Bulk Power System Dynamics and Control IV - Restructuring, August 24-28, Santorini, Greece.

Improving Pacific Inter-tie Stability Using Existing Static VAR Compensators and Thyristor Controlled Series Compensation

Vaithianathan Venkatasubramanian, Karl W. Schneider
School of Electrical Engineering and Computer Science
Washington State University, Pullman, WA 99164-2752
Email: mani@eecs.wsu.edu

Carson W. Taylor
Transmission Operations and Planning
Bonneville Power Administration
Vancouver, WA 98666-0491

Abstract: The paper summarizes new control designs developed at Washington State University for the control of existing SVC's, and TCSC owned by Bonneville Power Administration. The new controls are primarily aimed at improving transient stability of the WSCC western electric power system. The proposed controls are heuristic and are nonlinear. They are shown to be very effective in increasing the operating capability ratings of the California-Oregon pacific inter-tie under varied operating conditions.

1. Introduction

Design of stabilizing controls for thyristor devices in a practical power system is a challenging problem, owing to their complex effects on the entire interconnected electric power grid. The problem is especially difficult since the control has to provide consistent benefits under wide variations in operating conditions.

This paper summarizes recent control studies conducted at Washington State University (WSU), Pullman in a project funded by Bonneville Power Administration (BPA). The project has been carried out in close collaboration between the WSU team and the BPA engineers in order to keep the project sharply focused on tangible benefits.

The objectives of our project have been 1) to test and to rank the relative controllability of various thyristor devices in BPA, namely, A) Keeler SVC, B) Maple Valley SVC, and C) Slatt TCSC (on the Slatt-Buckley 500 kV line); and 2) to design robust controls for the controllable devices. The controls are primarily aimed to provide fast transient stabilizing control during the first few swings of critical contingencies. Mid-term small-signal stability enhancement is the secondary control objective.

The control benefits were measured by the “MW margin” the change in active power-flow on the pacific AC inter-tie called the California-Oregon Inter-tie (COI) for the critically stable cases for specified severe contingencies with and without the proposed controls.

In the project, we have developed new nonlinear controls for fast control of the Slatt TCSC and the SVCs, which have been tested to show significant benefits for COI operating ratings. These heuristic controls were developed based on dynamic voltage control needs for the stability support of COI lines in the Pacific Northwest system.

The proposed controller for Slatt TCSC is shown to provide COI MW margins ranging between +100 MW to +200 MW for critical contingencies for different seasonal operating conditions. The proposed controllers for the SVC's provide between +50 MW to +200 MW each for severe contingencies. Clearly, the controls appear to be very effective in transient stability enhancement of western inter-tie.

This paper is organized as an overview of the results and detailed analysis of the controls will be presented elsewhere. In Section 2, simulation methodology is discussed. Section 3 includes a brief discussion of preliminary controllability studies. Section 4 is on the proposed new controls for the thyristor devices and their benefits.

2. Simulation tools

The studies have been performed on large-scale seasonal models of the western electric grid which typically contain about 6500 buses and 900 generators. Five base-case power-flow scenarios were considered: 97 summer peak case, 97 summer off-peak case, 98 Spring peak, and validated models of the July 2, 1996 and August 10, 1996 western black-outs.

Dynamic models include most updated representations of generator data, and detailed representations of all thyristor controls of interest. The detailed models for Pacific DC Inter-tie (PDCI) and Intermountain Power Project (IPP) HVDC controls have been developed and tested previously by BPA engineers. Sensitivity to load variations was tested in some cases. The studies were primarily carried out using the EPRI transient stability program ETMSP and EPRI small-signal stability program PEALS. BPA power-flow program PF was our primary power-flow analysis tool.

3. Controllability studies

For testing the controllability of the devices, two test procedures were developed.

