

IEEE Transactions on Power Delivery, Vol. 11, No. 2, April 1996

CAPS: Improving Power System Stability Using the Time-Overvoltage Capability of Large Shunt Capacitor Banks

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Abstract — A new special stability control termed CAPS improves power system stability by exploiting the time-overvoltage capability of large shunt capacitor banks. During low voltage emergencies, several series groups of wye-connected capacitor banks are shorted to increase reactive power output. We describe successful commissioning tests on a 241.5-kV, 168-MVAr capacitor bank.

I. INTRODUCTION

Voltage instability and voltage collapse concern electric utilities [1]. Although main circuit reinforcements are more robust, control-based countermeasures are usually more cost-effective [2]. Voltage collapse is often only a threat during unusual conditions such as very high load and major outages. For these low probability conditions, only low-cost emergency controls are justified. Time-coordinated steps of emergency controls ensures reliability—undervoltage or other load shedding is the final step.

Compared to transmission line, series capacitor, or synchronous condenser additions, reactive power compensation by shunt capacitor banks increases power system vulnerability to voltage collapse. This is because the reactive power output of shunt capacitor banks is proportional to the voltage squared.

In an earlier paper, we explored a novel method to improve voltage stability using large shunt capacitor banks [3]. The basic idea is simple: Compensate for the voltage squared characteristic by reducing the capacitor bank reactance during low voltage.

\[ Q_c = \frac{V^2}{X_c} \]

We reduce the capacitor bank reactance by shorting several series groups (layers) of wye-connected banks.

Used on several large capacitor banks, the additional reactive power output allows time for corrective actions such as generation rescheduling, line restoration, or operator-directed load tripping.

The new emergency control is termed CAPS (CApacitor bank series group Shorting). We report on a prototype installation on a Bonneville Power Administration 241.5-kV, 168-MVAr capacitor bank.

We describe the successful commissioning tests. The scheme is now in commercial service.

We also discuss possible design refinements and potential for future applications on large 500-kV capacitor banks.

CAPS can also improve transient angle stability.

II. SHUNT CAPACITOR BANKS

Historically, the generation and distribution subsystems supplied most of the reactive power compensation needs of power systems. Shunt capacitor banks, however, often have lower life-cycle costs than generators with a low power factor rating [4]. Because of the flexibility in locating shunt capacitor banks, total reactive power requirements are lower.

As we load transmission networks well above surge impedance loading, large EHV shunt capacitor banks tend to supplement shunt capacitor banks at lower voltages. Bonneville Power Administration, which operates the world's largest 500-kV network (7049 km), has nine 500-kV shunt capacitor banks rated 300-350 MVAr. These banks support voltages in the Seattle and Portland load areas, and some are mainly used for voltage stability emergencies. Chapter 7 of reference 1 describes voltage stability problems and solutions in the Pacific Northwest.

Two 500-kV, 200 MVAr banks are installed on the Pacific Intertie for fast insertion to improve both transient angle stability and voltage stability [5].

III. CAPS 230-KV PROTOTYPE

CAPS improves stability by using the time-overvoltage capability of capacitors. We have implemented and tested the method on a 241.5-kV, 168-MVAr capacitor bank at Olympia Substation, located south of Seattle, Washington. For impending voltage collapse, controls initiate shorting of three out of fourteen series groups to increase reactive current by a factor of 14/11 or 127%. We partially exploit capacitor overvoltage capability (approximately thirty minutes at 125% of rated voltage).

Figure 1 shows the Olympia Substation capacitor bank schematic and the switching equipment. Shorting is performed near the grounded end to

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reduce equipment cost. CAPS equipment includes:

- Vacuum switch and current limiting reactor for shorting of three series groups.
- Magnetic potential transformer in shunt with the three series groups that are shorted. The MPT discharges trapped charge.
- Microprocessor voltage controller,
- An additional voltage differential relay in service for the shorted series group condition.

Figure 2 shows the capacitor bank reactive power versus voltage characteristic.

