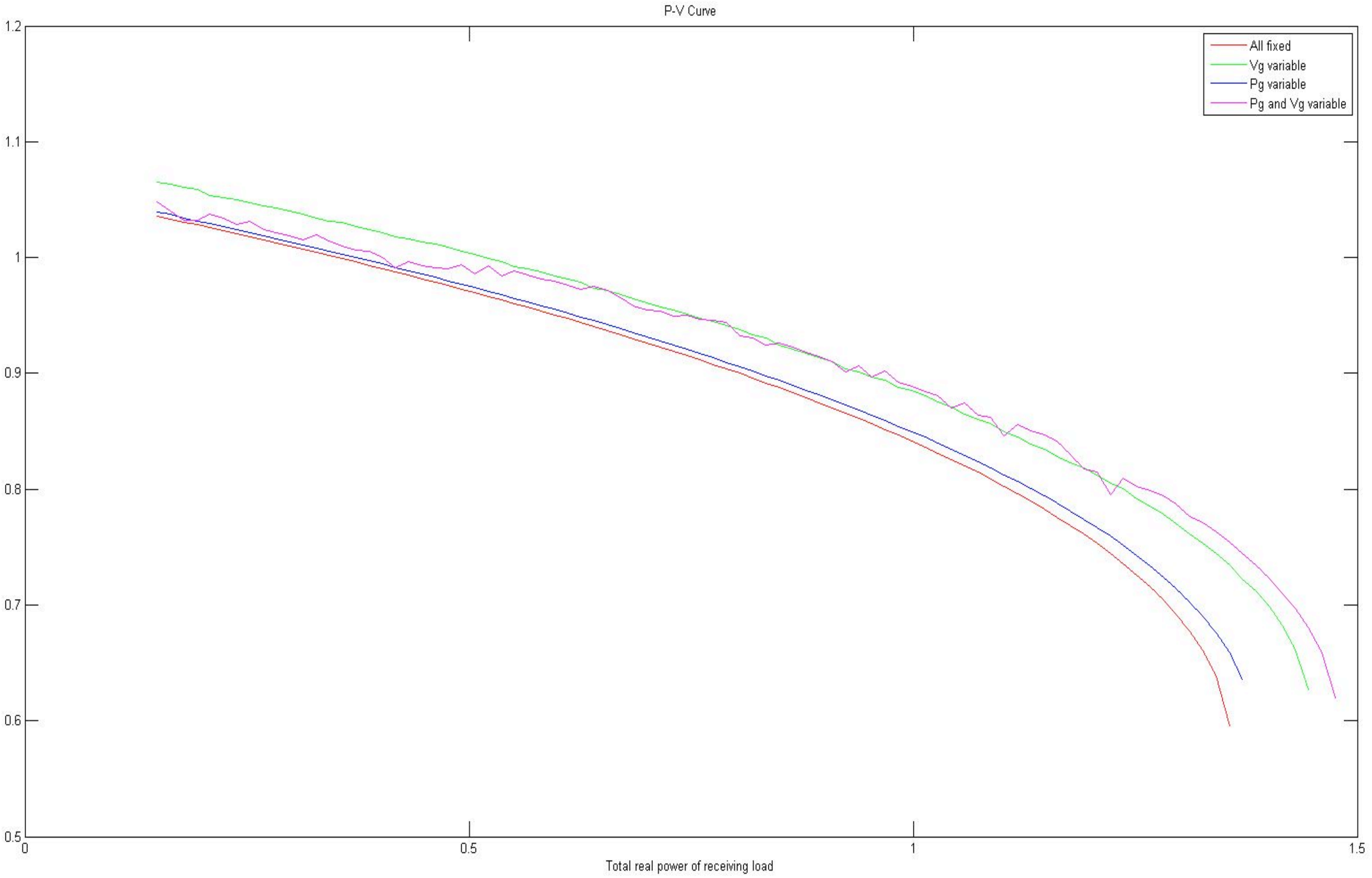
Optimization Setup: Pg variable

- Optimization objective:
  - Loss minimization
  - Cost of all generators is $100/MWh
- Constraints:
  - Voltage magnitude limits are equal to
    - Generator set points at generator regulated buses
    - Vmin= 0.3pu, Vmax=2pu at all other buses
  - Real power generation limits are equal to
    - Originally specified real power generation limits
  - Reactive power generation limits are
    - Observed/Ignored in two different scenarios
  - All AC and transformer thermal limits are ignored
- For each point on PV curve this optimization is executed after increasing source generation by *X* MW and the sink load by *X* MW

