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Power Flow Control Solutions for the Bonneville Power Administration Transmission System

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SUMMARY

This paper discusses a study conducted by EPRI and the Bonneville Power Administration (BPA) to identify and design power flow control solutions to mitigate overloads in the BPA's transmission network. Power flow control (PFC) technologies were considered as potential alternative for relieving congestion along a major transmission corridor as opposed to building new transmission infrastructure. The study covered most of the facets involved in scoping out a project for application in the transmission system including, location of power flow controllers, size and ratings, flexibility for various contingency conditions, and associated control requirements. The issues of concern were mainly associated with transmission paths that are at risk to reach, or exceed, the operating limits under various operating conditions. For this purpose, information and power flow scenarios representing critical system conditions were identified in the first part of the case study. A methodology to evaluate and design PFC devices with minimum investment cost was then devised. The developed methodology includes a linear optimization model that uses linear phase shift sensitivity factors to find the optimal location and capacity of phase-shifting transformers. The sensitivity factors are evaluated using a full ac power flow solution in a commercially available positive sequence power flow solver, General Electric (GE) – PSLF™, while the optimization model was scripted in Matlab. The developed methodology is intended to provide a guideline for planning and pre-specification studies, but not for detailed engineering design of the solutions.

KEYWORDS

Transmission, congestion, phase shift sensitivity, power flow controllers, optimization

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INTRODUCTION

Power flow control (PFC) technologies such as phase-shifting transformers, series reactors, and FACTS devices can be used in some cases to divert power flow from heavily loaded lines to other lines with spare capacity, increasing the utilization of existing transmission assets and, consequently, reducing the potential need for transmission upgrades. The Bonneville Power Administration (BPA) is interested in evaluating various PFC technologies as a potential alternative for relieving congestion in their transmission system. For that purpose, the Electric Power System Institute (EPRI) along with BPA's guidance performed a study to identify possible solutions using PFC devices. A systematic methodology was developed in the approach to identifying and evaluating available PFC devices, their locations, sizes and ratings, and associated controls requirements. In the following sections, a general background and motivation for this study will be presented, followed by a detailed discussion on the devised methodology. Subsequently, results and concluding remarks will be provided.

BACKGROUND AND MOTIVATION

The transmission system in BPA's footprint moves most of the Pacific Northwest's high voltage power from generation facilities to customers. Apart from the system in the Northwest, large interregional transmission lines connect BPA's system to the systems of Canada, California, the Southwest, Idaho, and eastern Montana (forming a large portion of the Western Electricity Coordinating Council Interconnection). The Portland, Oregon-Vancouver, Washington metropolitan area is the major electric load center in northwest Oregon and southwest Washington, with high concentrations of residential, commercial, and industrial loads. Various generating resources which serve the load centers include hydroelectric dams on the Columbia River and other rivers west of the Cascade Mountains along the Interstate-5 (I-5) corridor, thermal plants along the I-5 corridor west of the Cascades, and wind turbines east of the Cascades in Washington and Oregon. In addition, there are hydroelectric resources in Canada which contribute to through flows in this area to serve load south of this metro area. Power from these generating resources flows to the metro area and beyond through high voltage transmission lines. The high voltage lines that enter the metro area from the north are together known as the South of Allston (SOA) path, as shown in Figure 1 [1].

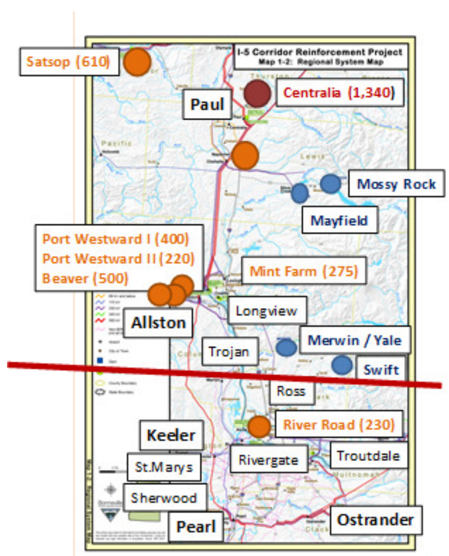

Figure 1: South of Allston transmission path

Studies performed by BPA and historic performance have shown that SOA path can become highly congested due to several reasons; continually increasing loads in the metro area, high

