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BPA'S PACIFIC AC INTERTIE SERIES CAPACITORS: EXPERIENCE, EQUIPMENT & PROTECTION

Gerald E. Lee, Senior Member, IEEE   Daniel L. Goldsworthy, Member, IEEE
Bonneville Power Administration
Portland, OR

Abstract - **Over BPA's 40 years of series capacitor experience, equipment evolution has dramatically reduced the complexity of capacitor protection systems. BPA and other utilities in the Pacific Northwest recently installed 13 new metal oxide varistor (MOV) protected series capacitors. Nearly all the banks use a simplified design which eliminates the typical triggered gap bypass protection for the MOV. The decision to use a gapless design, the MOV energy sizing, and the protective bypass thresholds require extensive EMTP fault simulations. A large number of staged system fault tests were performed to evaluate the integrity of the banks.**

Keywords - **Series Capacitors, Series Compensation, MOV, Varistor, Transient Simulations, EMTP, Fault Tests.**

I. INTRODUCTION

Due to the distances which often separate generation resources from load centers, utility planning engineers have searched for ways of increasing transfer capability while maintaining system stability on long lines. The traditional solution to this problem has been to reduce transfer impedance and increase reliability by constructing additional transmission lines. Today, however, utility planners are facing increasingly severe restrictions on new line construction, creating very long lead times and possibly even eliminating construction as an option. Series capacitors, which provide a direct means of reducing the transmission line inductive reactance, have become an attractive method of increasing transfer capability and improving steady-state and transient stability margins. It is clear that series capacitors cannot substitute for the reliability and operational flexibility provided by additional transmission circuits. However, compared with line construction, series capacitor cost is very low, the lead time is relatively short, and the facilities are placed in substations, where environmental effects are minimized.

For a long intertie, such as the Pacific AC Intertie, series capacitors are a requirement. As part of the Third AC Intertie Project, Bonneville Power Administration (BPA) and other utilities in the Pacific Northwest replaced six older facilities and installed seven new series capacitors on the intertie. A one line diagram for the Project and basic equipment ratings are shown in Figure 1. The facilities were energized in a two year period between the fall of 1991 and the fall of 1993. Successful field tests of four of the 13 new series capacitors verified the design and equipment capability. The completion of this project increased the transfer capability on this intertie between the Pacific Northwest and Pacific Southwest from 3200 to 4800 MW.

BPA's history with series capacitors spans more than 40 years and includes facilities at 230, 345 and 500 kV. Through the years the design of the installations has evolved considerably. The original series capacitors for the ac intertie were put in service in the late 1960s, using the very complex gap and switch protection systems available at the time [1]. The development and successful testing of zinc oxide (ZnO) material for varistor protection on this intertie in the 1970s [2], established a new generation of simple and reliable methods of protecting series capacitors from overvoltages due to system faults. The new intertie series capacitors are unique even from those built in the 1980s. This paper provides background on BPA's series capacitor experience, discusses the important equipment and protection features of the new intertie banks, and describes the computer studies and specification requirements leading to the metal oxide varistor (MOV) designs. Terms such as metal oxide varistor (MOV or varistor) and silicon carbide (SiC), which are used throughout this paper, describe materials which exhibit extreme non-linear V-I characteristics.

II. BPA EXPERIENCE AT 500 KV

Since the energization of BPA's first 500-kV series capacitor facilities at Fort Rock, Sand Springs, Bakeoven and Sycan in 1968 and 1969 the design of equipment and control systems has evolved significantly. These original facilities, which have been replaced by the new intertie capacitors, consisted of three segments in series. Each segment was located on its own platform due to voltage limitations of the

