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Mr. Sam Duraiswamy, Reactor Eng.,
Nuclear Regulatory Comm.,
Adv. Comm. on Reactor Safeguards
Washington, D.C. 20555

Dear Mr. Duraiswamy:

In previous correspondence it was stated that valve blocks using zinc oxide instead of silicon carbide have been developed for use in surge arresters for power systems. With the new type of valve block, the series gap is eliminated and columns of ZnO valves can be readily connected in parallel for increased thermal capacity.

THIS DOCUMENT CONTAINS
POOR QUALITY PAGES

RSR-3
x-I.B. Johnson

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AN APPLICATION USING MULTIPLE PORCELAINS IN PARALLEL EACH PORCELAIN CONTAINING FOUR COLUMNS OF DISKS HAS MADE FOR THE PROTECTION OF SERIES CAPACITORS. THIS APPLICATION IS DESCRIBED IN THE ATTACHED IEEE PAPER "A ZINC OXIDE VARISTOR PROTECTIVE SYSTEM FOR SERIES CAPACITORS", IEEE NO. 80 SM 694-0, WHICH WILL BE PRESENTED AT THE IEEE 1980 SPM, IN MINNEAPOLIS. PERHAPS YOU MAY WISH TO PREPARE A DISCUSSION THEREON, INCLUDING SOME QUESTIONS.

SINCERELY YOURS,

80 SM 694-0

A ZINC OXIDE VARISTOR PROTECTIVE SYSTEM FOR SERIES CAPACITORS

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ABSTRACT

A new series capacitor protective system based upon zinc oxide varistor technology has been developed. The new system offers the advantages of instantaneous reinsertion of the series capacitors after an external line section fault and elimination of mechanical action for normal protective operation. This paper describes the general operation of the new system and the equipment and testing of a field prototype.

INTRODUCTION

Series capacitors are an attractive means of compensation because they reduce system impedance. As a complicating factor, however, a parallel protective device is required to provide overvoltage limitation during system faults. Series capacitors in transmission systems have traditionally been protected against these overvoltages by complex combinations of gaps and mechanical bypass switches. These complexities were particularly evident in applications where system load carrying capability and transient stability limits required high speed reinsertion of the capacitors in the unfaulted line section. Furthermore, voltage rating limitations of some of the protective device components often required that the capacitor bank contain two or more segments in series, each with its own complete protective device components. During high speed reinsertion of the capacitor, reinsertion transients could be escalated by trapped charges due to random sequential reinsertion of the individual segments. This could lead to an increased voltage requirement for the capacitor bank, and additional switch and reinsertion resistor control equipment. Unfortunately, the complexity of previously available protective equipment has caused some undesirable operating and maintenance problems.

To eliminate these problems, a protective device using a silicon carbide varistor was specified by BPA and a three-phase prototype was developed by BPA and applied (1976) at Bakeoven in the Pacific NW-SW AC Intertie.[1] In this arrangement, the varistor was placed in series with a gap and connected in parallel with the series capacitor. This allowed lower reinsertion transient voltages and lower protective gap sparkover levels than was possible with protection schemes. In addition, instantaneous reinsertion of the capacitors in the unfaulted line was achieved and thus provided improved stability margins over previously available equipment having longer reinsertion times.

The availability of zinc oxide valve blocks[2] suitable for power system application has permitted the development of a new series capacitor protective system. The protective system consists of four basic elements as shown in Figure 1. On a three-phase installation, each phase would have an identical circuit. Each of the elements has a specific role to play in the overall operation of the device. Most important is the zinc oxide varistor which is connected directly in parallel with the capacitor and which provides the fault overvoltage protection. Connected across the capacitor and the varistor, through a current limiting reactor, is a triggered air gap. The gap does not limit the voltage across the series capacitor - the varistor performs that function. Rather, the firing of this gap is initiated by the control logic that monitors the duty to the zinc oxide varistor. Thus for certain system faults where the varistor current magnitude or duration becomes excessive, the gap is fired, shorting the varistor and protecting it from further duty. In addition, a bypass switch in parallel with the gap automatically closes for abnormal system conditions that cause prolonged current flow through the gap or for certain platform contingencies. The switch also allows an operator to manually insert or bypass the series capacitor. The current limiting reactor limits the capacitor discharge current through the gap and/or switch.

