Power Flow Control Solutions for the Bonneville Power Administration (BPA) Transmission System

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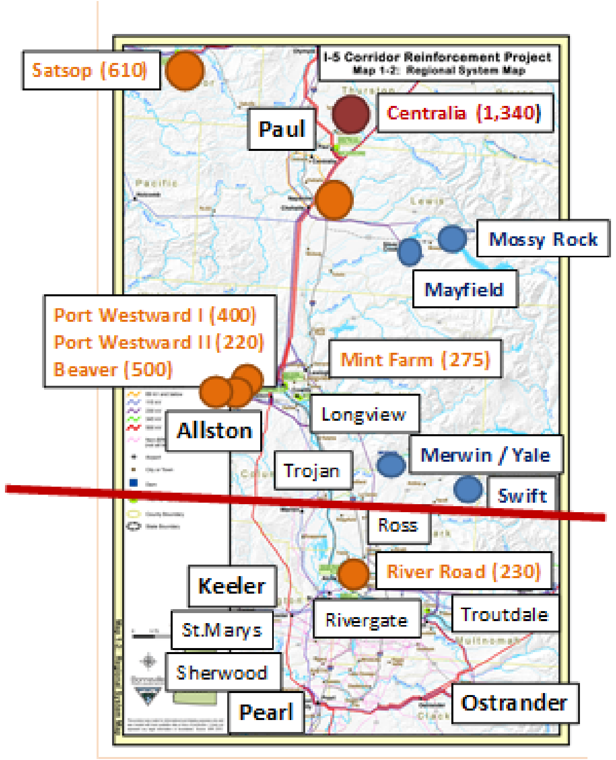
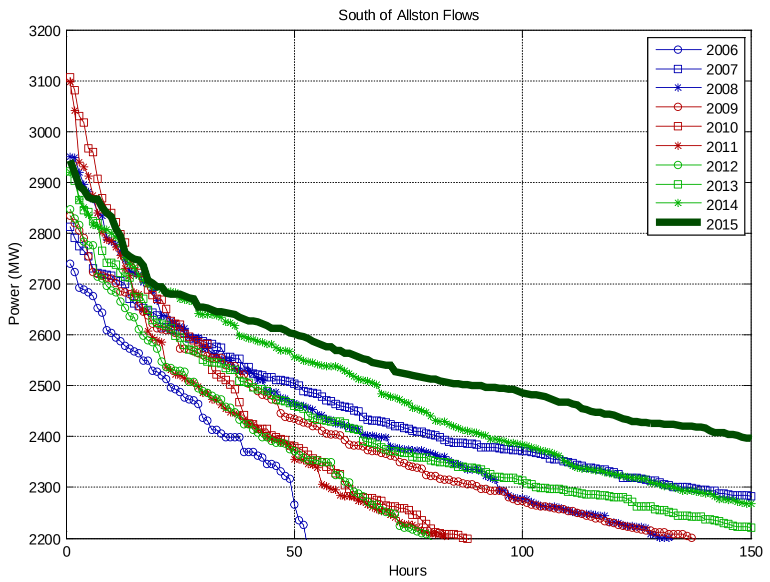
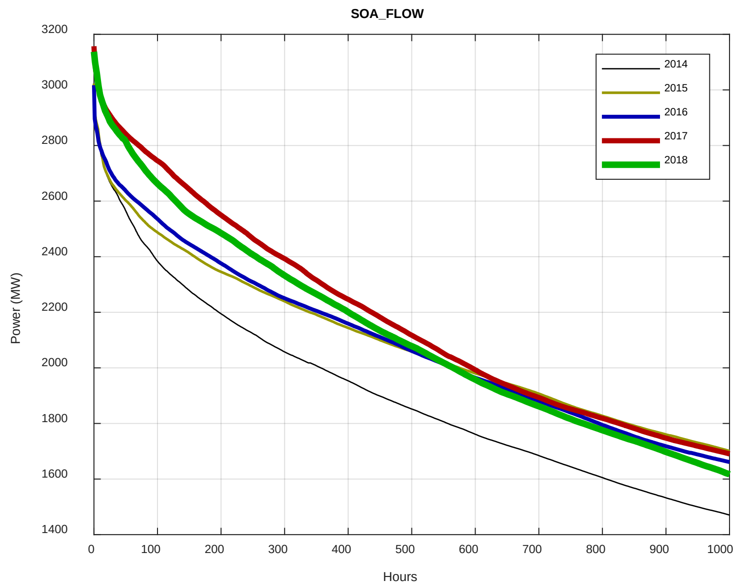
Motivation/Background