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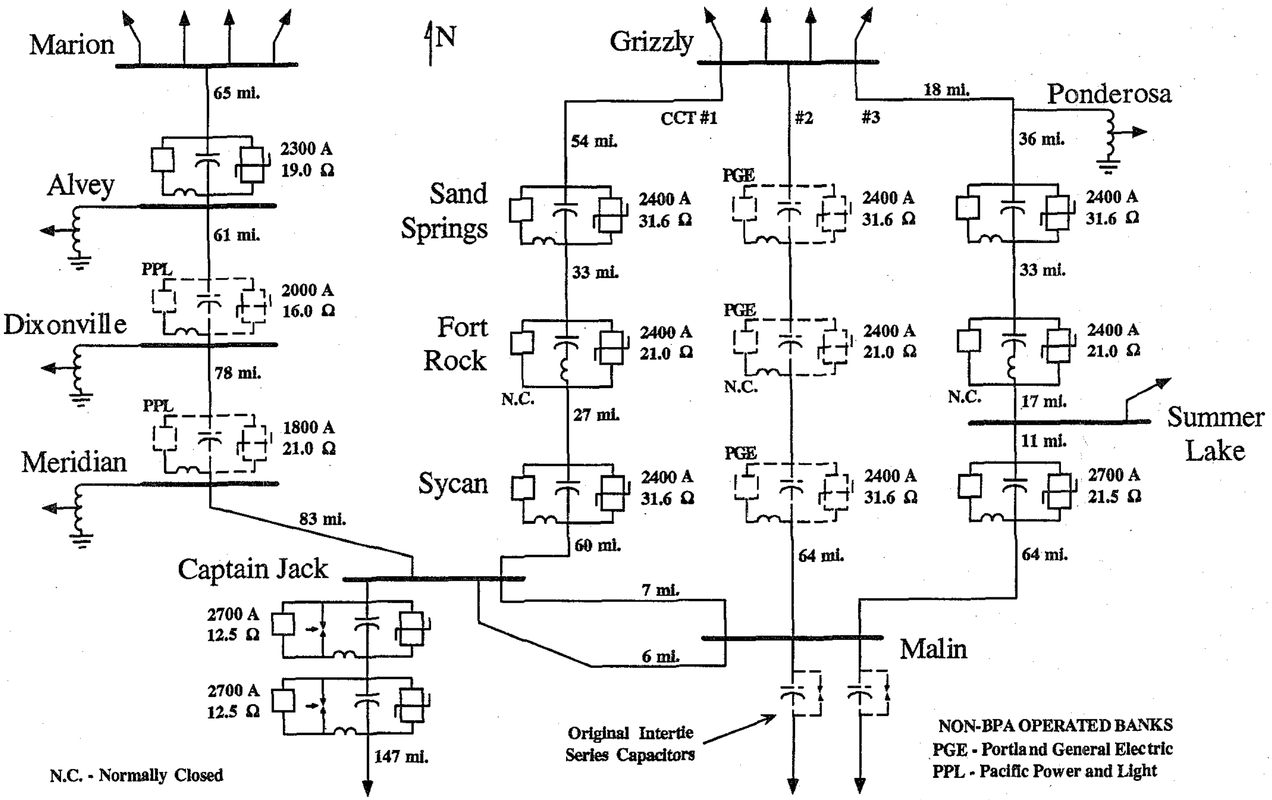


Fig. 1. Series Capacitors for the Third AC Intertie Project in the Pacific Northwest

"gap/switch", a combination gap and bypass switch for capacitor overvoltage protection. Figure 2 provides a simplified schematic of one segment of the original series capacitor bank at Fort Rock. The capacitors utilized an oil/paper dielectric and were protected by a gap/switch, which sparked over via a pilot gap if the voltage across the capacitors exceeded roughly 3.5 times the capacitor voltage present at rated current. If the gap conduction exceeded 20 cycles (1/3 second) then the bypass portion of the switch closed to protect the gap.

A compressed air reservoir (not shown) was located on the platform to supply air for extinguishing the gap arc to reinsert the capacitor after a sparkover. The reservoir was recharged by a compressor at ground level. Discrete relays were located on the platform to perform the control and protective functions and CTs were used to both sense platform quantities as well as provide power. High speed communication between platform and ground was provided via "light pipes", which are the predecessors to fiber optics. Following the destructive failure of gap/switches at Fort Rock in 1973, nonlinear resistors were added to control insertion transients (Figure 2). This solution was successful, though the facility, like the others, still required considerable maintenance due to the mechanical complexity of the gap/switch scheme, the light pipe, pneumatic controls and capacitor/fuse failures. Although some catastrophic failures had occurred, the reliability of these banks was generally acceptable due to effective maintenance practices.