N-S exports to California, and a combination of both high loads and transfers. Figure 2 shows how the utilization of the SOA corridor has increased in the last decade, with significant rise in 2015. The studies concluded that the SOA path has become congested during the summer months mainly because of growing summer peak loads, and new power plants that have interconnected to BPA's transmission system north of the path, and, to a lesser extent, power transfers from the North to load centers south of the metro area. Congestion of the SOA path is expected to become even more critical in the near future.

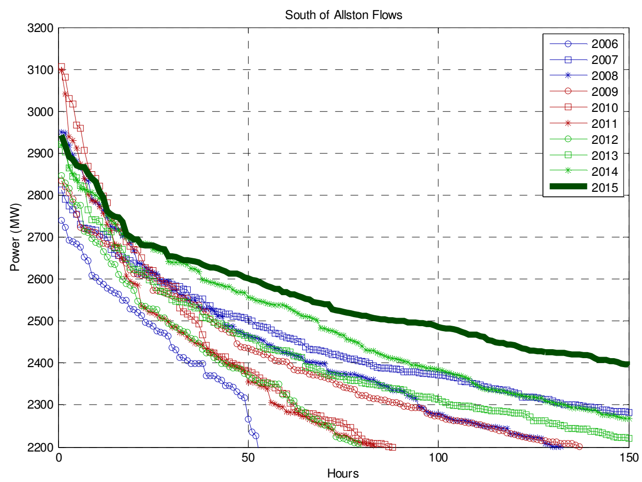

Figure 2: SOA utilization over the years

The transmission capacity of the SOA path is highly dependent on line outages, as can be observed in Table 1. The outage of a 500kV transmission line in the vicinity severely stress the 230kV network fed from nearby substations. Under such conditions, a second outage of transmission line in the affected network can lead to overloads. BPA has implemented remedial action scheme (RAS) to protect the transmission network in those events. If such an outage occurs, the RAS is activated and rapidly disconnects (or "drops") selected generation in the Northwest and Canada to reduce the flow of power and avoid overloading the lines that remain in service.

Table 1: Operating limits of the SOA paths**

Condition	Path Limits
All lines in service	2,770 to 3,200 MW
Lower voltage "significant" lines or transformers	2,010 to 3,200 MW
500-kV line outage	1,050 to 1,680 MW*

*For worst 500kV outage
** Based on 2017 Summer

Although the RAS is effective in these situations, its use may have undesirable consequences if higher levels of RAS are needed. Certainly, if the amount of generation dropped is too large, it may be difficult to find and deliver replacement generation. Even if replacement power is available, it may be difficult to deliver due to constraints on the alternate paths. In such cases the only alternative is load curtailment, which will severely impact system reliability, especially in the metro area. For that reason, BPA is interested in alternatives solutions, such as power flow control technologies – to mitigate power flow issues without degrading system reliability and quality of service.

STUDY APPROACH

The first step was to identify and characterize the power flow control issues and challenges in the BPA transmission system. The issues of concern were mainly associated with transmission paths that are at risk to reach, or exceed, the operating limits under certain operating conditions. As the next step, EPRI developed a methodology to evaluate and design PFC-based solutions. The methodology is intended to provide a systematic approach to identify the location and ratings of PFC devices to solve the power flow problems identified, with the minimum investment cost possible. Various possible technical solutions were identified applying the proposed methodology, which also considers potential operational challenges and general control requirements.

