Transient Excitation Boosting at Grand Coulee Third Power Plant: Power System Application and Field Tests

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Abstract - Transient excitation boosting (TEB) has been installed on the Grand Coulee Third Power Plant hydrogenerators (three 600 MVA units and three 700 MVA units). TEB is initiated for outages of the 3100 MW Pacific HVDC Intertie, and results in a decaying pulse input to the generator voltage regulators. TEB temporarily raises Pacific Northwest transmission voltages which increases voltage-sensitive loads. The increased load brakes Northwest generators which are accelerating because of the loss of HVDC Intertie power. Transient stability of the parallel Pacific AC Intertie is thus improved.

Power system-wide commissioning tests were conducted on May 7, 1991. We describe the tests and compare test results with simulation results.

keywords - transient stability, excitation systems, emergency controls, phase angle measurement

Introduction

Special stability controls. Special stability controls (also known as special protection systems, emergency controls and remedial action schemes) are increasingly being used as cost-effective means for better utilization of generation and transmission resources. The IEEE Special Stability Controls Working Group (formerly Discrete Supplementary Controls Working Group) has published several papers describing controls such as generator tripping, fast valving, single-pole switching, and discontinuous excitation controls [1, 2]. These controls are often of the open-loop (feed-forward) variety, actuated by detection of a major disturbance.

Special excitation system controls. Reference 2 lists several papers on special excitation system controls. The discontinuous excitation control implemented by Ontario Hydro on a number of units is especially interesting [3]. This Transient Stability Excitation Control (TSEC) improves stability for interarea swings. Following local detection of a severe fault, a signal proportional to rotor angle is applied to the voltage regulator. This is a closed-loop system, since the signal is removed based on local measurements.

Another application relates to underfrequency excursions. The underfrequency could be due to islanding, or due to generator tripping to improve stability. Because of the underfrequency excursion, power system stabilizers (PSS) will tend to depress excitation and reduce transient stability performance. Using the PSS speed or frequency input signal, R. Lee Cresap proposed a speed-acceleration phase-plane trigger to detect the frequency decay. A decaying pulse injected into the PSS would enhance transient stability.

This paper describes application and implementation of transient excitation boosting based on direct detection of a critical disturbance. Using telemetry, a signal is sent to inject a decaying pulse into the excitation systems of large generators with very powerful static exciters. This open-loop control improves interarea transient stability. For interarea modes, where the swing center is remote from the generating plant, the excitation system would otherwise be underutilized. Local detection of critical disturbances (similar to the Ontario Hydro method) is not always possible because the disturbance may not involve a severe short circuit, and because nearby generator tripping or dynamic breaking may hinder detection of acceleration relative to receiving end generation.

Application of Transient Excitation Boosting

System description. The western North American interconnection is a large loop system with complex dynamic properties. The loop is formed around

92 SM 533-0 PWRS A paper recommended and approved by the IEEE Power System Engineering Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1992 Summer Meeting, Seattle, WA, July 12-16, 1992. Manuscript submitted January 28, 1992; made available for printing May 22, 1992.

sparsely populated desert areas in Nevada and adjacent states. California, on the western side of the loop, comprises the largest load area and usually imports power. Large hydro generating plants are located in the Pacific Northwest, and major coal--fired generating plants are sited on the eastern side of the loop. Power transfers are generally north to south and east to west. The interconnection generating capability is over 100,000 MW.

The Pacific AC Intertie runs from the Columbia River to the San Francisco Bay area to Southern California—forming a longitudinal subsystem. The Oregon portion, and parts of the California portion, consist of three 500-kV lines, with two line segments from the Oregon-California border to the San Francisco area. The transfer capability on these two line segments is 3200 MW. The average series compensation level of the intertie is about 60%. In 1993, a third 500-kV line will be added between the Oregon border and the San Francisco area; the new power rating will be 4800 MW.

The parallel Pacific 500-kV HVDC Intertie runs from the Columbia River (Celilo Converter Station, usually the rectifier) to Los Angeles—1362 km. The bipole rating is 3100 MW; each terminal consists of two converters rated 2000 MW and 1100 MW. A second HVDC link runs from Utah to the Los Angeles area (Intermountain Power Project—1920 MW).

Figure 1 shows the interconnection and Pacific Intertie schematically.