To reduce the reliability problems associated with mechanical complexities and capacitor can failures, a new prototype protection scheme was developed and tested at Bakeoven Substation in 1976 [3]. This scheme involved the installation of silicon carbide (SiC), in parallel with the capacitors of one segment. In 1978 prototype MOV protection using ZnO disks was installed in parallel with one-half segment. Due to the difference in the nonlinear coefficient (alpha) between SiC and ZnO, the SiC scheme was somewhat more complex since it required a gap in series with the resistor. In any case both of these schemes were quite simple compared to the older gap/switch. In the years since the MOV protection was installed, the rate of capacitor can failures in the protected half-segment has decreased to nearly zero, demonstrating an important benefit of the lower protective levels and fewer discharges associated with modern facilities. It was clear from these tests that future facilities could be successfully protected with varistors for reduced complexity and increased reliability.

The next series capacitor installations at BPA were six banks at Garrison and Columbia Substations, which were initially energized in 1984. These facilities use MOVs for capacitor protection, a triggered gap to control MOV duty,

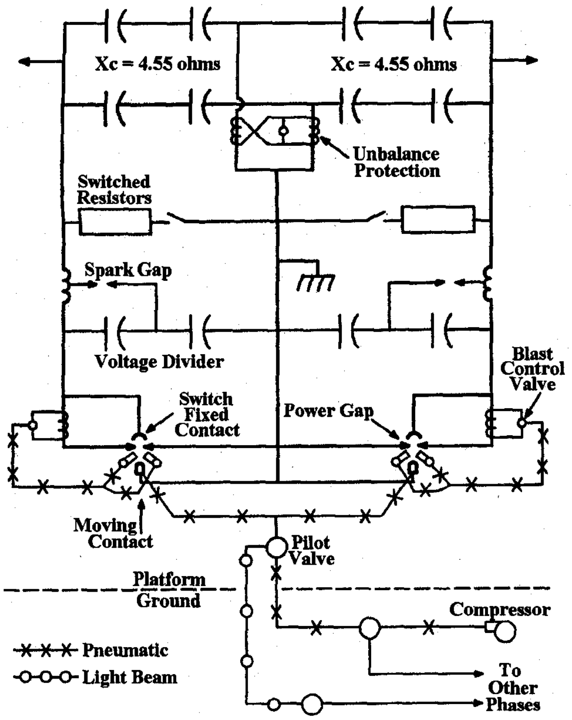


Fig. 2. Single platform of original Fort Rock bank with switched resistor modification. Bank ratings: 1600 A, 27.3 ohms, 210 MVAR

and a platform-based control and protection system with annunciation at ground level via fiber optics. Figure 3 provides a simplified schematic of the major equipment and control configuration of one of the Garrison banks.

Due to design deficiencies in these banks, four years (1984-1988) were required to complete field testing and modifications to raise the reliability and availability to acceptable levels. It became clear from these experiences that future designs should strive for simplicity through the development of facilities which: eliminate the need for transformers across the series capacitors, minimize the platform-mounted control and protection system, and reduce the dependence on triggered gap bypass systems to control varistor duty.

III. NEW SERIES CAPACITOR FACILITIES

With the completion of the Third AC Intertie Project, the northern end of the Pacific AC Intertie now includes four series-compensated, 500-kV circuits. Figure 1 shows the principal lines and the 13 new series capacitor banks for these circuits. The three banks on the Grizzly-Malin Line #2 are owned by Portland General Electric and the banks at Dixonville and Meridian are jointly owned by Pacific Power and Light and BPA. All remaining banks are owned by BPA. The three lines extending south from Grizzly are constructed in the same transmission corridor and all pass through three series compensation stations: Sand Springs, Fort Rock and Sycan. The transmission circuit beginning at Marion and extending to Captain Jack is well to the west of the other three north-south lines.