Referring to Figure 2, the earlier paper [3] proposed two switches in binary sequence to obtain a smoother characteristic akin to the thyristor switched capacitor type of static var compensator. One switch could short one series group and a second switch could short two series groups. One switch, however, is more reliable and cost-effective.

IV. CAPS CONTROL AND PROTECTION

The voltage at the Olympia 230-kV bus is normally held between 234 kV and 239 kV, with 239 kV being the target during on-peak hours. The controls restrict CAPS operation to low network voltage conditions thereby reducing overvoltage duty on the capacitors. The CAPS control algorithm is:

1. Close shorting switch if bus voltage is less than 224 kV for twelve seconds. The reactive power output increases by 27% or about 39 MVar.
2. Open switch if bus voltage is greater than 230 kV for twenty seconds. (With the three series groups shorted, 230 kV bus voltage, and no blown fuses, the voltage on the unshorted capacitors is 121 percent of capacitor rated voltage. With one blown fuse and 230 kV bus voltage, the maximum capacitor voltage is 127% of rated.)
3. Open switch for a second blown fuse. (In normal mode the bank trips with three blown fuses.)
4. Open switch if it has been closed more than fifteen minutes. (The time delay could be coordinated with the time for corrective actions such as starting and loading gas turbines, but would not exceed thirty minutes.)
5. To prevent repeated stress on capacitors for controller malfunctions (e.g., pumping), limit operation, arbitrarily, to once every sixty minutes.

A commercially available microprocessor-based voltage controller initiates switch operation (Schweitzer Engineering Laboratories SEL-187V [6]). The voltage measurement is accurate to ±0.25 volts based on a 67-volt PT source; for 230-kV, this corresponds to about ±0.86 kV phase-phase primary RMS voltage. Control is based on the average voltage of the three phases.

BPA uses identical controllers for voltage differential relaying. Practice for many years has been to detect blown fuses by a BPA-developed voltage differential scheme [6,7]. For each phase, this relay compares bus voltage with the scaled voltage across the bottom group of the capacitor bank.

* The voltage differential relay for each phase computes \( \Delta V = V_{bus} - K(V_{tap}) \). \( K \) is a scaling factor that changes with the number of series rows on either side of the tap. \( \Delta V \) is zero with no blown fuses.
The voltage differential relaying presents difficulties since the relay settings must be changed whenever the three groups are shorted. Two relay sets are used, with the active set enabled by the auxiliary contacts of the shorting switch. EMTP simulations showed that enabling the relay used with the bank normal should be delayed about one second. This allows damping of the transients associated with shorting switch opening. This time delay is acceptable for capacitor bank protection.

The energy that the capacitor/fuse must handle during a capacitor failure depends on the type of failure. The worst case scenario is a direct short (i.e., bushing failure) yet this is a low probability occurrence. For this case while in the shorted mode the total energy discharge possible is 17.5 kJ. This assumes one fuse already blown, the bus voltage at 230 kV, a parallel energized 168 MVAR bank, and capacitor tolerance less than +3%. Most of this energy will be absorbed by the fuse; the rest by the capacitor and buswork. The capacitor manufacturer was consulted regarding the energy capability of the capacitor and fuse tube.

V. SHORTING SWITCH

The shorting or bypass switch is a 69-kV Joslyn VBU vacuum switch with four interrupter contacts per phase. The switch rating is 600 A continuous, 40 kA momentary. For closing, the manufacturer designed the switch for up to 10 kA. To handle 12 kA, stiffer overtravel springs were used. The switch includes zero-voltage closing control to reduce closing transients (capacitor outrush current).

VI. CURRENT LIMITING REACTORS

The air-core reactors are rated 24.5-kV, 0.5 mH. The reactors limit capacitor outrush current if the zero-voltage closing control malfunctions. EMTP simulations showed the 0.5 mH rating limits outrush current to 12 kA (12 kA was based on the switch manufacturer's previous design limit).