Optimization Setup: Pg and Vg variable

- Optimization objective:
  - Loss minimization
  - Cost of all generators is \$100/MWh
- Constraints:
  - Voltage magnitude limits are equal to
    - Vmin=0.9pu and Vmax=1.1pu at generator regulated buses
    - Vmin= 0.3pu, Vmax=2pu at all other buses
  - Real power generation limits are equal to
    - Originally specified real power generation limits
  - Reactive power generation limits are
    - Observed/Ignored in two different scenarios
  - All AC and transformer thermal limits are ignored
- For each point on PV curve this optimization is executed after increasing source generation by *X* MW and the sink load by *X* MW

IEEE 14 bus PV curves without Q limits



IEEE 14 bus-Dependence of DC OPF efficiency on PV-curves

Case	PV curve voltage dispatch	Int. Defn.	Voltages	PG 2 (MW); PL 14 (MW)	Line flows (MW)	Interface flow (MW)	DC OPF cost with PV curve ($/hour)	Power loss (MW)
1	No	2-3; 2-4; 2-5; 1-5	VL,14=.585; VG,1=1.06;VG,2=1.045; VG,3=1.01; VG,6=1.07; VG,8=1.09	PG,2=.3999; QG,2=2.61; PL,14=1.356; QL,14=.455	P2,1=-3.91; P2,3=.975; P2,4=.984; P2,5=.775	Pint,1=.399	$7650	0 MW
2	No	14-13; 14-9	VL,14=.585; VG,1=1.06;VG,2=1.045; VG,3=1.01; VG,6=1.07; VG,8=1.09	PG,2=.3999; QG,2=2.61 PL,14=1.356; QL,14=.455	P14,13=-.58; P14-9=-.775	Pint,2=1.356	$7650	0 MW
3	Yes	2-3; 2-4; 2-5; 1-5	VL,14=.606; VG,1=1.10;VG,2=1.10; VG,3=1.09; VG,6=1.10; VG,8=1.10	PG,2=.399; QG,2=2.848; PL,14=1.4485; QL,14=.4860	P2,1=-4.07; P2,3=1.016; P2,4=1.003; P2,5=.788	Pint,1=.399	$7650	0MW
4	Yes	14-13; 14-9	VL,14=.606; VG,1=1.10;VG,2=1.10; VG,3=1.09; VG,6=1.10; VG,8=1.10	PG,2=.399; QG,2=2.848; PL,14=1.4485; QL,14=.4860	P14,13=-.83; P14-9=-.616	Pint,2=1.448	$7650	0MW

New net load (PL,14=1.40; QL,14=.5)

- Could happen either because of load increase or loss of (coal) plant
- Thermal limits of lines 1
- DC OPF not feasible with V=1

IEEE 14 bus-Dependence of DC OPF efficiency on PV-curves (new load at 14)

Case	PV curve voltage dispatch	Int. Defn.	Voltages	PG 2 (MW); PL 14 (MW)	Line flows (MW)	Interface flow (MW)	DC OPF cost with PV curve ($/hour)	Power loss (MW)
1	No	2-3; 2-4; 2-5; 1-5	VL,14=.585; VG,1=1.06;VG,2=1.045; VG,3=1.01; VG,6=1.07; VG,8=1.09	PG,2=.3999; QG,2=2.61; PL,14=1.356; QL,14=.455	P2,1=-3.91; P2,3=.975; P2,4=.984; P2,5=.775	Pint,1=.399	Fails	
2	No	14-13; 14-9	VL,14=.585; VG,1=1.06;VG,2=1.045; VG,3=1.01; VG,6=1.07; VG,8=1.09	PG,2=.3999; QG,2=2.61 PL,14=1.356; QL,14=.455	P14,13=-.58; P14-9=-.775	Pint,2=1.356	Fails	
3	Yes	2-3; 2-4; 2-5; 1-5	VL,14=.606; VG,1=1.10;VG,2=1.10; VG,3=1.09; VG,6=1.10; VG,8=1.10	PG,2=.399; QG,2=2.848; PL,14=1.4485; QL,14=.4860	P2,1=-4.07; P2,3=1.016; P2,4=1.003; P2,5=.788	Pint,1=.399	Fails	
4	Yes	14-13; 14-9	VL,14=.606; VG,1=1.10;VG,2=1.10; VG,3=1.09; VG,6=1.10; VG,8=1.10	PG,2=.399; QG,2=2.848; PL,14=1.4485; QL,14=.4860	P14,13=-.83; P14-9=-.616	Pint,2=1.448	Fails	

Beyond PV curves--New load can be served with AC OPF!!!

- Voltages found which make the delivery feasible
- No load shedding required
- Critical in the future when plants retire and new come on
- AC OPF makes the system feasible by adjusting voltages!!!