OPERATING CONDITION AND SCENARIOS USED IN THE STUDY

Twenty one operations scenarios on the 2030 Heavy Summer case were used as a basis for this analysis. These scenarios encompassed critical contingencies and operating conditions that have historically been known to impact the limits on the SOA path. The scenarios encompassed N-1 as well as N-1-1 contingency cases, and varying dispatch levels of PacificCorp's 510 MW Lewis River hydroelectric facilities [2]. Cases 1-7 are cases with high hydro generation, cases 8 to 14 with medium generation, and cases 15 to 21 are with low hydro generation levels. For each of those sets, there are one base N-0 scenario (cases 7, 14 and 21), three N-1 scenarios, one N-1 scenario with post-fault adjustments, and two N-1-1 scenarios, as shown in the Table 2. This table shows the overloads observed in each of these scenarios. The values in the tables are branch loading in per unit of the branch rating.

Table 2 : Overload in the operations scenarios

			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

POWER FLOW CONTROL TECHNOLOGIES – PHASE SHIFTING TRANSFORMER

Power flow controlling (PFC) devices have been a well-known technology for quite some time. Traditional technology solutions to control power flow—such as phase-shifting transformers (PST)—have been extensively used for reducing loop flows or to maintain scheduled power flow on certain paths. They have also been used in some cases to reduce overloads by diverting power flow from heavily loaded lines to other lines with spare capacity, increasing the utilization of existing transmission assets and, consequently, reducing the need for certain transmission upgrades [3]-[8]. In this study, PSTs are considered as the main option for power flow control. Solutions that combined PSTs with series reactors, or new technologies such as distributed series reactors (Smart Wires devices) have also been considered [9][10]. PST is a well-known technology, and will not be described in this paper.

Interested readers can refer to references [5][6][7] for background information about this technology.

METHODOLOGY TO DESIGN PFC SOLUTIONS

In general terms, the problem of defining a PST-based solution for specific power flow transmission issues consists in identifying the least-cost alternative that satisfies all operating constraints. In this particular case, the specific objective and basic assumptions for the analysis are as follows:

- Identify the best location, size and rating of PSTs to solve all the transmission constraints identified in the first part of the study
- The number of PSTs should be as low as possible
- Preferably the PSTs will be located in lower voltage, and lower rating lines, to reduce their cost
- The PSTs will operate in preventive (pre-contingency) mode to the extent possible, however, post-contingency control can be considered as well, if it is necessary to optimize the solution. In any case, the number of different control settings (shift angle) to cover all the operating and contingencies conditions considered should be as low as possible.

The analysis to identify the proper PST alternatives is done in most practical cases based on power-flow calculations at many grid operating points for several considered PST candidates [11]. Nevertheless, finding a solution with multiple PSTs that satisfy all the stated requirements by means of trial and error and manual inspection process is a very difficult task. In a highly-meshed network, a PST will impact the power flow of not only the lines intended to be controlled but also on other lines. Moreover, various PSTs can adversely interact with each other if their control is not properly coordinated. Therefore, an analytical approach is needed to find a feasible solution.

Various methodologies for control and operation of PSTs are based on sensitivity analysis, considering the sensitivity of power flow with respect to PST shift angle. In [15] such sensitivity is denoted as Phase Shifter Distribution Factor (PSDF), which indicates the influence of a PST on the active power flow on a certain line. In [16][16] PSDFs are used to derive analytical expressions to investigate how PSTs must be controlled to make optimal use of the transmission capacity. Numerical examples of generic as well as actual power system models are provided to illustrate how the PSTs can be controlled to improve the total transmission capability of selected corridors. An analysis presented in reference [17] shows that a comparison of power flow obtained from the linearized model and a full power ac power flow model reveals discrepancies no larger than 0.2 MW on the line flow. To further demonstrate this statement, Figure 3 shows the variation of active power flow at various selected lines in the BPA network, with respect to the phase angle changes of a PST located on a 230kV line. The analysis has been done with full ac power flow. The figure shows shift angle variation for a limited range due to space limitations. However, the analysis reveals that the linearity holds for phase angle, up to 40-45°.