Critical disturbance. Since both poles of the 1362 km HVDC Intertie are on the same towers, a 3100 MW bipolar outage with unsuccessful restart is a credible disturbance. The 3100 MW bipole outage is obviously a very severe disturbance. For the HVDC outages, Pacific AC Intertie stability is imperative to prevent massive load shedding and probable blackouts. Planning and operating criterion requires that swing voltages at load centers be no lower than 80% of pre-disturbance voltage.

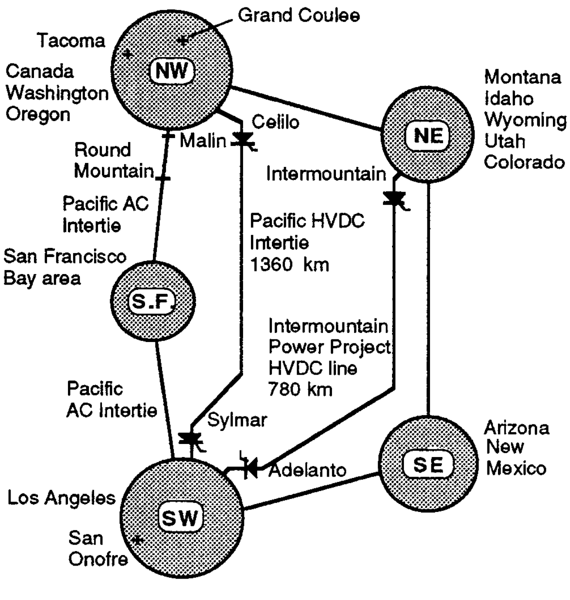

Fig. 1. Western interconnection and Pacific Intertie.

Special stability controls for Pacific HVDC Intertie outage are high speed series capacitor insertion on the Oregon portion of the Pacific AC Intertie [4], high speed 500-kV shunt capacitor bank insertion at Malin substation on the Oregon-California border [5], and Pacific Northwest hydro generation dropping. Generator dropping is limited to 2850 MW. This limit minimizes the interconnection frequency excursion and prevents load shedding on foreign systems. The generation dropping limit also reduces the risk of instability on the Alberta to British Columbia interconnection (single 500-kV line often heavily loaded east to west).

Even with these controls, simultaneous full power transfer on the Pacific Intertie system is not possible. This led to the development and implementation of "transient excitation boosting" (TEB) to reduce transient stability-related limits. Voltage stability limits [6] must also be removed.

Implementation at Grand Coulee. The swing center (electrical or impedance center and low voltage point) on the Pacific AC Intertie is in Northern California, often as far south as the San Francisco area. This is quite remote from sending end generators in the Pacific Northwest. Power plants in northern Washington state may be 1300 km from the swing center, while plants in British Columbia, Montana, and Wyoming are even farther away. Following an HVDC Intertie outage, voltage regulators at sending end generators first respond to mild voltage rises due to the dc load rejection. Power system stabilizers respond to the nearby hydro generator dropping by also transiently depressing excitation. As the swing develops, generator terminal voltages do not sag enough for significant voltage regulator boosting.

Thus for critical disturbances, powerful excitation systems are underutilized.

This analysis led BPA and the U.S. Bureau of Reclamation to implement transient excitation boosting at the Grand Coulee Third Power Plant in northern Washington state. The 4000 MVA Grand Coulee Third Power Plant consists of six hydro units with 600–700 MW ratings. The units have static exciters with very high ceiling voltages (6.5–8.0 pu). The

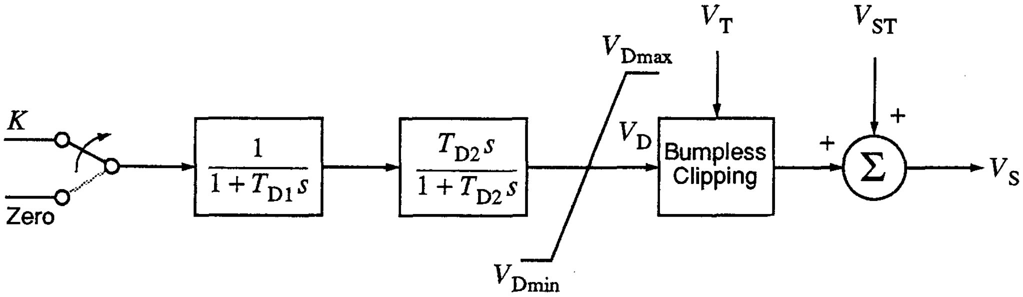

Fig. 2. Type DEC2A Discontinuous Excitation Controller—open loop transient excitation boosting [11]. V_{ST} is the PSS signal and V_S is the supplementary signal to the generator voltage regulator.

units are connected to the 500-kV transmission system.