Economic efficiency comparison of DC OPF with PV curve line limits and AC OPF

- The case of initial load.
- Generation cost appears to be lower with DC OPF
- Misleading because there are marginal costs associated with voltage limits and reactive power balancing
- Without enforcing these, the system is not physically implementable
- AC OPF more efficient with voltage dispatch (easy to show): cost = \$9911 with $V_g = 1.05$; cost = \$8126 with $V_g \leq 1.05$.
- Must have market for AC OPF

ERCOT PV CURVE SETUP

Optimization Setup: All Fixed

- Optimization objective:
  - Loss minimization
  - Cost of all generators is $100/MWh
- Constraints:
  - Voltage magnitude limits are equal to
    - Generator set points at generator regulated buses
    - Vmin= 0.3pu, Vmax=2pu at all other buses
  - Real power generation limits are equal to
    - Real power generated (except for slack buses: 5920, 6103, 86101, 110015)
  - Reactive power generation limits are observed
  - All AC and transformer thermal limits are ignored
  - All transformers and shunts are fixed
- For each point on PV curve this optimization is executed after increasing
  - source generation (wind in the west)by *200* MW proportional to capacity of each generator
  - the sink (NCEN) loads by *200* MW evenly across loads

Optimization Setup: Vg variable

- Optimization objective:
  - Loss minimization
  - Cost of all generators is $100/MWh
- Constraints:
  - Voltage magnitude limits are equal to
    - Vmin=0.95pu and Vmax=1.05pu at generator regulated buses
    - Vmin= 0.3pu, Vmax=2pu at all other buses
  - Real power generation limits are equal to
    - Real power generated (except for slack buses: 5920, 6103, 86101, 110015)
  - Reactive power generation limits are observed
  - All AC and transformer thermal limits are ignored
  - All transformers and shunts are fixed
- For each point on PV curve this optimization is executed after increasing
  - source generation (wind in the west)by *200* MW proportional to capacity of each generator
  - the sink (NCEN) loads by *200* MW evenly across loads

Optimization Setup: Pg variable

- Optimization objective:
  - Loss minimization
  - Cost of all generators is $100/MWh
- Constraints:
  - Voltage magnitude limits are equal to
    - Generator set points at generator regulated buses
    - Vmin= 0.3pu, Vmax=2pu at all other buses
  - Real power generation limits are equal to
    - Originally specified real power generation limits
  - Reactive power generation limits are observed
  - All AC and transformer thermal limits are ignored
  - All transformers and shunts are fixed
- For each point on PV curve this optimization is executed after increasing
  - source generation (wind in the west)by *200* MW distributed in proportion to capacity of each generator
  - the sink (NCEN) loads by *200* MW evenly across loads

Optimization Setup: Pg and Vg variable

- Optimization objective:
  - Loss minimization
  - Cost of all generators is $100/MWh
- Constraints:
  - Voltage magnitude limits are equal to
    - Vmin=0.95pu and Vmax=1.05pu at generator regulated buses
    - Vmin= 0.3pu, Vmax=2pu at all other buses
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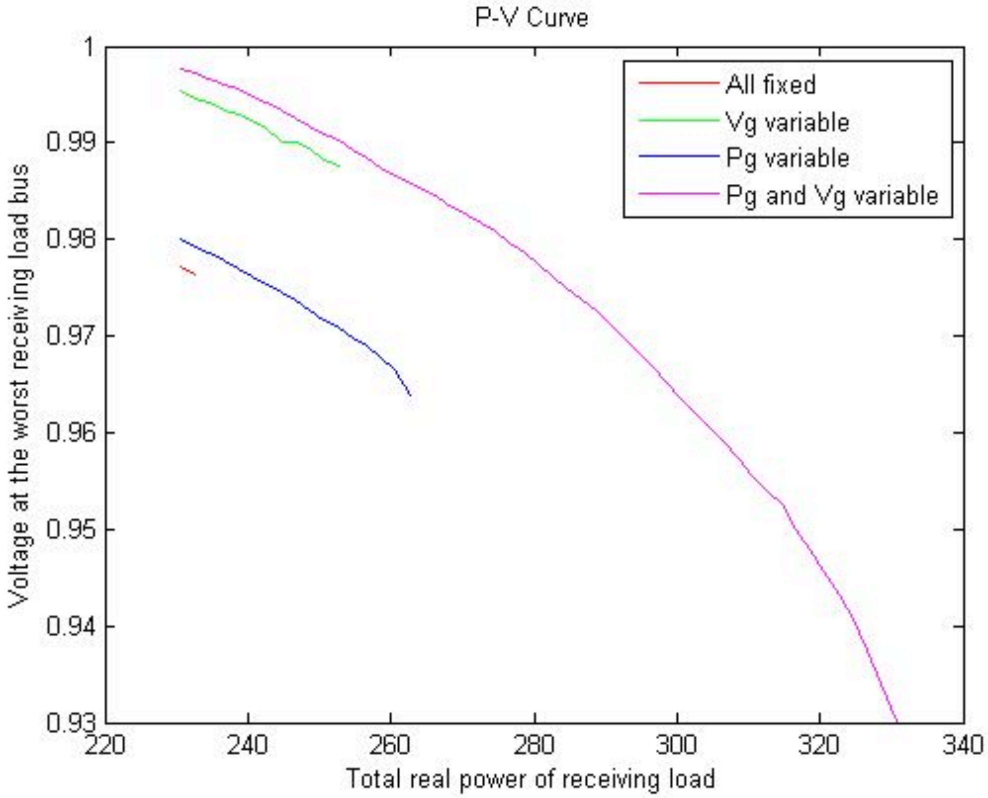
- For each point on PV curve this optimization is executed after increasing
  - source generation (wind in the west)by *200* MW distributed in proportion to capacity of each generator
  - the sink (NCEN) loads by *200* MW evenly across loads