VII. MAGNETIC POTENTIAL TRANSFORMER

The discharge magnetic potential transformer (MPT) rapidly eliminates the dc offset causing over-voltage across the capacitors and shorting switch when the switch opens to reinsert the shorted capacitor groups. The voltage across the three series groups and switch oscillate at 60 Hz between zero and two times normal peak voltage with full dc offset (1-cosine waveform, see Figure 6). This is due to the shorting switch interrupting near zero capacitor current with the voltage across the capacitor bank near voltage peak. The three series groups begin charging from zero voltage causing a new distribution of voltage across all the series groups in the bank. The dc voltage level of the three series groups, \( V_{dc} = 3V_{peak} \), is distributed equally among the other eleven series groups resulting in \( V_{dc} = (3/11)V_{peak} \) across each group. The dc charge saturates the MPT, discharging the capacitor groups with a time constant of the MPT primary winding dc resistance and “air-core” inductance. The discharge energy capability was evaluated by testing.

Initially, we were concerned about the overvoltages on the capacitors causing a failure at a critical time. If a complete short circuit failure did occur at two per unit peak voltage, the expulsion fuses are not coordinated to withstand the parallel discharge energy. Current limiting fuses on the three shorted series groups could be used. As it turns out, shunt capacitors are expected to see dc offset when a fuse clears a short-circuited (failed) capacitor. In any case, the discharge MPT significantly reduces the likelihood that a weak capacitor unit would evolve into a complete short circuit internal fault. In addition, the discharge MPT also reduces the duration the switch must withstand two per unit peak voltage. The dc stress or peak voltage on the other eleven series groups is also quickly removed. This also shortens the duration the voltage differential relaying PT (on the bottom series group) is in saturation, which affects the protective relaying. The energy the relaying PT must discharge is not excessive. The dc offset due to opening the shorting switch is one-tenth of the dc offset normally trapped when de-energizing the bank during normal service.

VIII. CAPACITOR TESTING

There is some concern since capacitor over-voltage capability suggested by standards [9] is a guide only, and is not a BPA specification requirement verified by factory or acceptance testing.

The IEEE Standard for Shunt Power Capacitors states: A capacitor may reasonably be expected to withstand, during normal service life, a combined total of 300 applications of power frequency terminal-to-terminal overvoltages without superimposed transients or harmonic content, of the magnitudes and durations given in the Table 1:

<table>
<thead>
<tr>
<th>Duration</th>
<th>Maximum permissible voltage in per unit of rated RMS voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 cycles</td>
<td>2.20</td>
</tr>
<tr>
<td>15 cycles</td>
<td>2.00</td>
</tr>
<tr>
<td>1 second</td>
<td>1.70</td>
</tr>
<tr>
<td>15 seconds</td>
<td>1.40</td>
</tr>
<tr>
<td>1 minute</td>
<td>1.30</td>
</tr>
<tr>
<td>30 minutes</td>
<td>1.25</td>
</tr>
</tbody>
</table>

BPA requires capacitors to withstand a three per unit, five second ac voltage hi-potential test. We are,
however, considering longer duration tests that evaluate partial discharge inception voltages. BPA laboratory tests investigated the potential for capacitor failure during overvoltages up to thirty minutes duration. We tested eighteen capacitors from three U.S. manufacturers, most of standard design. The capacitors were all rated 7960 volts, 100 kVAr.

All capacitors were energized at rated voltage for at least thirty minutes prior to step voltage tests. The capacitors were then reenergized at 130% rated voltage for thirty minutes. The voltage was then raised to 140% for an additional thirty minutes, and so on in 10% steps until failure. Partial discharge inception voltages were measured with a 60 kHz ultrasonic transducer. Average discharge inception levels varied by manufacturer from 143% to 173% rated voltage. Minimum failure levels varied by manufacturer from 160% to 230% rated voltage.

The laboratory testing suggested that the effect of CAPS should be minimal, provided that any transient induced partial discharge does not continue at steady-state operating voltages below 130% of rated.