Power flow challenges at BPA's transmission grid: Loading of South of Allston (SOA) path







- SOA path has become highly congested during summer months due several reasons:
  - Increasing loads in the Portland, Oregon - Vancouver, WA metropolitan area
  - High North to South exports to California during sunset hours
  - Combination of both high loads and through transfers

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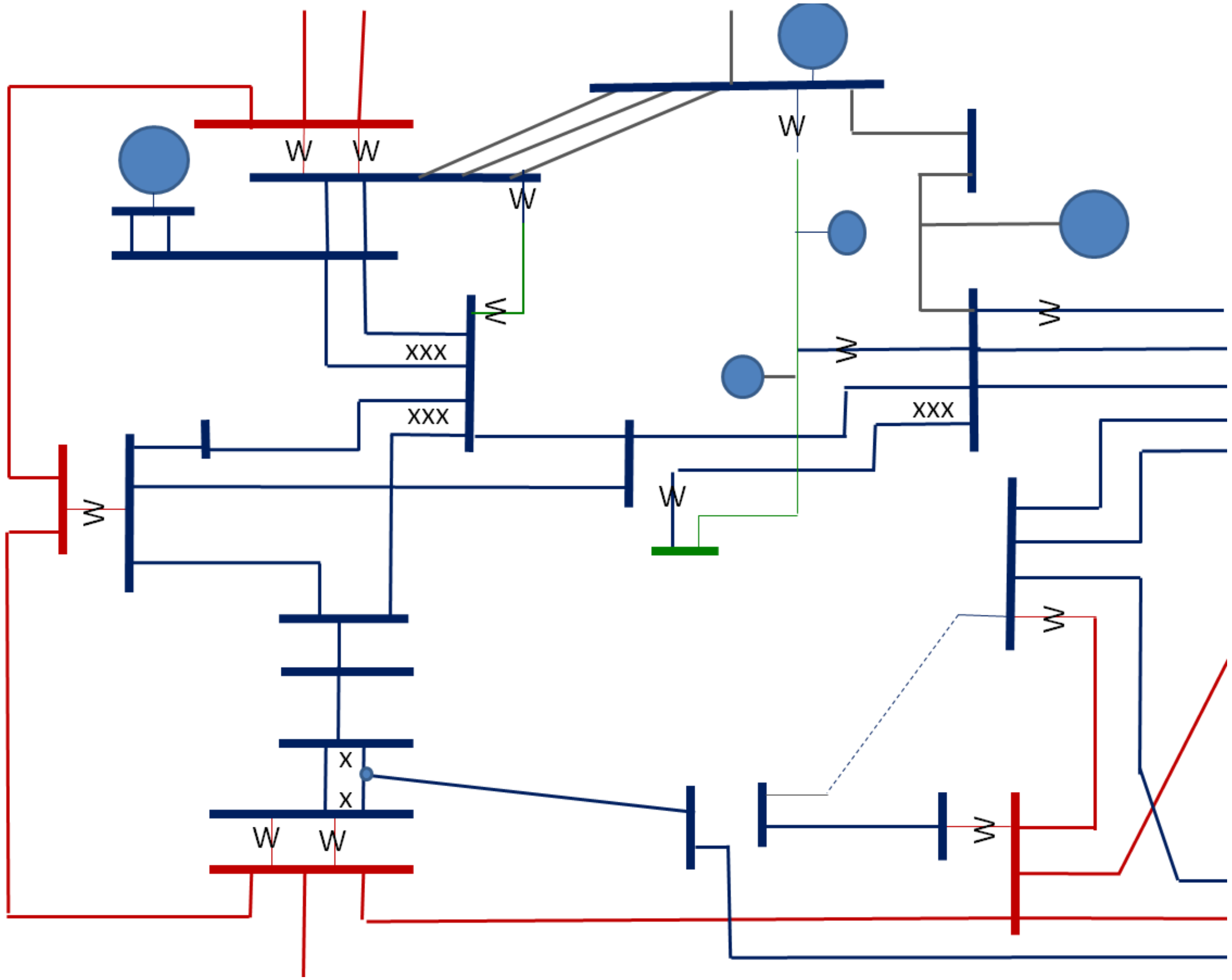
Conceptual representation of transmission system