HVDC outage are detected directly at the Celilo Converter Station (Pacific HVDC Intertie northern terminal, normally the rectifier). A transfer trip signal is transmitted to Grand Coulee over microwave channels. A decaying pulse is then injected into the voltage regulator and excitation system of each unit. The same HVDC outage detection equipment is used for generator tripping, and series and shunt capacitor insertion.

The decaying pulse temporarily raises Northwest system voltages. The higher voltages raises loads (which are voltage sensitive), thereby braking generators that are accelerating relative to Southwest generators. The effect of TEB is strongly dependent on load characteristics.

Preliminary simulation studies [7,8] showed that the Grand Coulee TEB significantly improves Pacific AC Intertie transient stability.

Reference 9 describes the hardware and software installed at Grand Coulee. Reference 10 describes equipment testing at Grand Coulee prior to power system-wide tests. The rise time of the excitation system pulse is set at 0.1 second and the decay or washout time is set at 10 seconds. The pulse amplitude is about 6% on a generator terminal voltage base. A limiter freezes the filter block if terminal voltage exceeds a fixed level (1.1 per unit). The output is released when terminal voltage drops below this level and the filter block output drops below its value at the time output was frozen (bumpless clipping using digital logic). Figure 2 shows the IEEE Standard block diagram model implemented in several transient stability programs [11].

System-Wide Commissioning Tests

System-wide Grand Coulee transient excitation boosting commissioning tests were conducted on Tuesday, 7 May 1991, between 2127 and 2322 hours. The tests consisted of:

- Excitation boosting of the four available Grand Coulee Third Power Plant generators with no other disturbance. This was done three times with the trigger signal originating from Celilo.
- Pacific HVDC Intertie fast power reduction (1000 MW) without and with TEB.

Test conditions. The Appendix summarizes the tests and test conditions. At Grand Coulee Third Power Plant, units 19–21 and 23 were on-line and generating (the units can operate as synchronous condensers).

Test instrumentation. Instrumentation was the following:

- Power System Disturbance Monitor (PSDM) at BPA's Dittmer Control Center [12]. The recording of telemetered analog data plus Ross frequency was triggered manually for each test.
- Macintosh LabVIEW system (Portable Power System Monitor, PPSM). Thirty-one Dittmer analog channels were recorded continuously during the test period [13].
- Phasor measurement system [14] using GPS satellite. Time synchronized voltage and current phasors were measured at Grand Coulee 500-kV Switchyard, at the John Day 500-kV Switchyard along the Columbia River at the northern end of the Pacific Intertie, and at the Malin Substation on the Oregon–California border. Active and reactive power flows were computed for the Grand Coulee–Hanford, John Day–Grizzly #1, and Malin–Round Mountain #1 500-kV lines [15].
- Strip chart recorders at the Grand Coulee 500-kV Switchyard and Third Power Plant.
- Digital fault recorders at Grand Coulee Third Power Plant.

Results from the PPSM and from the phasor measurement system were provided in spreadsheet format for the plots shown below.

Test results for transient excitation boosting with no HVDC disturbance. We describe results from Test 2 with Grand Coulee voltage at 540 kV prior to the test. We compare test results with large-scale transient stability simulation results. A 1990 light spring base case was adjusted to approximately represent the test conditions. We did not attempt to match test conditions throughout the entire western interconnection.

Figure 3 shows the Grand Coulee 500-kV voltage is temporary boosted by about 21 kV or almost 4% of the initial voltage. This voltage pulse and the corresponding reactive power injection may be considered the power system test input.