Some researchers use this linear control characteristic to derive methods to locate PSTs. In reference [18] the concept of power controller plane is introduced. The controller plane describes the working area of the PC graphically in one plot showing all possible steady-state operating points of the device for all possible grid configurations and load cases. It is intended to simplify the analysis of contingencies and facilitates the design of PFCs. The concept is expanded in [19] to develop a new methodology for preliminary design of power controllers in the electric power grid. In this work, a linear optimization model that uses PST sensitivity factors is proposed to find the location and size of PSTs.

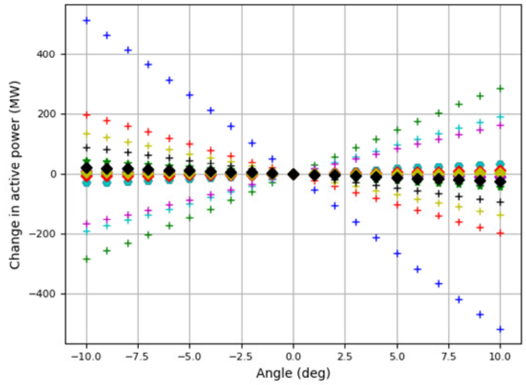

Figure 3: Power flow change at various lines as a function of phase angle of a PST located on one line

Optimization model

The optimization developed in this project is as follows:

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

Subject to

$$S_{ij}^k \cdot \varphi_{ik} + \cdots + S_{inPST}^k \cdot \varphi_{inPST} + Pini_i^k < P_i^{max}\ \forall i \in nML, \text{ for } 1 \le k \le NC \qquad \text{Eq.(2)}$$

$$|\varphi_{ik}| < |\emptyset_j| \qquad \text{Eq.(3)}$$

$$|\varphi_{iq}| = |\varphi_{ip}|\ \forall q\ \forall p \in Q \qquad \text{Eq.(4)}$$

$$\emptyset_k < \emptyset_k^{max} \qquad \text{Eq. (5)}$$

Where

F: total investment cost of PSTs [M$]

C_j: cost coefficient (cost vs. max shift angle)

w_j: weighting factor

$\emptyset_j$: Max/Min shift angle of PST$_i$. This is the decision variable of the optimization model. It determines the max/min phase angle shift needed for each PST to solve the overloads

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

nML: number of monitored lines

$S_{ij}^k = \frac{P_i^k - Pini_i^k}{\Delta\ \emptyset_j}$: sensitivity of active power flow on monitored line *i* with respect to variation of phase shift angle of PST *j*

Q: set of cases for which PSTs settings should be the same

This optimization model is intended to find the least-cost combination of PSTs that satisfies the power flow constraints for all the cases considered. The cost of a PST is modeled as a function of the maximum shift angle of the device, which is the design parameter of the PST in the optimization model. As previously described, the cost of a PST is mainly driven by the maximum shift angle and the MVA rating. The first step is to define the candidate locations for the PSTs. It is assumed that a PST has the same MVA rating of the line where it is installed. Therefore, the MVA rating of the candidate PST is not a decision variable of the optimization problem, but rather an input data once a candidate location is selected. The following linear approximation is used to represent the cost of PST of a given MVA rate, as a function of the Max/Min shift angle.

$$C_j = f(MVA_j, \emptyset_j) = BC(MVA_j) * CAF(\emptyset_j) \qquad \text{Eq. (6)}$$

Where

$BC[\$] = \ 5{,}787 * MVA + \ 1{,}446{,}759$, and CAF = 0.0592*C7+0.06

These cost coefficients have been estimated based on reference costs for PSTs provided by Siemens. It is important to emphasize that this is only a reference cost used for screening and preliminary analysis of solutions. There are several other factors that impact the cost of PST, that are considered in advance stages of the solution design process.

Equation (2) represents the power flow constraints. For each case considered in the analysis, the sensitivity matrix **S** needs to be built**.** The number of rows of matrix $\boldsymbol{S_k}$ for each case k is equal to the number of monitored lines (nML), and the number of columns is the number of the PST candidates (*nPST*). Matrix **S** combines all individual matrices for all cases. In this work, the sensitivity factors are calculated via numerical perturbation method using full ac power flow analysis. A script for PSLF was developed to automate the process. Also, the vector of initial power flows for the monitored lines needs to be obtained for each case. Then, the vector of initial power flow for all cases is simply obtained by assembling the vectors from each individual case. Pmax is the maximum active power flow permitted on each monitored line. It a representation of the branch rating expressed in MW.