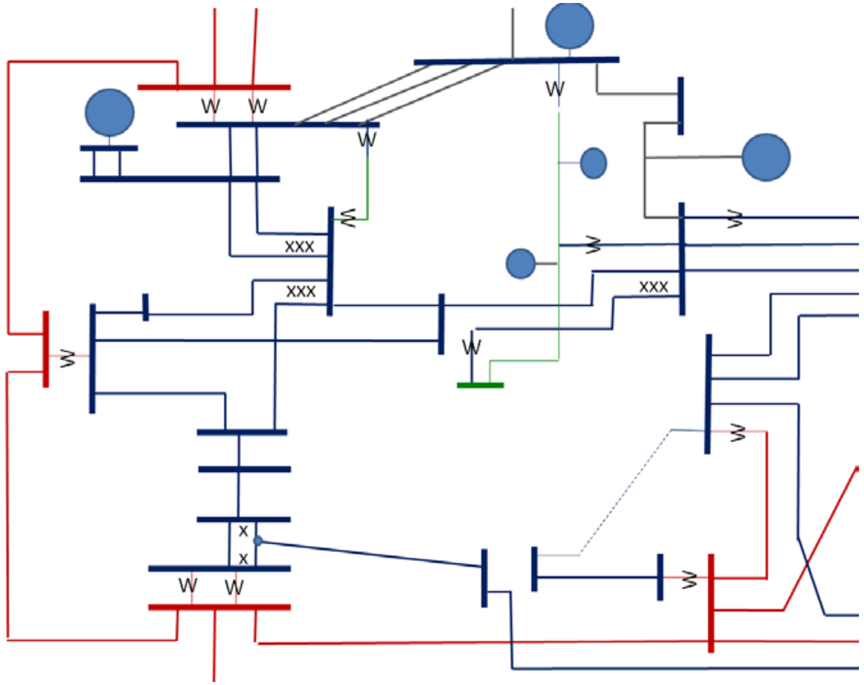
- Transmission capacity of SOA path is highly dependent on outages in the vicinity
  - Primary outage of 500kV transmission line followed by 230kV secondary outage

Study Objective and Approach

- **Objective**
  - Evaluate the use of power flow control technologies as alternatives to relieve congestion

- **General Approach**
  - Identify and characterize the power flow control issues and challenges in the BPA transmission system:
    - transmission paths that are at risk to reach, or exceed, the operating limits
  - Develop a methodology to evaluate and design PFC-based solutions:
    - systematic approach to identify the location and ratings of PFC devices
    - guideline for planning and pre-specification studies, not for detailed engineering design of the solutions
  - Evaluate PFC options
  - Provide conclusions and recommendations

Power flow issues



Scenarios considered in the analysis

			N-1-1		N-1 adj	N-1			Base High	N-1-1		N-1 adj	N-1			Base Med	N-1-1		N-1 adj	N-1			Base Low
Line #	**To kV**	**MVA or Amp**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
1	230kV	599.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2	230kV	630.1	1.0	1.0	1.0	1.0	1.0	0.9	0.9	1.0	1.0	1.0	1.0	1.0	1.0	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0
3	115kV	50.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
4	115kV	850.0	1.0	1.0	0.9	1.1	1.0	1.1	0.8	1.0	1.0	0.9	1.1	1.0	1.0	0.8	0.9	0.9	0.8	1.0	0.9	1.0	0.7
5	115kV	322.0	0.8	1.0	0.9	1.0	0.9	0.9	0.7	0.9	1.0	0.9	1.0	0.9	1.0	0.8	0.8	0.9	0.8	0.9	0.9	1.0	0.8
6	230kV	1070.1	0.1	1.0	0.9	1.1	1.0	1.0	0.7	0.4	1.2	1.0	1.2	1.1	1.2	0.9	0.4	1.0	0.9	1.1	1.1	1.2	0.9
7	230kV	1300.0	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
8	230kV	1498.6	1.0	0.0	0.9	1.1	1.1	0.0	0.8	1.0	0.0	0.8	1.1	1.0	0.0	0.8	0.8	0.0	0.7	1.0	1.0	0.0	0.8
9	230kV	1498.6	1.0	1.2	0.9	1.1	1.1	0.0	0.8	1.0	1.2	0.8	1.1	1.0	0.0	0.8	0.8	1.0	0.7	1.0	1.0	0.0	0.8
10	115kV	850.0	1.0	1.0	0.8	1.0	1.0	1.0	0.7	0.9	1.0	0.8	1.0	1.0	1.0	0.7	0.9	0.9	0.7	0.9	0.9	1.0	0.7
11	115kV	850.0	1.0	1.0	0.9	1.1	1.0	1.0	0.7	1.0	1.0	0.8	1.1	1.0	1.0	0.7	0.9	0.9	0.8	1.0	0.9	1.0	0.7
12	115kV	599.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.8