The basic power equipment for each new bank is shown in Figure 1, along with its rated continuous current and capacitive reactance. The 30 minute overload current ratings for these facilities range from 133 to 150 percent. All banks are equipped with motor-operated disconnect (MOD) switches (not shown) for isolating and bypassing the banks during maintenance. The bypass MOD on each BPA bank is fitted with arcing horns to reduce contact damage during opening under load. Both isolation MODs are equipped with resistors to limit surges when energizing and deenergizing the bank. Each series capacitor is equipped with an SF_6 single-pressure puffer bypass breaker to manually insert or remove the bank under load or to rapidly bypass for equipment failures or other critical conditions. The three banks at Fort Rock, however, are operated normally bypassed via the bypass breaker. These banks are high-speed inserted through a remedial action scheme for a rapid loss of 400 MW or more on the parallel Pacific HVDC Intertie. The resulting increase in compensation is important for improving stability on the ac intertie.

The new series capacitor banks use MOVs to protect the capacitors, but differ from previous facilities in a number of

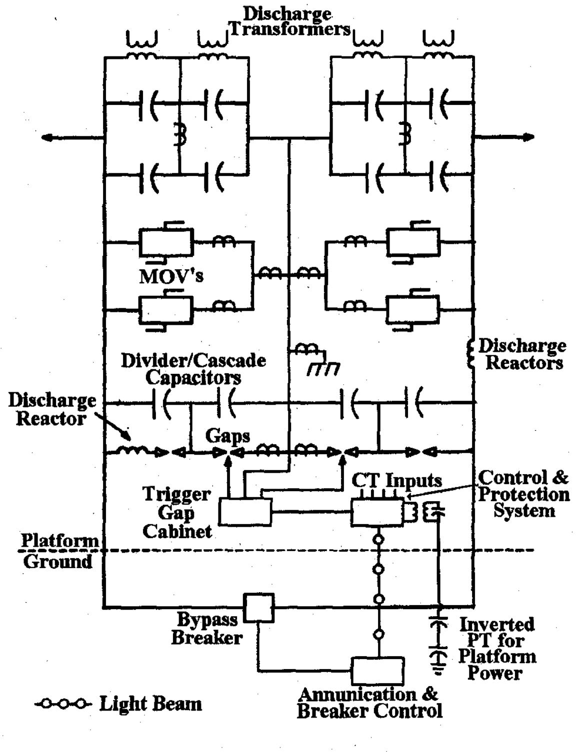


Fig. 3. Series capacitor installation at Garrison Substation. Total bank ratings: 2000 A, 39.5 ohms, 474 MVAR

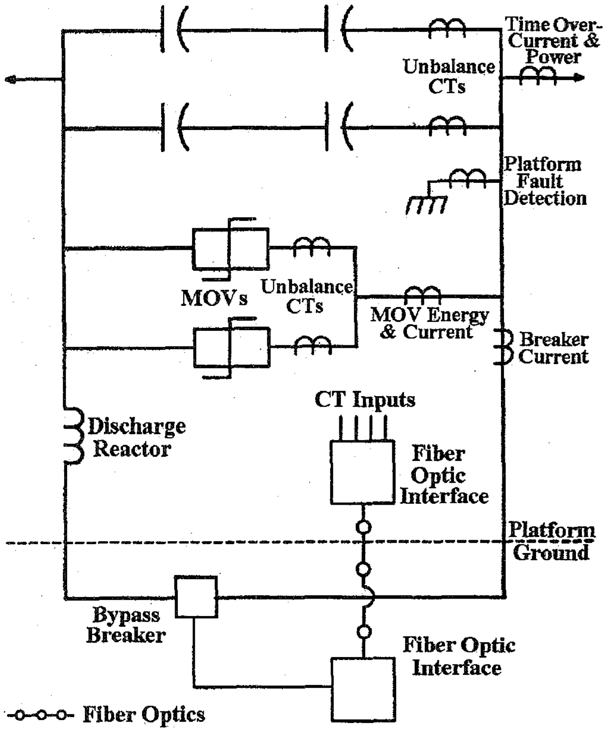


Fig. 4. New gapless series capacitor for Sand Springs. Total bank ratings: 2400 A, 31.6 ohms, 546 MVAR

ways. All but one of these banks are "gapless", using the bypass breaker to limit MOV duty rather than a triggered gap. Also, the entire control and protection system is fully redundant. Figure 4 provides a simplified schematic of the platform equipment and control for one of the gapless banks at Sand Springs. All platform quantities are monitored by CTs and converted at the interface cabinet to analog optical signals for transmission to ground via fiber optics embedded in non-ceramic insulators. At ground level another interface in the control house converts the optical signals to electrical signals for analysis by the controllers.