ERCOT PV curves with Qg limits



PJM OPS case EAST Interface

Case	PJM voltage limits	Generator Voltage dispatch	Contingency	Received load (MW)	Interface Flow (MW)
Base	N/A		None	10,584 (+0)	1,309
1	Normal	Yes	None	16,766 (+6,182)	4,881
2	Emergency	Yes	None	17,626 (+7,042)	5,369
3	Emergency	Yes	ALBURTIS-JUANITA	17,368 (+6,784)	4,628
4	Emergency	Yes	ALBURTIS-WESCOSVI	17,617 (+7,035)	4,744
5	Emergency	Yes	PEACHBOT-LIMERICK	16,931 (+6,347)	3,645
6	Normal	No	None	11,467 (+883)	1,730

Economic Dispatch for PJM

Voltages	Generation Cost [$]	Generator Revenue [$]	Load Charge [$]	Merchandise Surplus [$]	PJM Losses [MW]
Base	2,560,232				1113
Fixed	2,455,262	4,587,644	3,656,729	-930,915	1105
Variable	2,292,642	3,512,257	3,242,615	-269,642	991

(\$2,455,262 - \$2,292,642) * 24 * 365 ≈ \$ 1.4 B value of voltage dispatch in PJM

- PJM OPS case from 20 November 2010 at 10 AM
- Voltages maintained within normal operating limits
- Flows maintained within normal operating thermal limits
- Zonal LMPs within PJM used as the generation bids within the corresponding zones
  - LMPs taken from the corresponding date and time
  - 34.51 \$/MW-Hr $\le$ Bid $\le$ 48.15 \$/MW-Hr (approximately the fuel cost of coal)

Loss minimization for PJM

PJM Voltages	Load [MW]	Loss [MW]	Loss/Load [%]	Savings [MW-Hr/Yr]
Base	62167	1113	1.79	
Fixed	62167	1098	1.77	131400
Variable	62167	1047	1.68	578160

- PJM OPS case from 20 November 2010 at 10 AM
- Voltages maintained within normal operating limits
- Flows maintained within normal operating thermal limits
- PJM generator real power (and voltage) dispatched to minimize losses

PJM estimates that they save 220,000 MW-Hr/year for a savings of $17M.

Interface Transfer Study Using PJM Planning Case

Case	PJM VG	External VG	PJM Bus Voltage Limits	Total Sink Load [MW]	Increase [MW]
Base				23524	0
1	Fixed	Fixed	Not Used	23665	141
2	Fixed	Variable	Not Used	23978	454
3	Variable	Fixed	Not Used	25444	1920
4	Variable	Fixed	Normal	24581	1057
5	Variable	Variable	Normal	27439	3915

- Study PJM EAST Interface
  - Optimization objective is to increase the net load in the receiving region
  - Power increase is supplied only by generators in the sending region
  - Examine importance of voltage dispatch; voltage limited only as specified
  - Thermal flow limits are ignored
- PJM (FERC-715) planning case for 2017 truncated to 34171 buses

Electricity Prices With Fixed VG in PJM

Electricity Prices With Variable VG in PJM

Prices in $ / 100 MW-Hr

Conclusions

- Voltage dispatch plays major role in both physical delivery (feasibility and efficiency) and in economic efficiency
- Often variable voltage more valuable than line
- Prices less volatile with variable voltage dispatch
- Planning case closer to non-feasible condition than operations cases (higher loading conditions, less room for transfer increase)
- Market incentives are needed to reap benefits from voltage dispatch