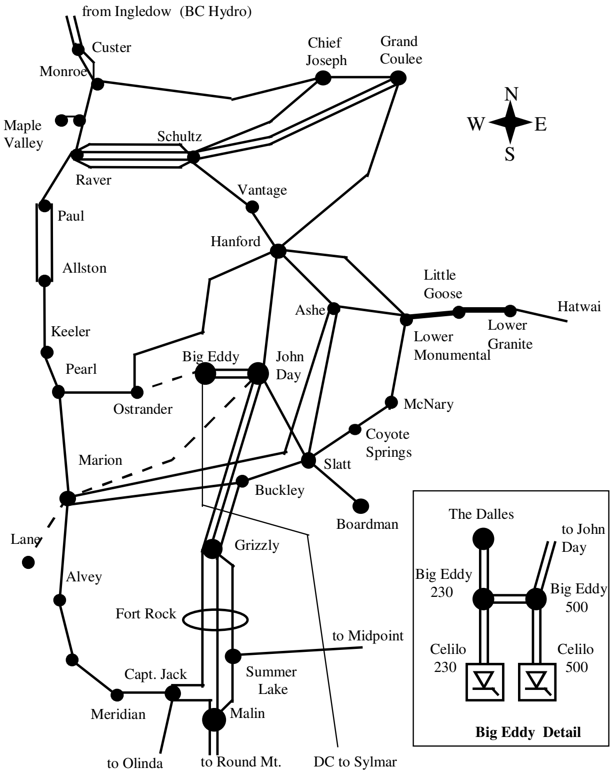

Figure 1. One-line diagram of the 500 kV transmission in Pacific Northwest.

Procedure 1) EPRI small-signal stability analysis program PEALS was used to generate linearized frequency response plots for studying the transfer function characteristics of the various controls. The Bode plots are useful in establishing the sensitivity of control performance to different control input signals. The sensitivities around the problematic inter-area mode frequencies 0.25 Hz and 0.7 Hz were of special interest. Candidate control input signals were local voltage and frequency measurements at the devices, as well as remote voltage, real power-flow and current magnitude telemetry signals from the COI lines.

We found that control analysis based on small-signal stability type linearization methods was of limited interest in our studies since our primary control objective was transient stability enhancement.

Procedure 2) Traditional phase-lead type linear test controllers were designed for each of the thyristor devices, and the closed loop performance of the devices was tested under different contingencies and power-flow conditions. The tests were repeated for various control inputs for ensuring that the observations were not restricted to the type of control input used.

Based on these controllability tests, we observed the two SVC's at Maple Valley and Keeler substations provided consistent enhancements for transient stability and small-signal stability for different power-flow scenarios. Hence the two SVCs were classified to be controllable for the BPA system.

From system operation considerations, Maple Valley SVC was decided to be more suitable for stabilizer implementation. The third device, Slatt TCSC, did not provide consistent benefits for different contingencies using traditional linear phase-lead/lag type test controllers. The topology of the BPA 500 kV network near Slatt TCSC makes the control of Slatt TCSC quite difficult.

In summary, based on traditional phase-lag/lead type linear test controllers, we concluded that the two SVCs offer controllability. In this sense, Slatt TCSC modulation was not controllable by linear controllers to provide consistent stability benefits. However, we present a nonlinear discrete controller for Slatt TCSC in Section 4.2, which is shown to be very effective for transient stability enhancement.

4. Control strategies for SVCs and TCSC

The stability controller design issues for Maple Valley SVC and Keeler SVC are quite similar. Therefore, we discuss only the stability controls for Maple Valley SVC in this paper.

4.1 Stability control designs for the Maple Valley SVC:

The main purpose of Keeler and Maple Valley SVC's is to provide voltage regulation at 230 kV for its metropolitan load center, along with fast reactive support for transient conditions. Each SVC includes Thyristor-Switched Capacitor (TSC) banks rated at 300 MVAR, and Thyristor-Controlled Reactor (TCR) banks rated at –350 MVAR. Harmonic filters provide 50 MVAR at nominal frequency of 60 Hz [1]. Thus, the nominal operating range of each SVC is +350 to –300 MVAR at 1.00 pu 230 kV voltage. Operation is most economical (least lossy) when both the TSCs and TCRs are bypassed, leaving the 50 MVAR filter output as the desired SVC operating point. During steady-state conditions, as much as 400 MVAR (Maple Valley) or 260 MVAR (Keeler) of external shunt capacitors may be switched as necessary to maintain set-point 230 kV voltage with low-loss operation. Keeler also has a 180 MVAR reactor bank for this purpose.

The voltage regulator of these SVC's designed by Asea Brown Boveri (ABB) is integral-based. A voltage error signal, calculated from 230 kV voltage set-point deviation, a susceptance-based slope function signal, and a slow MVAR regulator signal (presently deactivated), is input to an integrator block with rate-of-response gain. The integrator output, subject to dynamic limits based on SVC primary (19.6 kV) voltage and 230 kV current, becomes the SVC susceptance order [1].

The existing ABB voltage regulator has been designed as a fast responsive integral (phase-lag type) voltage control. In the output stage of the existing ABB control, there is a provision to either add a stabilizing susceptance order, or to switch in an entirely different stabilizing susceptance order [1]. Both approaches were pursued in the project.