IX. COMMISSIONING TESTS

Figure 3 shows one phase of the Olympia Substation capacitor bank.

BPA commissioned the CAPS scheme on July 14–15, 1994. Comprehensive testing verified EMTP simulations and verified that the equipment worked as expected. EMTP simulations [8] corresponded well with field tests.

For the tests, the voltage control cutin/cutout levels were adjusted to higher settings to allow energization without making major transmission changes to obtain abnormally low voltages. The 230-kV bus voltage for the tests was around 238 kV.

The shorting switch was closed and opened over thirty times under high voltage to adjust the timing of the zero-voltage closing on each phase, and to exercise the scheme. Figure 4 shows a typical closing operation with zero-voltage closing control. Figure 4a shows the increase in bank current of about 27% following series group shorting. The bus voltage increases about 0.5% (not shown). Bank reactive power increases from 167 MVAR to 215 MVAR.

Figure 4b shows the switch voltage and the performance of the zero-voltage closing control. Figure 4c shows typical switch currents using controlled closing. The transient frequency superimposed on the 60 Hz current is around 1170 Hz, corresponding to the current limiting reactor and the parallel capacitance (L-C) circuit. To account for possible drift in the timing, the closing is delayed until 0.3 milliseconds (±0.1 ms) after the zero-voltage crossing. Measurements of delay times of 0.00, 0.30, and 0.55 milliseconds resulted in peak current magnitudes of 1.2, 2.1, and 3.0 kA respect-
failures that could evolve into a short circuit. Since the discharge MPT reduced the overvoltages so quickly, we did not expect more than one or two rolls to fail at one time. The capacitor units had six internal series groups. Although the measuring instrument was considered adequate to determine one internal roll failure out of twenty parallel units, measurements varied too much to be useful.
Tests verified that the voltage differential relaying did not operate in the shorted mode. In the normal mode, the bank remains in service with two blown fuses.

Overall, the commissioning tests were successful. Minor problems in the control circuits were corrected. In pre-commissioning testing for adjustment of the shorting switch zero-voltage closing, one switch pole became stuck in the close position due to contact welding. Because of this problem, stiffer springs were installed to increase contact pressure and minimize possible contact bounce. During one commissioning test, a shorting switch failed to latch closed; a switch pole did close, then tripped by pole discordance relaying. We suspect faulty contacts on the pole discordance timer.

The CAPS scheme is now in commercial service at Olympia Substation. BPA plans to exercise the scheme each fall prior to heavy load winter conditions when voltage stability is a concern.

X. COST CONSIDERATIONS

CAPS, which consists of relatively low voltage equipment and controls, is economically attractive in some circumstances. Indeed, CAPS has some of the variable reactive power output capabilities of very expensive static var compensators.

If switching in large increments is acceptable, additional shunt compensation can be obtained at low incremental cost by simply using larger bank sizes. This, however, causes larger voltage changes during daily capacitor bank switching. The 241.5-kV, 168-MVAR banks at Olympia are, in fact, an example where operators avoid switching because of the large voltage change.

For emergency needs, CAPS is economical compared to additional conventional capacitor banks. For the Olympia case, 27% additional output (about 45 MVAR at rated voltage) is gained. A new 230-kV bank of this size would be much more expensive, especially if a circuit breaker rather than a circuit switcher was required. (For 230-kV capacitor banks, BPA uses one circuit breaker with fault interrupting capability for several banks that are individually switched by circuit switchers. For 500-kV capacitor banks, only circuit breakers are used. Current limiting reactors are used when parallel banks are switched.)

Perhaps a better comparison related to the Olympia installation is to compare four 168-MVAR banks equipped with CAPS to five 168-MVAR banks without CAPS, with the fifth bank used during emergencies. The installed cost of CAPS is about $126,000 or $504,000 for four installations. The cost of a 168-MVAR bank is about $1.16 million.