Equation (3) states that the phase shift angle of PST for any case must be less or equal the maximum shift angle of that PST. With this formulation, the candidate PSTs can have a different setting for different cases, but of course, those settings cannot be larger than the max angle, which is a design parameter of a PST. The output of this optimization model includes not only the design max shift angles of the candidate PSTs, but also their settings for each case. The optimization model is implemented in Matlab, with CVX modeling tool. CVX is a modeling system for constructing and solving disciplined convex programs [20].

Overall Procedure

The linear optimization model is just an aid to be able to find a feasible and optimal solution among the many possible alternatives. The model has some limitations; first, it is a linearized model, hence, the solutions need to be verified with a full ac power flow model to assure that no violations of the technical constraints occur. Also, there are no binary decision variables in it (this is not a mix-integer model). Hence, the model cannot select the optimal locations and discard those that do not produce optimal results. The locations to discard are selected by inspection of the results of the analysis in which all candidate PST locations are enabled. Those locations where the resulting PST shift angle is very low are discarded, and the process is run again with those candidate locations disabled. Therefore, the overall procedure comprises various steps, including a comprehensive power analysis with full ac model, as described in Figure 4.

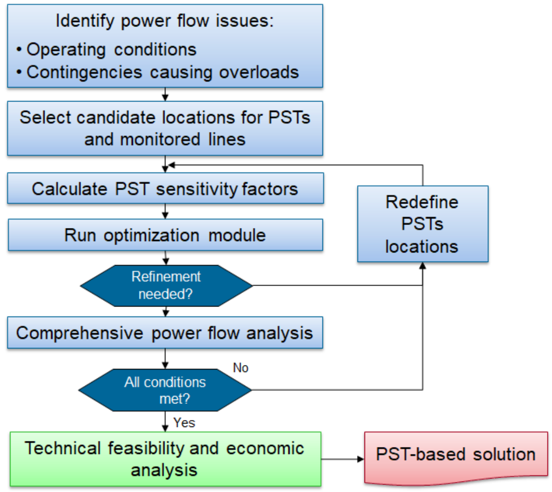

Figure 4 : Overall process to identify PST-based solutions

The candidate locations for PSTs are basically determined by engineering judgement and knowledge of the system. The optimization module can be run multiple times to refine the solution. The final step is a verification with a full ac power flow model. The PST settings for each case obtained from the optimization are considered for validation with the power flow model. If the analysis shows that some overloads are not solved, it is necessary to review the solution and implement refinements.

RESULTS

The described methodology was applied to identify PFC-based solutions for BPA's transmission system. For that, BPA identified 16 lines to be considered as initial candidate locations for the PSTs. All those lines are either in the Portland-Vancouver metro area or nearby areas. A set of 101 branches comprising lines and transformers was identified as monitored branches. The PST sensitivity matrix was calculated for these 101 lines and transformers for each of the 21 scenarios.

The first analysis was performed with all the candidate PST locations enabled. The initial analysis showed that the optimal solution was comprised of 6 PSTs. Even though this is the minimum cost solution, it does not satisfy the objective of using the fewer number of PSTs possible. Because of the limitations of the linear optimization model, it is not possible to include a constraint in the model to limit the number of PSTs (a mix-integer model is needed for that). Hence, many alternatives were evaluated in a trial and error manner, enabling/disabling PST candidates in the optimization model, to find options with small number of PSTs. The option of combining PST devices with other traditional solutions was also analyzed. Among different options, the upgrade of a 230kV line was considered to alleviate the bottleneck produced by that line, and reduce the number of PSTs needed. The possibility of using series reactor instead of PST in some locations was also considered in the analysis of alternatives.