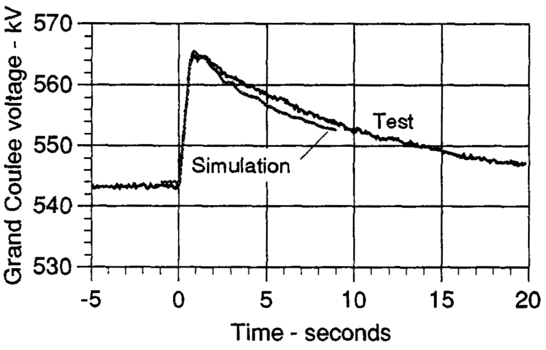

Fig. 3. 500-kV bus voltage at Grand Coulee. Test 2.

Figure 4 shows measured voltage and load power at the Tacoma 230-kV bus. The voltage increases about 1.65% and the power about 1.96%. The $\Delta P/\Delta V$ is then 1.19 per unit/per unit. Because of the proximity to the Grand Coulee–Raver double circuit, series compensated 500-kV line, the load increase at Tacoma is probably greater than at other locations in the Puget Sound area. The Puget Sound area (about 250 km west of Grand Coulee) is the largest load area in the Pacific Northwest. Voltages at other load busses were not measured.

For Tacoma 230-kV voltage, Figure 5 shows the comparison between test results and simulation. The simulation produced 33% higher voltage change; this would cause greater load increase and generator braking than the field tests. The cause of the discrepancy is not known.

Figure 6 shows the voltage swing at the Malin 500-kV bus on the Pacific AC Intertie (same scale as Figure 3). Again there is discrepancy between test and simulation results, with simulation showing greater voltage swing.

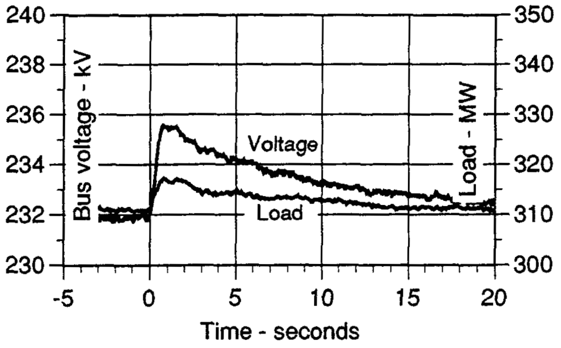

Fig. 4. Tacoma 230-kV voltage and Tacoma N.E. power. Results from system test. Test 2.

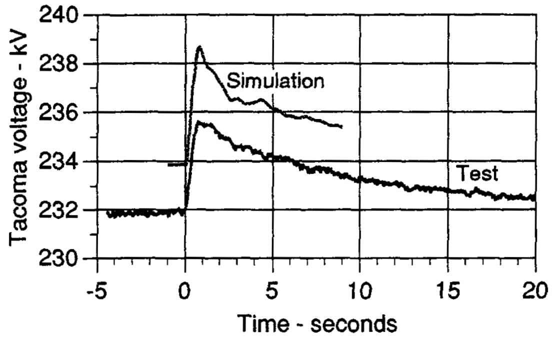

Fig. 5. 230-kV bus voltage at Tacoma. Test 2

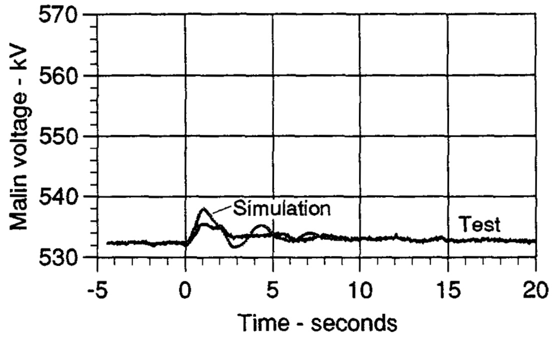

Fig. 6. 500-kV bus voltage at Malin. Test 2.

Figure 7 shows the Coulee 500-kV bus to Malin 500-kV bus voltage phase angle. TEB causes a bus voltage angle first swing of about -2.4°. Test and simulation results correspond well for the initial deceleration. From the simulation, *rotor* angle swing between Grand Coulee Third Power Plant and the San Onofre power plant is about 12°. San Onofre is a large nuclear plant located between Los Angeles and San Diego.