XI. 500-KV IMPLEMENTATION

We are investigating CAPS for BPA's 500-kV capacitor banks of around 300 MVAR rating. At 500-kV, BPA is currently using a double-wye bank design. For CAPS to be attractive, a design where both legs are controlled by a single shorting switch is required. We are currently developing designs. Now that the Olympia prototype has been successfully demonstrated, we are proceeding with value engineering of capacitor bank and CAPS designs that may allow cost reductions. We are evaluating the following changes for either cost or performance improvement:

1. The zero-voltage closing control and the current limiting reactor perform the same function. A smaller current limiting reactor with thirty minute rating could be used. A circuit switcher with pre-insertion inductors could be used. A circuit breaker with closing and opening resistors could eliminate the need for the MPTs and current limiting reactors.

2. The switch opening control could keep the switch closed longer than fifteen minutes if the bus voltage remains severely depressed. The switch could remain closed for a variable time based on the capacitor time-overvoltage capability.

3. Integrated control and protection (e.g., programmable logic controllers) will reduce relay complexity and may yield savings.

4. Alternate protection methods [11], internally fused or fuseless capacitors may eliminate the need for voltage differential relay switching.

5. Current limiting fuses could be considered on the shorted series groups, replacing the MPT.

6. Additional factory or acceptance testing of capacitors and switchgear could increase confidence in overvoltage capabilities, reducing the need for the MPT.

7. The bank insulation system should be evaluated by the capacitor manufacturer at the design stage. For the Olympia 230-kV prototype, the bank impulse strength with group shorting is reduced from 1130 kV to 925 kV BIL, which still exceeds station levels of 900 kV. Consideration of overvoltages due to blown fuses is also important in evaluating the necessary insulation.

CAPS may be compared to series capacitor banks which are usually designed for temporary overvoltage capability [10]. Both design review and factory tests verify this capability. The temporary overvoltage capability avoids very large bank ratings that would be required for outage of parallel lines. Similar design considerations (involving additional cost) and the overall economic considerations apply to CAPS.
XII. APPLICATIONS FOR ANGLE STABILITY

Utilities have applied switched shunt capacitor banks/shunt reactors or static var compensators for transient stability improvement. Application is generally near the midpoints of long interconnections. CAPS is applicable here also. Series group shorting following detection of a severe disturbance need only be for seconds, rather than minutes.

Severe disturbances requiring fast series group shorting can be detected by established methods used for series or shunt capacitor bank insertion. Local or remote signals may be used. BPA has considerable experience with high speed insertion of series and shunt capacitor banks for stability improvement.

XIII. CONCLUDING REMARKS

CAPS is an innovative, simple, and proven emergency control using only local measurement to counteract voltage or angle instability, and improve power system "flexibility." Widespread use on today's highly shunt compensated power systems could, at relatively low cost, reduce voltage collapse problems. CAPS would be applied in urban or suburban load areas where space for additional conventional capacitor banks may be limited.

CAPS could be applied to ensure voltage stability for infrequent, very severe, first contingency disturbances. CAPS would operate before undervoltage load shedding [12] and would reduce the frequency of undervoltage load shedding.

One argument against CAPS is that the reactive power support is available at most for thirty minutes. Considering probabilities in voltage stability planning (value-based planning), this should not be a major factor. BPA has found that 60% of non-momentary 500-kV line outages are restored in less than fifteen minutes. If line restoration or generation rescheduling (including gas turbine start-up) is not successful, manual load tripping before capacitor group reinsertions is a last resort. Load tripping frequency would be very low.

CAPS could be integrated into HVDC or static var system schemes. CAPS would be used with HVDC power factor correction capacitors or with mechanically switched capacitors controlled by an SVC.

XIV. ACKNOWLEDGMENTS

Many BPA engineers contributed to the CAPS project. Jerry Nordstrom (now retired) simulated CAPS using the EMTP. Sam Perkins designed the high voltage installation. Jules Esztergalyos and Jenene Schafman were responsible for the control and protection. Ron Denis, Randy Suhrbier, Kelly Messer, and others helped test and commission the Olympia Substation installation.