The series capacitor bank at Captain Jack Substation is at the north end of the new Third AC Intertie circuit connecting the California transmission grid with the Pacific Northwest. This bank is unique from the others in Figure 1 in that it is segmented and incorporates triggered gaps. The two 12.5 ohm segments allow greater load flow control. The reasons for the triggered gaps on these banks and the absence of them on the others are discussed below.

IV. MODERN SERIES CAPACITOR PROTECTION

Series capacitors require protection from the overvoltages resulting from large currents, such as faults. The most important protective equipment for modern banks is the metal oxide varistor (MOV), which is made from zinc oxide (ZnO) disks, and connected directly across the capacitor.

The MOV shunts excess current around the capacitor to hold the capacitor voltage at or below a specified "protective level", even at the highest possible peak fault current. This protective level voltage is typically 2.0 to 2.5 times the peak voltage across the capacitor at rated current and is designated in per unit. The protective level is normally set well above the voltages produced by overload and peak swing currents. The new intertie series capacitor banks use protective levels of 2.2 and 2.3 pu.

The basic circuit for a typical MOV-protected series capacitor consists of five components as shown schematically in Figure 5. Representative voltages and currents for a typical fault are also provided. In this illustration the capacitor bank is initially carrying normal, steady-state load when a fault occurs at about 32 ms. The heavy current from the fault causes the capacitor voltage to rapidly increase until it reaches the MOV conduction voltage. The fault current is immediately shunted into the MOV. Due to the extreme nonlinear characteristic of the MOV, the capacitor voltage is held nearly constant. The current through the MOV results in accumulated energy, which rises in the typical staircase fashion shown in Figure 5.

The MOV current, the accumulated MOV energy and the calculated MOV temperature are monitored by a control and protection system. If any of these quantities exceeds a threshold value, a bypass signal is sent to the triggered gap, or to the bypass breaker, if there is no triggered gap. Reaching a threshold value generally indicates that the MOV is accumulating energy at a rapid rate due to a high-current fault, or that the MOV has been subjected to a series of lesser faults or an extreme overload. In either case the MOV must be bypassed to prevent potential thermal damage or to avoid thermal runaway. In Figure 5 a bypass occurs at 73 ms, about one cycle before the line breakers clear the fault. The ringdown shown is at the natural frequency of the series capacitor and discharge reactor. The air-core discharge reactor is used to limit the discharge current from the capacitor to a safe level and provide damping for the ringdown. Thus, the MOV automatically protects the capacitor from overvoltage while the triggered gap or bypass breaker, via the control system, protects the MOV from absorbing excessive energy.