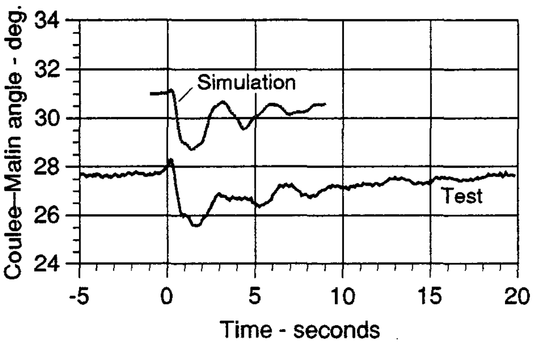

Fig. 7. Voltage phase angle between Grand Coulee and Malin 500-kV busses. Test 2.

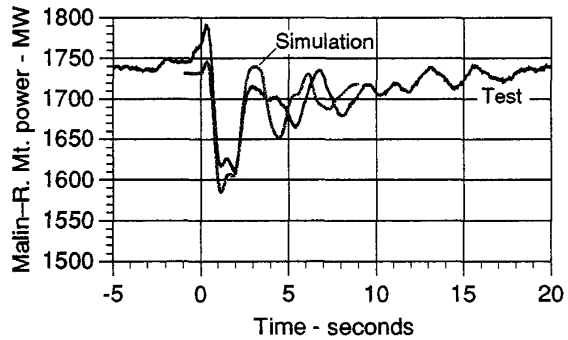

Fig. 8. Total Malin–Round Mountain power. Test 2.

Figure 8 shows power on the two Malin–Round Mountain lines of the Pacific AC Intertie. Initially, the power increases in response to the Coulee voltage rise. As Northwest generators decelerate, however, the power is reduced by about 150 MW. This is evidence of the effectiveness of TEB. The first swing comparison with simulation is pretty good. There are significant discrepancies in the backswing and in subsequent swings.

HVDC fast power reduction tests. The HVDC fast power reduction was 1000 MW. Test 3 without TEB was at 2244 hours and Test 5 with TEB was at 2322 hours. Between the tests, the AC Intertie power transfer reduced from about 1500 MW to about 900 MW (AC Intertie was at about 1750 MW for Test 2). Other system changes also occurred. This was unfortunate since the tests are therefore not directly comparable. Also, the AC Intertie level of stress was much lower than desired. Although disabling series capacitor insertion would have increased stress, both tests were run with series capacitor insertion. Figures 9–13 compare results without and with TEB. No attempt was made to simulate these tests.

Figures 9 and 10 show response at Tacoma. Without TEB, there is a momentary voltage and load increase due to the HVDC load rejection. With TEB, the voltage rise is much higher, and the voltage and load increase is sustained for the first swing and beyond.

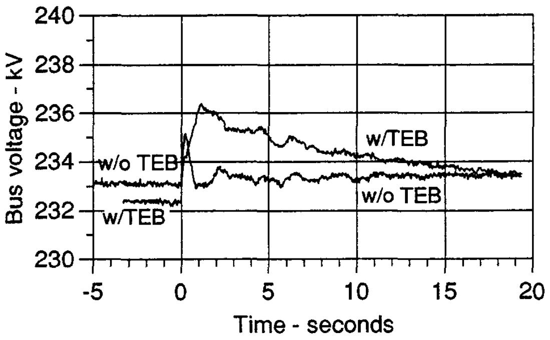

Fig. 9. Tacoma 230-kV voltage. Tests 3 and 5.

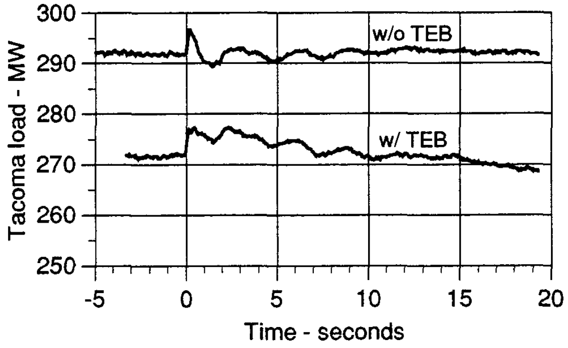

Fig. 10. Tacoma 230-kV power. Tests 3 and 5.

Figure 11 shows Malin voltage magnitude. The first swing voltage dip is about 11 kV without TEB and about 3.2 kV with TEB.

Figure 12 shows Grand Coulee 500-kV bus to Malin 500-kV voltage phase angle.