Table 3 is a summary of the feasible solution options found among the many alternatives analyzed. This table indicates which of the PSTs candidates are considered in each alternative, and the maximum and minimum shift angle. The cost described in this table represents only an estimate of the PSTs cost based on the information available, and it is used only as a reference to compare the alternatives. It does not include the cost of reinforcing/rebuilding the 230kV line.

Table 3 : Summary of alternatives

			Alt 1	Alt 2	Alt 3	Alt 4	Alt 5
Upgrade 230 kV line			Y	N	Y	Y	N
PST#	**kV**	**Rate [MVA]**	Min/Max Shift Angle	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°	9.5/-0°
6	230 kV	700			8/-8°	8/-8°	9.5/-0°
7	230 kV	430					0/-5°
8	230 kV	740	0/-35°	0/-40°			
9	345 kV	760			8/-26°	8/-26°	0/-29°
14	115 kV	170			Reactor 7 Ω/ph	2/-2°	12/0°

Alternatives #1 and #2 consider the use of 500kV PSTs with very high MVA rating, which would require the installation of at least two units in parallel to handle such power. Also, design and manufacture of PSTs for 500 kV or higher voltage pose important challenges. As described before, only one PST has been built for that voltage level. This would be a serious limitation for practical implementation of this option. The advantage of this alternative is that only three devices are needed, and their control is simple. Indeed, it is possible to find a single setting for the PSTs valid for all the 21 cases.

Alternative #3 is more practical. It includes the upgrade of a 230kV line, and the use of a series reactor in line 14. Smart Wires devices could be used in this line instead of a fixed series reactor, which would provide greater controllability and flexibility. In this case, it is not possible to have a single setting to cover all the 21 cases. However, with two sets of PSTs setting it is possible to maintain power flows in secure regions in all the 21 scenarios, as shown in Table 4. As can be seen in this table, the 345 kV PST (PST #9) can be maintained at fixed angle, while the two 230 kV PSTs (#5 and #6) can have a fixed angle for all the cases except for cases 2, 9, and 16. These three cases represent N-1-1 contingency at the High, Medium and Low Lewis River hydro generation scenarios respectively. The contingencies in those cases are the outage of a 500kV line (N-1), followed by the outage of one of the 230kV circuits where PSTs #5 and #6 are connected. Therefore, a possible way to operate the PSTs in this alternative is maintaining the settings of the two 230 kV PSTs at +3.0° all the time, and increase the angle to +7.2° if the contingency on one of the 230kV lines occurs, while the line 500 kV line is out of service (N-1-1). The angle of the 345kV PST is kept fixed at -26.5° all the time.

Table 4 : PSTs setting for Alternative 3

			Phase Angle (deg)/CASE						
PST #	**kV**	**Rate [MVA]**	**1**	**2**	**3 to 8**	**9**	**10 to 15**	**16**	**17 to 21**
5	230kV	697	3.0	7.2	3.0	7.2	3.0	7.2	3.0
6	230kV	697	3.0	7.2	3.0	7.2	3.0	7.2	3.0
9	345kV	759	-26.5	-26.5	-26.5	-26.5	-26.5	-26.5	-26.5
14	115kV	169	Reactor						

Because the two 230kV PSTs are controlled together, there are two decision variables in the optimization problem, and consequently it is possible to draw a two-dimensional feasibility region, which in mathematical terms is the set of all possible points (sets of values of the choice variables) of an optimization problem that satisfies the problem constraints. Figure 5 shows the feasibility region PST settings for this alternative, applicable to all cases except cases 2, 9, and 16. The feasibility region indicates that the PSTs angles do not have to be exactly as the values in Table 4 to assure that that no overloads will occur. They can take any value from within the region. Adjustments are needed for cases 2, 9, and 16.