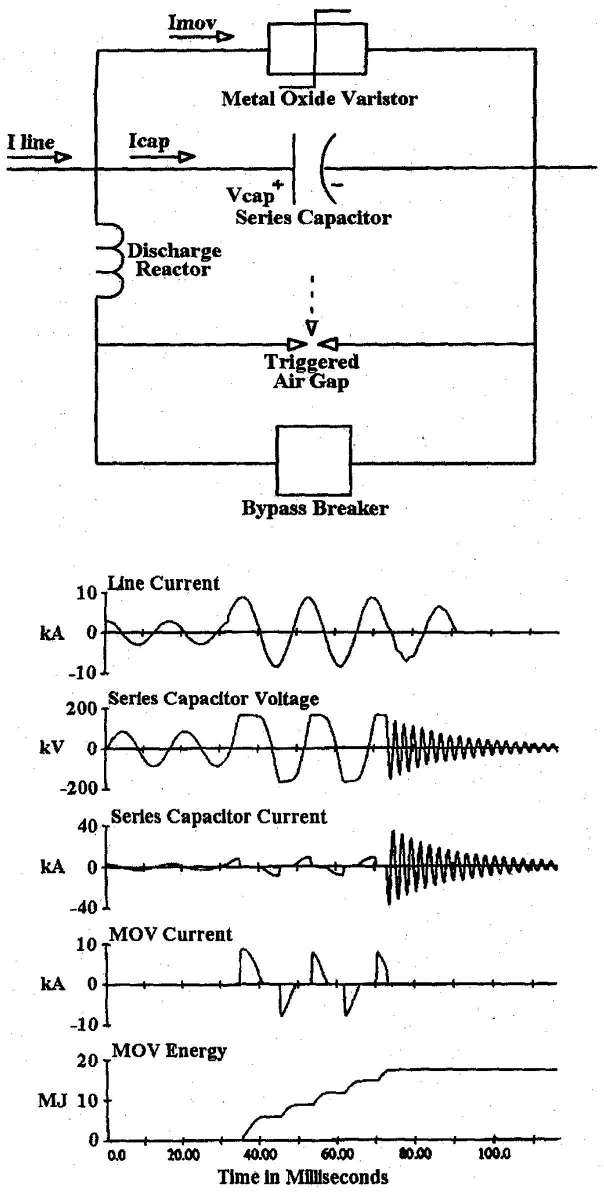


Fig. 5. Basic circuit of an MOV-protected series capacitor with typical voltage and current waveforms during a fault, including bypass.

The critical difference between utilizing a gap or a breaker for MOV protection is the time to bypass the varistor after the control signal to bypass is generated. A fast-closing breaker will take about three cycles while a gap operates within a millisecond. This difference in bypass time translates into additional energy accumulation and therefore a higher required MOV energy capability (more ZnO material) for a gapless bank. The MOV energy accumulated prior to a bypass breaker operation is directly related to the maximum amount of fault current available at the capacitor bank site. Thus, for strong (high MVA) buses, the additional MOV energy requirement for a gapless bank would be very large, making a triggered gap the economical solution. This was the situation for the bank at Captain Jack Substation. The remaining 12 new capacitor banks shown in Figure 1, however, are all 80 km (50 miles) or more from a strong bus and therefore have relatively weak fault current levels. For these banks the reduction in cost from eliminating the triggered gap essentially offset the cost of additional MOV energy requirements. Other considerations, including less complicated, more reliable banks, with reduced maintenance requirements also contributed to decisions favoring gapless designs.

The capacitor bank protection for these new gapless banks has been further simplified by designing the control system thresholds so the bypass breaker need only operate in a three-phase mode to protect the MOV and only for conditions which produce a "line lockout". A line lockout results from a multi-phase fault or an unsuccessful single-pole reclosure. The bypass control thresholds are therefore set above the highest MOV currents and energies expected for a successfully-reclosed single line-to-ground (SLG) fault. This strategy is expected to result in a very small number of high-speed bypass operations for the gapless banks. After a three-phase bypass the bank requires manual reinsertion, which would normally be by a Supervisory Control and Data Acquisition (SCADA) operator after the line is returned to service.

V. VARISTOR SIZING STUDIES AND SPECIFICATIONS

Transient fault studies are required to identify some important characteristics of a series capacitor bank, including the MOV energy requirements, the control system threshold levels, the peak bank fault currents, and even the feasibility of a gapless design. Prior to developing specifications, all the series capacitor banks in Figure 1 were extensively studied at BPA using the BPA Electromagnetic Transients Program (EMTP). The parallel lines from north of the Grizzly bus to south of the Captain Jack and Malin buses along with the associated MOV-protected series capacitors were modeled in detail for these simulations.

Prior to performing the series capacitor protection studies, criteria was developed for defining the type and locations of faults, equipment outage contingencies, breaker operating times, breaker failure conditions and required series capacitor bank performance. The overall criterion and the studies were then divided into two categories of external faults and internal faults.