Figure 13 shows total Malin–Round Mountain power. With TEB, the first swing is reduced by 87 MW. In comparison, the Test 2 swing (without HVDC disturbance and series capacitor insertion, and with different system conditions) was 150 MW.

Summary and Concluding Remarks

We have described application and implementation of a novel and effective special stability control at the 4000 MW Grand Coulee Third Power Plant. We have described system-wide commissioning tests. The system tests are in general agreement with expectations based on large scale simulations.

Some discrepancies between field results and simulation are unresolved. Load modeling effects may be the biggest contributor to discrepancies. Other field

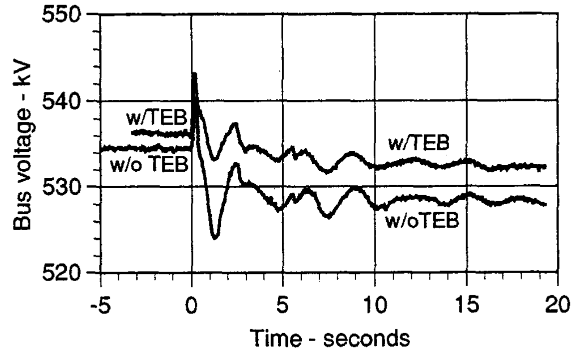

Fig. 11. Malin 500-kV voltage. Tests 3 and 5.

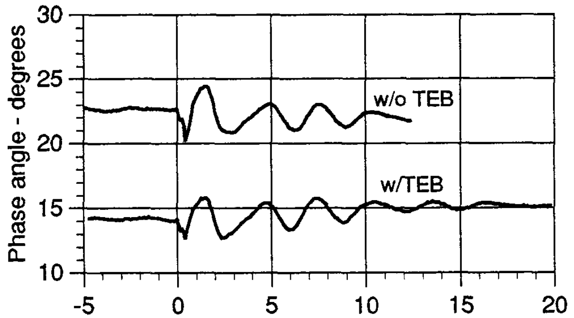

Fig. 12. Grand Coulee to Malin voltage phase angle. Tests 3 and 5.

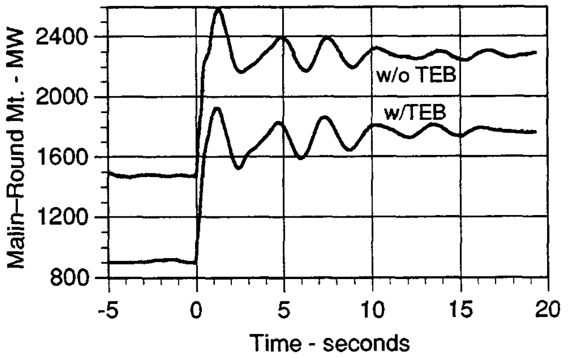

Fig. 13. Total Malin–Round Mountain power. Tests 3 and 5.

tests, with frequency domain processing have also shown significant discrepancies [16].

Since the power system conditions changed between Tests 3 and 5, and since the power system was not heavily stressed, it would be desirable to repeat the tests under more ideal conditions.

The instrumentation for the system tests was highly successful, and included phase angle measurement between geographically distant substations.

Open-loop transient excitation boosting is a relatively low cost method to improve stability by taking advantage of high performance excitation systems. Transient excitation boosting is applicable whenever conventional automatic voltage regulators do not provide field forcing consistent with excitation system capability.

Transient excitation boosting is a robust, non-disruptive control that can be initiated by "trigger-happy" sensors. As an open-loop control, it's much more immune to instabilities and modal interactions than closed-loop controls.

Acknowledgments: Many USBR and BPA engineers contributed to the implementation and testing of Grand Coulee transient excitation boosting. Dennis Erickson and Ken Martin from BPA's Division of Laboratories recorded the test data reported in this paper.

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Mr. Taylor is an IEEE Fellow. He chairs the IEEE Working Group on Special Stability Controls and is active in other work of the System Dynamic Performance Subcommittee. He is convenor of CIGRE Task Force 32-02-10, "Modelling of Voltage Collapse Including Dynamic Phenomena." Mr. Taylor has authored or co-authored many IEEE and CIGRE papers.

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Mr. Matthews is currently a planning engineer with the Bonneville Power Administration. He is also a member of the IEEE Power Engineering Society and Tau Beta Pi.