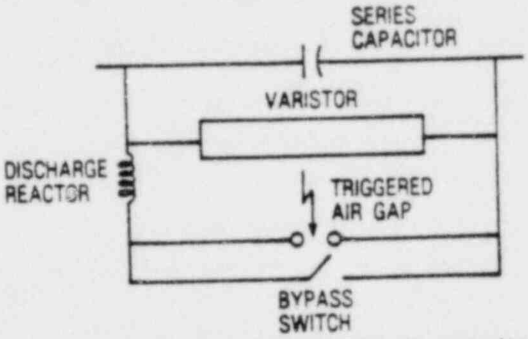

Fig. 1. Basic circuit for new series capacitor protective system.

A prototype installation of the new protective system was supplied under contract to BPA for field testing and long term evaluation. This paper describes various aspects of the zinc oxide varistor, the general operation of the protective scheme and then the particulars of the prototype installation and the associated field tests.

VARISTOR

The varistor consists of a number of zinc oxide disks electrically connected in series and parallel. The disks are the same as those used in the zinc oxide station arrester manufactured by the General Electric Company. The voltage-current characteristics of the columns of disks are carefully matched at the factory to ensure balanced current distribution among the columns. The resultant voltage-current characteristic of the varistor, Figure 2, can be approximated by $I=kV^n$,

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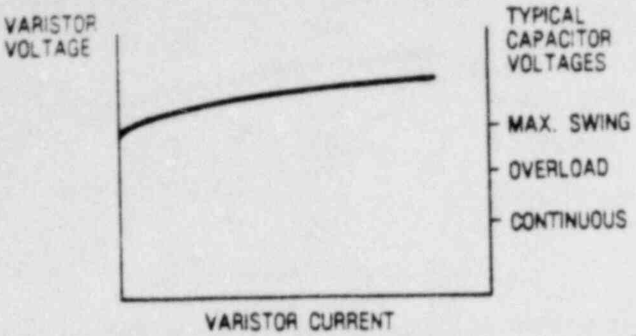

Fig. 2. Voltage-current characteristic of varistor and its general relationship to typical capacitor voltages.

where k depends on the series - parallel arrangement of the disks and n is about 50 over the varistor operating range.

The properties of this zinc oxide make such a varistor practical. Zinc oxide has essentially a zero temperature coefficient of resistance in the high current conduction region, resulting in stable current sharing among columns during a lengthy conduction period. High energy operations do not have any significant permanent effect on the characteristic of the material. In addition, the stability of this zinc oxide allows the varistor to withstand continuous AC voltage stress without significant deterioration. This latter point, in concert with the exceptional nonlinearity of the material, allows the connection of the varistor directly in parallel with the capacitor without the complication of a series gap.

For a particular application the major considerations for the varistor are its required voltage and energy ratings. The voltage rating and the related volt-ampere characteristic are established by the maximum non-fault voltages that are anticipated across the series capacitor. Series capacitors are generally required to carry various magnitudes of current for various time periods. Values often specified are the continuous, the emergency overload and the maximum system swing current the capacitor is anticipated to carry. The latter current is associated with the machine angle fluctuations that occur in a system following a major disturbance. These currents result in voltages across the capacitor and the varistor. The varistor must have enough series disks per column to withstand these continuous and temporary overvoltages. The volt-ampere curve of the varistor must, therefore, be situated above these voltages in the manner illustrated in Figure 2. Although the relationship of the three system voltages shown is fixed for a given system, this relationship will change from system to system. The placement of the varistor voltage characteristic thus reduces to the problem of showing that the varistor will not be overstressed when any of these voltages are maintained for their specified times. For example, if the emergency overload voltage were significantly greater than the continuous operating voltage, this would cause the protective level of the varistor to be higher than it would be if the overload voltage were close in magnitude to the continuous operating voltage.

GENERAL SYSTEM OPERATION

The essential features of the zinc oxide varistor protective system can be described by reviewing simulations of its operation on the 500 kV, 60 Hz idealized system illustrated by the one line diagram in Figure 3a. The varistor indicated for each phase has a protective level at 25 kA crest of 2 p.u. crest of the rated capacitor voltage. The capacitor rated current was assumed to be 1600 A rms. The system at each end of the compensated line section was represented by an equivalent inductive reactance of 16 Ω.