XV. REFERENCES


Carson W. Taylor is a Principal Engineer at the Bonneville Power Administration.

Mr. Taylor is a Fellow of the IEEE and chairs its Special Stability Controls Working Group. He is convener of two CIGRE task forces on voltage stability.

Mr. Taylor is the author of the EPRI-sponsored book Power System Voltage Stability, and is the author of many IEEE and CIGRE papers.

Mr. Taylor is also the principal of Carson Taylor Seminars, a seminar and consulting company.

Allen L. Van Leuven received his BSEE degree in 1982 from Oregon State University. He currently is a high voltage equipment expert supporting transmission planning at BPA.
Discussion

D. N. Kosterev, Oregon State University, Corvallis, Oregon and W. A. Mittelstadt, Bonneville Power Administration, Portland, Oregon: The CAPS represents a cost-effective alternative to existing (such as SVC) and new (such as Static Condenser) controlled shunt compensators, when used for low-probability emergencies. The presented concept of CAPS can be generalized for a device consisting of several controlled modules. In this case, the device reactance can vary in discrete steps depending on the number of bypassed modules (shorted series groups):

$$X_c = \text{SUM}(X_i \times S_i),$$

where

- $X_c$ - net reactance of the shunt compensator
- $X_i$ - reactance of the $i$-th capacitor module (series group)
- $S_i$ - status of the $i$-th module (0 - bypassed, 1 - inserted).

CAPS control capabilities can be characterized using $V$-$I$ (bus voltage vs. capacitor current) plane, Figure A. Each line slope corresponds to the net reactance $X_c$ of the shunt compensator. In the presented example, five of fourteen groups are controllable, resulting in six available reactance levels.

The following current ratings of shunt capacitors are considered and used in planning studies:

- $I_{\text{rat}}$ - continuous current rating
- $I_{\text{temp}}$ - temporary (30-minute) overload rating
- $I_{\text{tran}}$ - transient (15-second) overload rating.

Table 1 in the paper gives relationships between them: $I_{\text{temp}} = 1.25 I_{\text{rat}}$; $I_{\text{tran}} = 1.4 I_{\text{rat}}$. For a given bus voltage $U$, the capacitor current $I_c = U / X_c$ should not exceed the corresponding current rating. In Figure A, continuous capability characteristics are shown by solid lines, temporary (30-minute) overload characteristics are shown by dashed lines, and transient (15-second) overload characteristics are shown by dotted lines. These capability characteristics can be used when sizing and rating CAPS equipment, and for designing stability controls.

Thyristor valves can be used as power switches instead of mechanical breakers, providing fast bypass and reinsertion of capacitor modules. Also, point-of-wave switching can be implemented using thyristors, resulting in continuous control range of the device.

We would like the authors to provide their opinion on the above comments and on the future development of CAPS.

Manuscript received August 15, 1995.

SIMON R. CHANQ, HYDRO-QUÉBEC MONTREAL, QUEBEC (CANADA): The authors are to be congratulated for a valuable and excellent paper regarding the use of the time-overvoltage capability of large shunt capacitor banks for the purpose of improving power system stability. The paper illustrates the withstand capability of the tested capacitor units which were designed and manufactured according to the existing standards without any additional specification requirements. The authors are invited to discuss in which ways and to what limits would the performance be improved if capacitors were specified to withstand three per unit rated voltage for five seconds (BPA hi-potential test requirement).

It is also not clear if the tests were performed on capacitors with conventional foil edge, folded foil edge design or other foil construction technique. The authors may elaborate and give details on the dielectric thickness per unit of rated voltage, indicate the volts per mil stress of the tested capacitor units and give the corona starting voltage to failure levels.