Appendix, Test Conditions—7 May 1991

Test	Time	Grand Coulee Voltage - kV	AC Intertie Power - MW	TEB	HVDC Drop MW	Series Capacitor Insertion
1a	21:27:12	530	1770	Yes	No	No
1b	21:34:17	530	1715	Yes	No	No
2	21:47:05	540	1775	Yes	No	No
3	22:44:46	540	1500	No	1000	Yes
5[a]	23:22:39	540	900	Yes	1000	Yes

[a] Test 4 not conducted.

Discussion

William A. Mittelstadt, Bonneville Power Administration, Portland, Oregon: The authors are to be congratulated for this significant application maximizing the effectiveness of available but underutilized system capability. This shows clearly that viable economic solutions to problems may be found in many cases if the point of reference goes beyond conventional off-the-shelf alternatives. Have the authors identified other areas of underutilized network element capability that could also be used for system disturbances? What would be the best way to simulate them when device availability is time limited by overload constraints, for example five or ten minutes.

At the paper presentation, new simulation results were presented showing the effect of transient excitation boosting for highly stressed conditions. Inclusion of these results in the closure would a valuable addition to the paper.

Manuscript received August 10, 1992.

Carson W. Taylor, **Jeff R. Mechenbier**, and **Charles E. Matthews**, Bonneville Power Administration, Portland Oregon: We thank Mr. Mittelstadt for his interest in our work.

Severe, but infrequent occurring, power system disturbances can often be effectively mitigated by special stability controls. ("Effective" is used in an engineering sense, meaning the same as "cost-effective.") Reliability of special stability controls can be made adequate by design.

For the problem described in the paper, other controls could be developed. Several years after the transient excitation boosting project was started, voltage stability became a concern in the Puget Sound and Portland load areas. This led to plans for installation of 500-kV mechanically switched capacitor banks (MSCs) and static var compensations (SVCs) in these load areas. Following detection of HVDC Intertie outages, energization of MSCs or increase of SVC voltage setpoints would increase voltage sensitive loads, and thus brake accelerating Northwest generators similar to transient excitation boosting. If voltages were abnormally high, MSCs would be switched off by local voltage control relays after some seconds.

A novel method to improve either angle or voltage stability is to utilize the short-term overvoltage capability of shunt capacitors by temporary shorting of series groups of large shunt capacitor banks [1]. For Pacific Intertie transient angle stability or longer-term voltage stability [2] or both, this technique could be applied to the 500-kV capacitor banks installed at the Malin and Table Mountain substations.

Modeling and simulation of special stability controls is generally straight-forward. However, it is important to design control and protection so that equipment damage will not occur. Depending on the conditions studied, this control and protection may need to be modeled. It's also important to assess system performance and control strategies after the short-term overload has been utilized.

The new simulations for highly stressed conditions are for light load spring conditions with the Pacific HVDC Intertie at 3100 MW and the AC Intertie at 2900 MW. The bipolar outage is followed by 2370 MW of Northwest generator tripping and by insertion of 800 MVAr of 500-kV shunt capacitor banks on the AC Intertie (Malin and Table Mountain). Insertion of series capacitors on the AC Intertie is assumed to fail.

Figure 1 shows angle swings of a Grand Coulee unit relative to the San Onofre nuclear plant in Southern California. Without transient excitation boosting, AC Intertie instability occurs on the second swing. With TEB on four Grand Coulee units, stability is maintained for the first three swings, but low frequency oscillations are growing. TEB substantially reduces the angle swings.

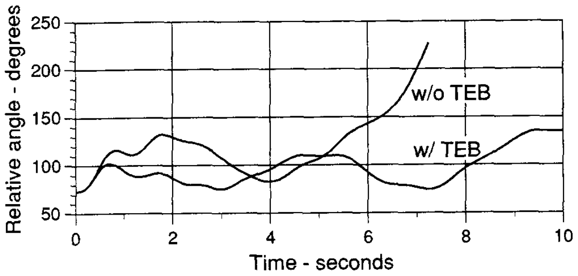

Fig. 1. Rotor angle swing of Grand Coulee unit 19 relative to the San Onofre nuclear plant in Southern California.

Related cases show that series capacitor insertion is very effective, resulting in a short first forward swing and stable subsequent swings. TEB appears to provide initial braking mainly on the backswing, causing the following swings to be somewhat larger.

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Manuscript received October 2, 1992.