Under normal system conditions, line current flows through the series capacitor and negligible current flows in the varistor. The bypass switch is open and the gap is not conducting. This condition is illustrated in the first cycle of waveforms shown in Figure 3b.

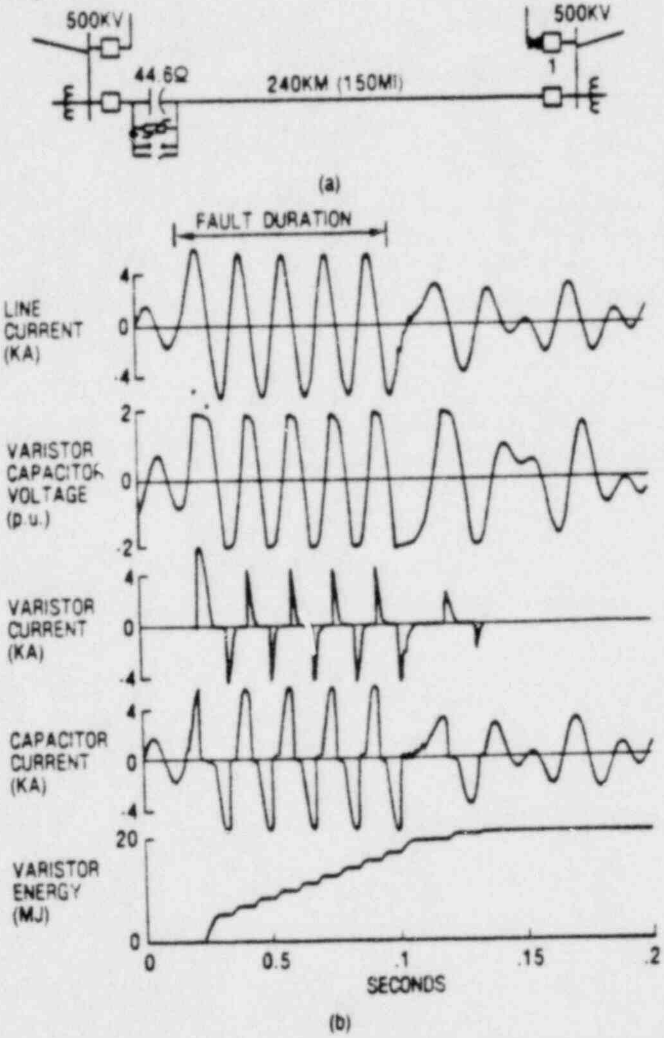

Fig. 3. a) 500 kV circuit with a three-phase fault external to the compensated line section

b) Voltage and current waveforms for a 5 cycle fault on the circuit of Figure 3a.

A fault occurrence on the system increases the capacitor current and voltage. If the capacitor voltage rises enough, the varistor conducts and limits further voltage increase. If the fault is external to the line section in which the capacitor is installed, as indicated in Figure 3a, the line fault current is modest since it is limited by the impedance of the total line. The action of the varistor for such a case is illustrated in Figure 3b for a three-phase fault. These waveforms were calculated using the Electromagnetic Transients Program (EMTP).[3] As shown, the varistor limits the voltage on each half cycle and the current alternates between the capacitor and the varistor. When the varistor clamps the voltage, $\frac{dv}{dt}$ is reduced which reduces the capacitor current to a low level. The capacitor-varistor shared conduction continues until the fault is cleared by the system breaker

#1 (Figure 3a) as directed by its own relaying. The line current then drops to the post fault level, re- ducing capacitor voltage and causing the varistor to virtually cease conduction. Thus the line current flow is fully restored to the series capacitor. This re- insertion or restoration is instantaneous and automatic and can markedly increase power system transient stability and power transfer as will be discussed in Appendix I.

For the condition studied the varistor on the phase with maximum energy absorbs 21 megajoules (MJ) with most of this energy absorbed during the fault. However, some additional energy is absorbed as the post fault power frequency and subsynchronous oscillatory currents combine and increase the capacitor voltage up to the varistor conduction level. The varistor con- duction limits the magnitude of these oscillations.