Comparing the PDIV levels stated in the paper (143% to 173% of rated voltage) to data which we received from one manufacturer (200% to 250% of rated voltage at 25°C dielectric temperature) depending on the foil edge design, one can conclude that the variation of the PDIV levels are dependent on the dielectric fluid and winding design. The worst PDIV levels are considered at -40°C and vary from 150% to 200% of the rated voltage for some impregnating fluids. Therefore, it is reasonable to assume that good performance of todays all-film capacitors can be achieved by more than one design approach which leads to different PDIV and PDEV levels. Consequently, the user should be aware of the true capacitor overvoltage withstand capability as a function of time if one wishes to operate capacitor banks at elevated voltages. In all cases, the effect upon capacitors to operate continuously to voltages of up to 1.3 p.u. should be negligible provided that cold temperature transient overvoltage duty is accounted for in capacitor specifications.
Views and comments by the authors would be much appreciated.

Manuscript received August 18, 1995.

GEORGE R. NEWCOMB, Senior Member IEEE, General Electric Co., Ft Edward, NY: The CAPS concept is a clever way of utilizing the short time overvoltage capability of capacitors. As the authors mention, this is similar to the short time overvoltage withstand required of series capacitors. But, as for most series capacitors, the capacitors subjected to this duty may have to be more conservative than "industry standard" shunt capacitors.

In section VIII, testing was done to check overvoltage capability of some capacitors, most of "standard" design. It is our understanding that this testing was done at room temperature. The overvoltage capability will be reduced at lower temperatures and DIV of 143-173% at room temperature may reduce to less than 130% at -40°C.

The last paragraph of this section states that "...the effect of CAPS should be minimal, provided that any transient induced partial discharge does not continue at steady-state operating voltages below 130% rated." Note that Table 1, showing expected overvoltage capability during normal service life, includes values that are to be limited (per IEEE Std 18) to a combined total of 300 applications and are not to include superimposed transients or harmonic content. Therefore, "industry standard" capacitors that are designed to withstand transients superimposed on power frequency voltages up to 110% may not be suitable for CAPS.

IEEE Std 18 - 1992, clause 7.2.1, states that "for systems with higher than normal overvoltages, a special design for capacitors rated 2400 V rms or higher may be used, for which this test (terminal-to-terminal routine test) will be increased to a dc test voltage of 6.25 x rated voltage rms ...". In the past BPA's specification required 6.25 x rated capability. Capacitors with this capability will better withstand the overvoltages imposed by CAPS. Also, use of capacitors with this extra overvoltage capability reduces the need for the MPT to avoid capacitor failure due to DC offset. The time to discharge the offset through the internal discharge resistor should be acceptable.

Manuscript received August 21, 1995.

Carson W. Taylor and Allen L. Van Leuven, Bonneville Power Administration, Portland, Oregon: We thank the discussers for their interest in CAPS, and for their valuable comments and questions.

Response to Mr. Chano and to Mr. Newcomb. Both discussions pertain to capacitor overvoltage capability. This is an important issue that requires additional industry work and utility/manufacturer dialog. Mr. Newcomb makes several points that question the ability of "standard capacitors" for CAPS applications. Most compelling is the question of partial discharge inception voltage (DIV), or more importantly the discharge extinction voltage (DEV) at cold temperatures. Both discussers debate this. We agree that the DIV and DEV must be understood to avoid failures or shortened life of the capacitor bank. The IEEE Standard 18 does not test for DIV or DEV, nor does it address momentary overvoltages and overcurrents at the minimum temperature of -40°C. Therefore the user is not sure of the capability of the capacitors at the coldest temperatures. This is true for standard shunt capacitor applications and for CAPS.

Most of our CAPS installations would be located in load areas west of the Cascade Mountains where the once-in-two year minimum temperature is -8°C and the once-in-twenty year minimum temperature is -17°C. We thus have some margin from the -40°C capacitor capability.