4.1.1 Additive stabilizing controls with wash-out filter:

For reasons of economy and reliability, it is preferable to use local signals as the modulation control inputs when feasible. Local 230 kV and 500 kV voltages are highly sensitive to SVC reactive output, and are therefore unsuitable by themselves as stability control inputs. Among other local signals, local frequency signal has been used in some other SVC installations for deriving the stability control, and accordingly, local frequency based controls were studied in detail.

In analyzing the transients of the western interconnection WSCC system, local frequency measurement is a representative signal for determining the inter-area mode oscillatory frequencies and their damping levels for mid-term dynamics. Indeed, in our simulations, excellent improvement of COI inter-area mode damping values could be achieved using phase-lead designs with local frequency input. However, we found frequency based designs to be difficult for transient stability support of generation tripping contingencies.

After a generation loss, frequency declines monotonously for first few seconds because of system-wide governor actions. The frequency based stability controller tries to make the SVC susceptance inductive during this decline while the COI voltage is swinging up and down in the first two swings. Therefore, the controller in fact contributes a destabilizing effect towards first few swings, which is unacceptable. To counter this effect, the inductive capability of the stability signal can be limited which on the other hand limits the usefulness of the controller for transmission tripping contingencies. Therefore, we pursued remote measurements as stability control inputs next.

Among remote input signals, Malin voltage (see Figure 1), COI line current and COI line active power-flow were studied as possible candidates. Design issues and benefits of the controllers based on the three types of inputs are similar. In contrast with the local frequency signal, the transient behavior of the remote voltage for instance the 500 kV Malin voltage is consistent for both types of contingencies namely, loss of generation and transmission tripping scenarios. A traditional phase-lead controller based on Malin voltage input signal was found to be quite effective in our simulations.

The limits of the controller were set aggressively at +/- 650 MVAR for the additive stabilizing signal for overriding the fast responsive ABB voltage regulator output during transients. The design consists of the three traditional stages namely, a wash-out filter, a low-pass filter and a phase-lead with gain. The presence of washout filter ensures that the stabilizing controller does not affect the static response of the SVC. The phase-lead stage can be replaced with a tuned PID stage with similar results.

To provide fast stabilization effect, the limits of the Malin voltage based stabilizing signal have been set aggressively in the study design at +/-650 MVAR. Since the design includes a wash-out filter, the new SVC controller should not react to slow changes in Malin voltage. Yet, since Malin is electrically quite distant from Maple Valley, there may be some disadvantage in controlling the Maple Valley SVC susceptance using the Malin voltage at all times. In some cases, the local voltage regulation at Maple Valley may be weakened by fault-initiated voltage variations in the vicinity of Malin.

Note that the same limitations apply for other remote input signals such as COI current and COI MW flow as well. In order to avoid these potential difficulties with the additive controller design, the alternate approach of either/or switching of local regulation mode and stabilization mode is discussed in the next section.

4.1.2 Nonlinear switching controller:

In this paper, we summarize a nonlinear switching controller for Maple Valley SVC which operates the SVC in either the voltage regulation mode or the intertie stability mode depending on system stress conditions. 500 kV Malin voltage is used as the deciding control signal and a 25 ms communication delay is modeled in the study. Malin voltage on the 500 kV side is normally operated at about 535 kV to 540 kV. When the Malin voltage goes below 500 kV for 8 cycles, or goes above 550 kV for 8 cycles, the operation is switched from local voltage regulator mode to inter-tie stability mode. After 30 seconds in stability mode, the operation is returned to local regulation mode.

In stability mode, the Malin voltage (after 25 ms time-delay) is passed through a low-pass filter, and the susceptance is determined by a (nonlinear) piece-wise linear function. The SVC is operated more on the capacitive side than inductive which we found effective towards dynamic voltage support for severe contingency cases.

In our simulations, the nonlinear controller has provided stability benefits in the order of +50 MW to +200 MW for COI power-flow limits for critical contingencies in the WSCC system. We discuss the MW margins for two severe contingencies here: 1) Simultaneous tripping of two Palo Verde units in the southwest (which is a generation loss of about 2700 MW) denoted PV2, and 2) Tripping of the two 500 kV transmission lines from Paul to Allston (which typically carry about 2200 MW) denoted 2PA.