External fault performance for the MOV-protected series capacitor is governed by transient stability requirements. Some important elements of BPA's external fault criteria include: a breaker clearing time of four cycles, a maximum of one line or piece of equipment out of service, no series capacitor bypass for any four-cycle external fault, and no bypass for 15-cycle breaker failure while clearing a SLG fault. Also the Fort Rock banks could be in service or out, whichever produced a more severe duty. Many transient fault simulations were then performed to find the maximum MOV currents and energies at each bank for external faults. To account for study uncertainties and prevent possible misoperations, a margin of 20% was added to these maximums to establish the external fault control thresholds. These thresholds were then used in some of the internal fault studies.

For internal faults, bypassing on the faulted phase(s) is usually allowed because the series capacitor will be de-energized when the fault current is interrupted by the line breakers. However, as described previously, only three-phase bypassing with manual reinsertion would be used on the gapless banks. Therefore, a second set of control thresholds above the internal SLG fault levels were developed for gapless bank studies. The criterion used at BPA for internal faults does not involve stability concerns, but is primarily to ensure that there is sufficient MOV energy capability for the bank to be self-protecting for a worst-case fault.

Elements of BPA's internal fault criteria include: a line breaker clearing time of four cycles, a breaker failure clearing time of 15 cycles, any system configuration or outage, any type of fault or location, breaker failures for any type of fault, reclosing for SLG faults, and series capacitor bypass time (including control action) of 1/2 cycle for a triggered gap and four cycles for a bypass breaker. Many internal fault cases were then performed to determine the maximum MOV fault currents and energies for each bank for both gap-protected and gapless designs. The specification for the MOV energy requirements was then developed using the transient study results. The specification described how the individual fault events from the studies were to be grouped together by the manufacturer when developing the final varistor design. The aim of this "duty cycle" is to provide a varistor which is sized to withstand, without damage, energy injections associated with worst-case system events, and be thermally stable for lesser events, thus avoiding the need to bypass the facility to allow the varistor to cool. With these objectives in mind the varistor duty cycle specifications were developed and are outlined below.

For gapless systems, the varistor is thermally stable at maximum continuous operating voltage following energy injections due to an internal fault, an external fault and operation at the overload current rating for 30 minutes. The varistor will remain thermally stable if the above duty cycle is repeated in six hours. The varistor is also capable of withstanding, without damage, two internal fault energy injections one minute apart followed by two more in six hours. The internal and external fault energy injections are for worst-case 3-phase faults.

For the gapped system at Captain Jack, the varistor is capable of withstanding two energy injections one minute apart, followed by two more in six hours. Each injection is equal to a full half-cycle of worst-case SLG fault, followed by a reclosure into the fault. In addition to the MOV energy capability for the duty cycles described above, a 15 percent increase in the varistor sizing was specified to account for variations in current sharing between ZnO disk columns. A ten percent redundancy requirement, which accounts for modeling uncertainties and system additions, and a five percent spare requirement, to offset for a unit(s) failure, were also specified.

VI. VARISTOR DESIGNS AND FIELD TESTS

After receiving proposals, BPA determined that seven of the eight series capacitor facilities would be protected using gapless designs. A second transient fault study was performed by the manufacturer for final varistor sizing and control system parameters. Table I provides a summary of the important study results for MOV energy injections and bypass threshold settings which have been used on the eight BPA banks. The internal fault energy injections listed in Table I

Table I. Summary of Bank MOV Protective Characteristics

Bank	Capacitive Reactance (ohms)	Current Rating (kA)	Protective Level (pu)	MOV Bypass Protection	Energy Injection (MJ/ph)		MOV Disks		MOV Bypass Threshold	
					External Fault	Internal Fault*	Parallel No./ph	Series No./ph	Current (kA)	Energy (MJ)
Sand Springs No. 1	31.6	2.4	2.3	Breaker	13.3	85.0	120	34	9.4	27.0
Sand Springs No. 3	31.6	2.4	2.3	Breaker	36.8	103.0	160	34	12.0	44.0
Fort Rock No. 1	21.0	2.4	2.2	Breaker	9.6	37.0	80	21	9.0	13.0
Fort Rock No. 3	21.0	2.4	2.2	Breaker	24.7	53.9	140	21	12.4	30.0
Sycan No. 1	31.6	2.4	2.3	Breaker	12.2	76.0	108	34	10.0	23.0
Sycan No. 3	21.5	2.7	2.2	Breaker	30.0	86.8	172	25	14.0	36.0
Alvey	19.0	2.3	2.2	Breaker	24.5	68.0	180	19	15.0	40.0
Captain Jack**	25.0	2.7	2.2	Trig.Gaps	12.6	47.0	92	14	10.0	17.6