In addition, the capacitors used for the Olympia Substation installation required a dc design test of 0.25 x rated voltage rms and an ac sample test of 3.0 x rated voltage rms. This apparently requires the manufacturer to add more dielectric capability than what a standard capacitor would require. The BPA units were designed with a voltage stress of 1400 V/mil. For the Olympia bank, the 60 hertz voltages can reach 127 percent of rated voltage. This yields a voltage stress across the capacitor units of less than the 1800 volts/mil that was the design limit for standard capacitors by the same manufacturer. The BPA specified units should be able to handle the 60 hertz overvoltages with switching transients since standard capacitor designs should handle 110% continuous voltage with switching transients down to -40°C.

Mr. Newcomb also points out that the momentary power frequency capabilities established for standard capacitors do not allow for transients or harmonics. Fortunately, the CAPS scheme switching does not cause voltage transients approaching 3 per unit like normal energization of a capacitor bank. When shorting series groups within the bank, the outrush current will be excessive and must be controlled to acceptable levels. The voltage transients on the unshorted series groups will not be significant since the capacitors are already charged to rated voltage and will only overshoot the final voltage by twice the difference between the initial (rated) voltage and final voltage. Transient voltages will be negligible if controlled closing is used such as the Joslyn vacuum switch zero-voltage closing scheme. Voltage transients occurring when the shorted capacitor groups are re-inserted are similar to what a series group would see when a fuse clears a shorted failed capacitor unit. As pointed out in the paper, this would be a 1-cosine recovery voltage approaching 2 per unit peak voltage—one per unit AC voltage with full DC offset.

Both discussers mention BPA's capacitor overvoltage
step tests. We stated that the capacitors tested had DIV ranging from 143% to 173%. For different manufacturers, these are actually the average voltage levels where acoustic readings began. Although we believe this is usually when partial discharge begins, there is some question. For example, we found units with acoustic onset at 1.0 per unit voltage, but with typical failure voltage. Although two of the tested units were BPA specified, most were standard “off the shelf” units. The initial acoustic onset of the BPA specified units were at the same level that failure occurred—2.2 per unit, whereas all of the standard units had onset levels of less than 1.9 per unit. More testing should verify these indications.

Although the utility is ultimately responsible for the trade-offs between conservative design and reduced cost, the capacitor manufacturers know the limitations of their equipment best and therefore can determine the most economical design for new shunt capacitor banks that incorporate CAPS. To achieve the most economical bank design, the manufacturer should also consider the bank insulation, fusing, and protection that are all interrelated. For example, Mr. Newcomb suggests removing the discharge PT since capacitors tested at 6.25 per unit dc should tolerate the offset voltage when the shorted groups are re-inserted. Without the discharge PT, saturating the PT used for bank protection relaying could be weighed against a different bank protection scheme.

*Response to Mr. Kosterev and Mr. Mittelstadt.* The discussers ideas should be pursued. We agree that thyristor or gate-turn-off thyristor valves could be used, resulting in a transformer-less static var compensator that would have important cost advantages over conventional SVCs. Mechanical switching should be more cost-effective, however, if SVC performance is not needed. For example, SVCs are not needed for longer-term voltage stability with voltage sensitive loads such as electric heating.

Thyristor control can reduce switching transients and capacitor overvoltage duty. Continuous control using a thyristor controlled reactor in parallel with shunt capacitor bank series groups would be like recently-developed thyristor controlled series compensation (TCSC). Similar to TCSC, the dc offset for capacitor bank group insertion can be minimized, removing the need for the magnetic potential transformer.

A continuously-controlled SVC results without a transformer, and probably without harmonic filters. For heavy load, normal operation would be at full continuous output with valves blocked and with very low loss. In contrast, a conventional SVC is normally operated at near zero output with some losses. The control capability (with high losses) is reserved for emergencies, with the reactive power capability seldom used. Separate fixed or mechanically switched capacitor banks are required for reactive power support during normal conditions.

Mr. Kosterev has shared EMTP simulations with us that demonstrate the reduced transients and continuous control using either thyristors or gate turn-off thyristors.

*Manuscript received October 26, 1995.*