- Scenarios: critical contingencies and operating conditions that have historically been known to impact the limits on the SOA path

Power Flow Control Technologies Considered

Phase-shifting transformer (PST)

Series Reactor

Smart Wires

(as an alternative to series reactors – not fully evaluated)

Methodology

- Planning process:
  - Identify potential location, size and rating of PSTs
  - Combine with other solutions: transmission line upgrade, series reactor
- Prerequisites:
  - PSTs preferably controlled pre-contingency
  - The number of PSTs should be the least possible
  - Preferably the PSTs will be located in lower voltage and lower rating lines, to reduce their cost
  - Solution selected by total cost and technical feasibility

Linear Optimization model

$$Min\ F = \sum_{j=1}^{nPST} w_j\ C_j(|\emptyset_j|)$$

Subject to

$$S_{ij}^k \cdot \Delta\varphi_{ik} + \cdots + S_{i\,nPST}^k \cdot \Delta\varphi_{inPST} + Pini_i^k < P_i^{max}\ \ \forall\, i\ \in nML\ monitored\ lines, \text{ for } 1\ \le k\ \le NC$$

$$|\Delta\varphi_{ik}|\ < |\emptyset_j|$$

$$|\Delta\varphi_{ik}|\ = |\Delta\varphi_{ip}|\ \ \text{force common settings for multiple cases}$$

$$\emptyset_k <\ \emptyset_k^{max}$$

Where

- F: total investment cost [M$]
- C_j: cost coefficient (cost vs. max shift angle)
- w_j: weighting factor
- Decision variables $\emptyset_j$: max/min phase angle shift
- φ_{ik}: shift angle of PST *i* for case k
- $Pini_i^k$: Initial flow on line *i* corresponding to case *k*
- *nPST*: number of candidate PST locations
- *NC:* number of operating and contingency cases considered in the analysis
- $S_{ij}^k = \frac{P_i^k - Pini_i^k}{\Delta\,\emptyset_j}$: sensitivity of active power flow on monitored line *i* with respect to variation of phase shift angle of PST *j*

Input:

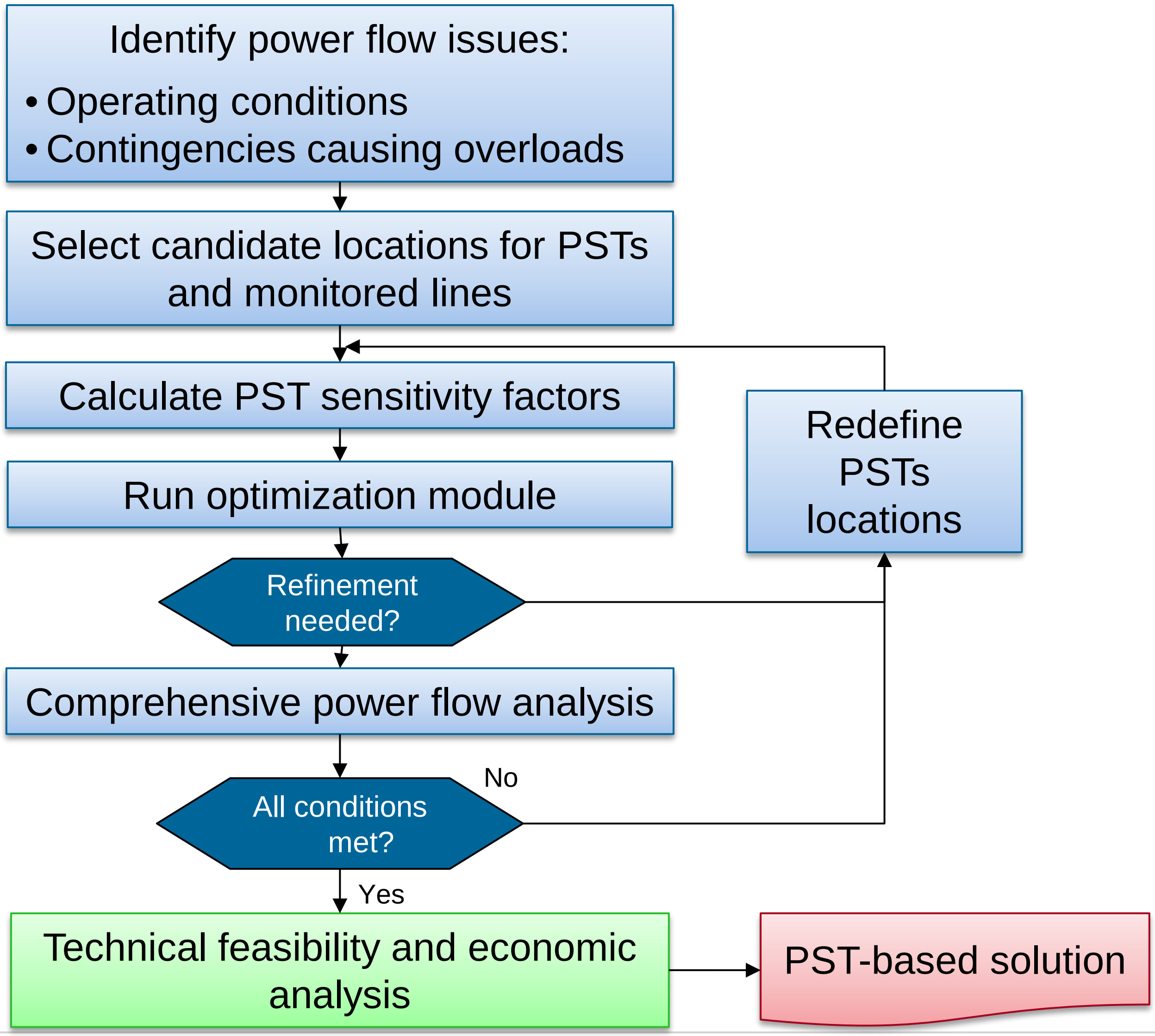
- Candidate lines for PST location
- Sensitivity matrix
- Vector of initial flow Pini
- Vector Pmax

Output:

- Max shift angle of PSTs
- Total cost
- Shift angle of each PST for each case

Methodology

Planning and pre-specification studies



Engineering studies

- Design and specification
- Technical studies
- Design of the Special Protection Scheme:
  - Define SPS components and architecture
  - Design of the control logic
  - Studies for validating and refine the initial design
  - Reliability analysis of the SPS

Case characteristics and results

- 21 scenarios
- 16 candidate locations for PSTs
- 90 monitored lines
- Large set of possible solutions evaluated
- Two sets of PSTs angle settings needed in any of the alternatives

			Alt 1	Alt 2	Alt 3	Alt 4
Upgrade 230 kV line			Y	N	Y	Y
PST#	**kV**	**Rate [MVA]**	Min/Max Shift Angle	Min/Max Shift Angle	Min/Max Shift Angle	Min/Max Shift Angle
1	500 kV	2800	0/-15°	0/-15°		
2	500 kV	2800		0/-15°		
5	230 kV	700			8/-8°	8/-8°
6	230 kV	700			8/-8°	8/-8°
7	230 kV	430				
8	230 kV	740	0/-35°	0/-40°		
9	345 kV	760			8/-26°	8/-26°
14	115 kV	170			Reactor 7 Ω/ph	5/-5°

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Conclusions and Next Steps

- A systematic approach to identify options and determine the location, rating and controls requirement for PFC devices was developed and implemented
- Based on this methodology, the most practical solution is one that combines three PSTs with one series reactor, plus the upgrade of a 230kV line
- Next steps:
  – Leverage these analyses to conduct further studies internally at BPA

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