Specifically for the 97 summer peak WSCC case, COI MW margin from the proposed controller for PV2 contingency was computed to be 50 MW, and for 2PA contingency was 200 MW. For 98 spring peak case, the COI MW margin for PV2 was computed to be 50 MW. Note that these margins are for the nonlinear switching controller with respect to SVC operation solely in the voltage regulation mode. The margins show that the stability control is especially effective in mitigating Northwest transmission loss type scenarios.

4.2 Stability control design for Slatt TCSC:

Slatt TCSC consists of six identical modules per phase. Each module can operate either bypassed or inserted. In discrete control mode, the TCSC Ohm order can be any one of the following: –1.2 Ohms (all caps off), 4 Ohms (continuous at 3400 Amps), 8 Ohms (normal rating at 2900 Amps), 12 Ohms (30 minute overload at 2900 Amps), 16 Ohms (10 second overload at 2900 Amps), 20 Ohms (10 second overload at 2500 Amps) or 24 Ohms (10 second overload at 2000 Amps) (see Figure 3-7 in [2]). In continuous Vernier operation, the TCSC order can be specified to be any value between –1.2 Ohms and 24 Ohms and there are nonlinear constraints on the Ohm order depending on the current through TCSC and the overload time characteristic. For instance, the Ohm order of 24 Ohms cannot be realized under typical operating conditions since the actual line current with TCSC at 24 Ohms would be much higher than permissible limit of 2000 Amps. The time-current overload capability of the TCSC specified in [2] has to be carefully accommodated in the stability control design to make sure that the design is realistic. At present, the TCSC is operated at a fixed 8 Ohms, and there is no dynamic control for the TCSC.

Since the Slatt TCSC by design is a discrete control system (consisting of six 4 Ohm capacitor banks), a discrete controller is a natural candidate for the stabilizing design. The discrete controller also provides "dead-bands" around different ohm settings so that the number of TCSC switchings can be reduced drastically during system transients. Also, the "dead-bands" in the discrete controller would prevent the TCSC from interacting with local modes and small-amplitude inter-area oscillations of distant areas such as possibly from California or Alberta/British Columbia modes.

4.2.1 Voltage proportional discrete Slatt TCSC control:

To provide effective dynamic reactive support at Slatt TCSC, a simple discrete controller was designed by us to vary the Slatt TCSC capacitance proportional to the local 500 kV Slatt voltage. The following voltage based controller has provided excellent transient support in our studies.

TCSC nominal => 8 ohms.
Slatt voltage > 540 kV => TCSC to 4 ohms.
Slatt voltage > 545 kV => TCSC all caps off (-1.2 ohms)
Slatt voltage < 530 kV => TCSC to minimum of
(16 ohms, IL based 10 sec limit) for Timer < 6 sec.
=> TCSC to 12 ohms for Timer > 6 sec.

Here, Timer counts operation at 10 sec overload limit (when voltage < 530 kV). During swings, whenever the Slatt voltage goes below 530 kV, this controller operates the TCSC at its 10 second capacitive limit for up to 6 seconds. After 6 seconds (that is, when 60% of overload capacity is reached), even when the Slatt voltage goes below 530 kV, the TCSC would be kept at 12 ohms. Note that 12 ohms is well within the 30 minute overload limit of the unit. Also, the controller would switch out capacitors whenever the Slatt voltage swings above 545 kV as stated. Essentially, the controller provides dynamic reactive support to COI lines based on local voltage input. The modeling of the discrete controller is representative of the installation by taking into consideration the timer operation of the 10 second overload.

For different seasonal cases, the MW margins from the proposed Slatt controller were computed with respect to fixed Slatt operation at 8 Ohms. For 97 summer peak, the COI MW margin for PV2 was +200 MW and for 2PA was +200 MW. For 98 spring peak case, the MW margin for PV2 was computed to be +100 MW. These results clearly show that the controller is very effective in improving pacific inter-tie stability.

Acknowledgements

The authors thank BPA engineers Dmitry Kosterev, Ravi K. Aggarwal, and Bill Mittelstadt for helping us with WSCC data and modeling of thyristor controls.

References

[1] W. Wong, "BPA SVC Transient Stability Model," BPA *Contractor report prepared under BPA contract #DE-AC79-92BP19175* by Asea Brown Boveri, April 30, 1992.

[2] J. Urbanek, R.J. Piwko, E.V. Larsen, B.L. Damsky, B.C. Furumasu, W. Mittelstadt, and J.D. Eden, "Thyristor controlled series compensation prototype installation at Slatt 500 kV substation", *IEEE Transactions on Power Delivery*, Vol. 8, No. 3, July 1993, pp. 1460-1469.