Faults within the line section where the series capacitor is located can result in a wide range of line fault currents depending upon the location of the fault and the capacitors. Consider the case shown in Figure 4a where the capacitor is located at the end of a line section. As the fault location is moved along the line toward the capacitor (Figure 4b) the energy absorbed by the varistor increases significantly. The extent of this increase is influenced by the equivalent impedance at the terminating substation. The type of fault is also a significant factor. Single-line-to-ground faults generally result in 50 to 60% less varistor duty than do three-phase faults. However, for many systems it is impractical to apply a varistor with sufficient energy absorption capability for the worst fault location. Based on these considerations, a triggered air gap and its associated control were designed. The control circuit has the ability to monitor the varistor duty during faults and to fire the gap as required. The gap firing effectively shorts the varistor, limiting varistor duty to a selected design magnitude.

Consider next the case where the capacitor is located away from the end of the line (Figure 4c). The maximum varistor duty (assuming no gap firing) for internal line faults is substantially lower as shown in Figure 4d. The varistor duty possible for internal faults exceeds that possible for external faults.

In general, the most economical approach for the protective system is to design the varistor with the energy absorption capability required by the worst case external line fault scenario. Thus, for external line faults, only the varistor would conduct, providing overvoltage protection for the capacitor during the fault and instantaneous reinsertion of the capacitor upon fault clearing. For faults within the compensated line section that exceed the varistor design limits, the air gap would be triggered. Fault current would then flow through the gap until cleared by the system line breakers. The gap would then deionize and recover its voltage withstand strength to be compatible with the high speed reclosing of the line breakers. If, however, there were an abnormal system contingency such that fault current continued to flow in the gap, the control circuit would close the bypass switch. Thus, only in the event of abnormal system contingencies or certain platform contingencies would mechanical switch operation be required.

The above presents in principle the new series capacitor protective system and its general system operation. The advantages are its simplicity, instan- taneous reinsertion and elimination of mechanical motion for the normal protective operation.

FIELD INSTALLED PROTOTYPE

Following extensive development work and feasi- bility evaluations, it was decided to proceed toward functional field tests and to obtain service experience

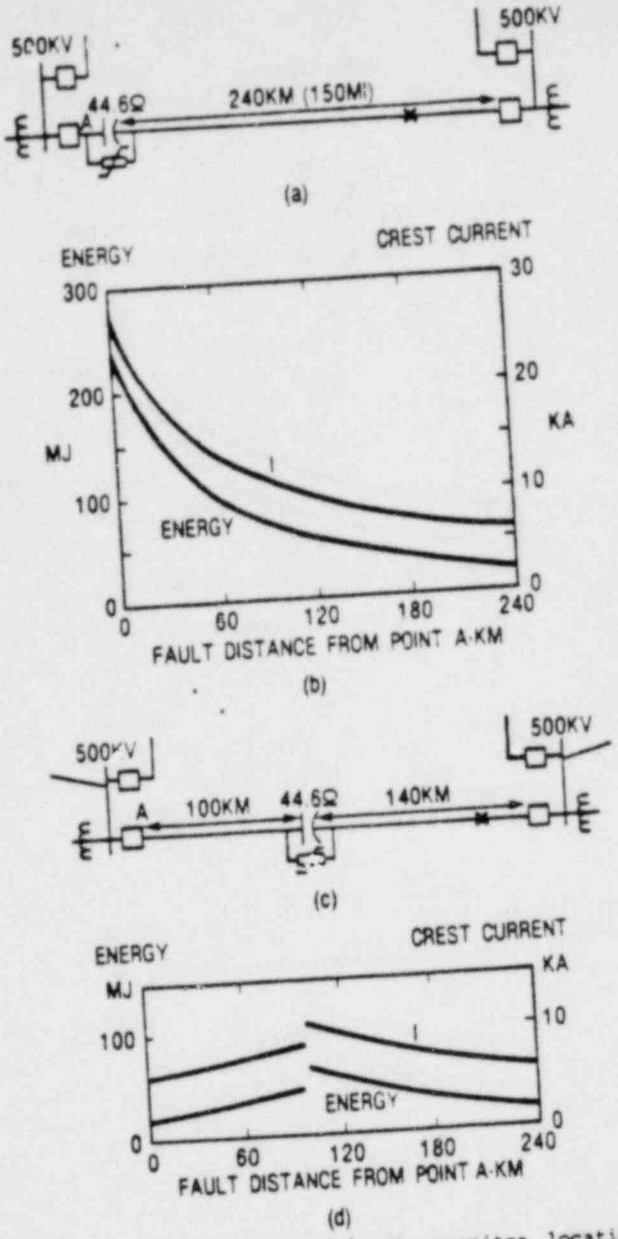

Fig. 4. Effect of fault and capacitor location on varistor duty for internal line section fault (assuming no gap operation).