* Also Rated One-Shot MOV Energy Capability

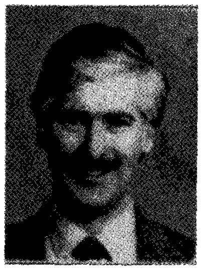
** Total Characteristics for Two Equal Segments are also the installed MOV one-shot energy ratings. It is interesting to note that the MOV one-shot energy rating for any of the gapless banks would have been about 20 percent greater than the external fault energy injections if triggered gap protection had been used. This provides an approximation of the actual amount of varistor which was added to each bank in order to eliminate the triggered gaps, as described in Section IV. The remaining five new and replaced series capacitors in the Pacific Northwest Third AC Intertie project include banks at Sand Springs, Fort Rock and Sycan on the Grizzly-Malin Line #2 line and banks at Dixonville and Meridian substations. These banks were designed with substantially the same criteria and study methods as the BPA banks and all five also incorporate gapless designs. The California-Oregon Transmission Project, the new 500 kV transmission line from the Oregon border to the San Francisco area, also called the Third AC Intertie, included construction of four additional series capacitor banks in California. Three of these banks also use a gapless design. Thus a total of 17 new series capacitor banks were installed for the Third AC Intertie project. Of these banks, 15 use a gapless design, and all were built by the same manufacturer.

BPA field test personnel conducted a total of five large-scale field tests on the new series capacitor banks between November, 1991 and March 1993. These field tests included a total of 41 faults, 36 single line-to-ground and five double line-to-ground. Faults were applied adjacent to eight of the 17 new series capacitor banks in the Third AC Intertie project. The field tests were remarkable in that the series capacitor banks performed fully up to expectations. With the exception of a single MOV column failure during one fault, all of the platform power equipment, including the capacitors, MOV, bypass breakers, discharge reactors, triggered gaps, and bypass controls were found be robust and reliable. The field experience thus far for this equipment has also been excellent.

VII. CONCLUSIONS

BPA and other utilities have installed 13 new MOV-protected series capacitor banks in the Pacific Northwest as part of the Third AC Intertie project. These new banks, which are nearly all gapless designs, are much less complex than earlier series capacitor facilities and have provided highly reliable and low-maintenance service. Field experience has shown that MOV protection significantly reduces capacitor unit failure rates. Extensive transient studies were performed to develop the MOV energy requirement specifications. A large number of staged faults were performed to evaluate the integrity of the new banks. The banks successfully completed all tests and have performed up to expectations since energization. Field test measurements, additional interesting developments and lessons learned during the application of these capacitors to the 500-kV network will be the subject of future papers.

VIII. BIOGRAPHIES



Gerald E. Lee (M' 1974, SM' 1990) was born in Seattle, WA on July 28, 1949. He received his B. Sc degree in Electrical Engineering from Portland State University in 1974. Mr. Lee joined BPA in 1974. For 19 years he has been an equipment specialist and insulation coordination engineer in System Engineering at BPA. Mr. Lee is Chairman of the IEEE/PES Applications of Surge Protective Devices Subcommittee, an industry advisor on the ASC for ANSI C62, IEC TC33 & IEC High Voltage Subcommittees, a project advisor on many EPRI research projects and is a registered Professional Engineer in the state of Oregon.

Daniel Goldsworthy (M' 1980) was born in Butte, Montana in 1955. He attended Montana State University where he received a B.S. in Civil Engineering in 1978 and an M.S. in Electrical Engineering in 1980. Since 1980 he has been employed by the Bonneville Power Administration in Portland, Oregon. His work has centered around transient simulation of ac and dc systems. He is a registered Professional Engineer in the state of Oregon.

IX. ACKNOWLEDGMENT

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