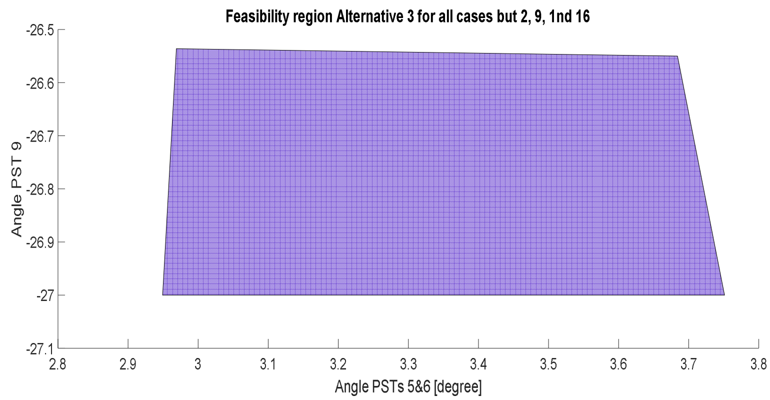

Figure 5 : Feasibility region of PSTs for Alternative 3

Alternative #4 is very similar to Alternative 3. In this alternative a PST is considered in the 115kV line instead of a series reactor. Even though this PST adds additional control, it is not possible to have a single setting for all the cases. Similar settings as for Alternative #3 can be obtained in this case. The control capability needed for this 115 kV PST is very low (±2°), so there is no appreciable benefit of using a PST as compared to a series reactor, or Smart Wires devices.

Alternative #5 represents the option with minimum number of PSTs possible, if no reinforcements of existing lines or any other conventional solutions are considered. Five PSTs are needed to solve the overloads problems in that case. Even though the number of PSTs is larger than in the other alternatives, various sets of PST control settings are needed, as shown in Table 5. Cases 3 and 10 are scenarios with adjustments after N-1 outage, and scenarios 1, 2, 8, and 9 are N-1-1 contingency cases over those scenarios. Hence, in practical implementation, the PSTs can be maintained at the Set 3, and changed to Set 2 when adjustments in scenario 3 are implemented. In similar manner, the PSTs can be maintained at the Set 5, and changed to Set 4 when adjustments in scenario 10 are implemented. In that way, the system will be ready in a preventive mode to cope with the N-1-1 contingencies (cases 2, 8 and 9).

Table 5 : PSTs setting for Alternative 5

			Phase Angle (deg)/CASE				
PST	kV	Rate [MVA]	1	2 nd 3	4 to 7	8 to 10	11 to 21
5	230kV	697	1.5	7.8	4.4	7.7	4.4
6	230kV	697	1.5	7.8	4.4	7.7	4.4
7	230kV	426	-1.0	1.7	0.1	0.2	0.1
9	345kV	759	-22.9	-30.8	-30.8	-30.4	-30.8
14	115kV	169	5.5	4.2	8.1	7.6	8.1
			Set 1	Set 2	Set 3	Set 4	Set 5

CONCLUSIONS

This study evaluated the use of PFC technologies as a potential alternative for solving power flow issues in the BPA's transmission system, more specifically, in the transmission grid surrounding the Portland-Vancouver metropolitan area. A systematic approach to identify options and determine the location, rating and controls requirement for PFC devices was developed and implemented. The developed methodology includes an optimization model that uses linear phase shifter sensitivity factors to determine the optimal settings of selected PSTs to alleviate overloads on affected lines. Various solution alternatives were identified with the proposed methodology.

The most practical solution is one that combines three PSTs with one series reactor, plus the upgrade of a critical 230kV line. The alternatives using PST at the 500 kV lines are the simplest and most effective from the operational point of view. However, the large MVA and voltage rating of the PSTs required for those alternatives make them much more expensive and technically challenging. Besides, it is possible to find a solution that uses PSTs at lower voltage levels, and no additional reinforcements or conventional options, but five PSTs are needed in that case. The next step is to select the one of the alternatives developed and perform further studies to determine the technical specifications to be provided to the manufacturer for final design. Parameters that need to be determined in that stage include but not limited to number of on-load tap positions, impedance, PST type, overload conditions, short-circuit capability, basic impulse level (BIL), environmental conditions, size and weight restrictions, testing requirements.

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