a) 500 kV circuit with series capacitor located at the end of the line section.

b) Varistor duty for a 5 cycle, three-phase fault at various locations on the internal line section of Figure 4a.

c) 500 kV circuit with series capacitor located away from the end of the line section.

d) Varistor duty for a 5 cycle, three-phase fault at various locations on the internal line section of Figure 4c.

on a prototype installation. BPA proposed that this be done on a 108 MVAR bank operating since 1960 at the 345 kV North John Day Compensation Station in Washington.

The McNary-Ross Compensated Line

The North John Day Series Capacitors are installed in the 345 kV line between the McNary and J.D. Ross Substations. This circuit is 175 miles in length and provides transmission from the generation at McNary Dam to the load center in the Portland area. The capacitors are located a distance of 74 circuit miles from McNary, and 101 circuit miles from J.D. Ross. Line autotransformers rated 230/345 kV, 600 MVA are installed at each terminal and are switched as part of the line by breakers on the 230 kV side. The autotransformers are connected wye with a solidly grounded neutral and a delta connected tertiary. The circuit arrangement is shown in Figure 5.

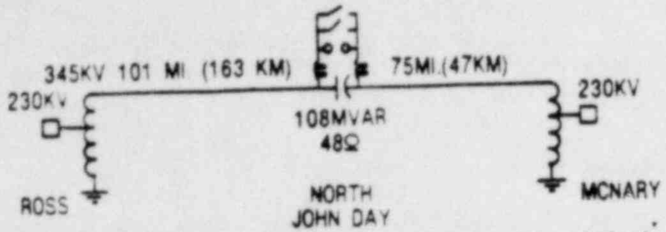

Fig. 5. Ross-McNary transmission circuit with original series capacitor protection scheme.

The North John Day installation provides either for 24 ohm or for 48 ohm connection with a current rating of 863 A rms for either connection. The 48 ohm connection provides 29 percent compensation for the line and connected autotransformers.

Installed Prototype

Since each phase of the North John Day capacitor bank contained two separate capacitor segment platforms, it was possible to install the prototype protective system across one segment of capacitors (X_C = 24 ohms) and to leave the remaining 24 ohm segment connected to the original protective equipment. The new protective equipment was installed on a separate platform in the "C" phase. An electrical diagram of the modified protective arrangement is shown in Figure 6. A plan view of the overall installation, a plan view of the prototype platform and a photo of the installed prototype are shown in Figures 7, 8 and 9, respectively.

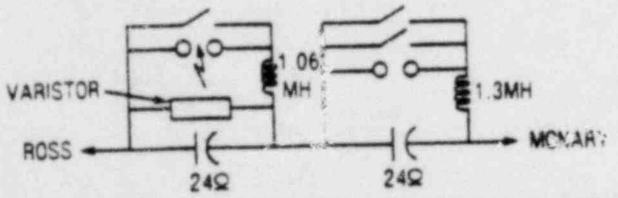

Fig. 6. Schematic of the prototype protective system (left) and the modified original protective system (right) at North John Day. C phase only.

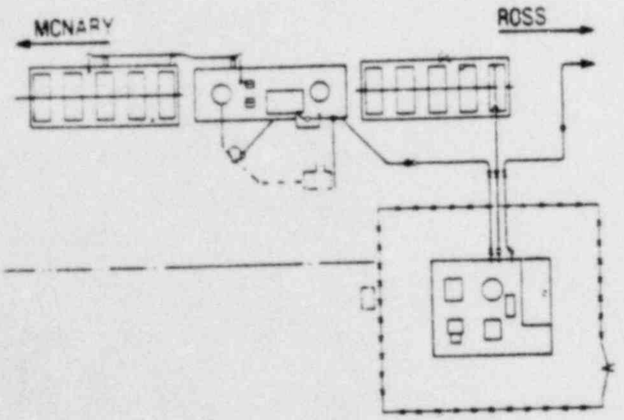

Fig. 7. Plan view of installation (CØ) showing existing capacitor bank and new prototype platform (lower right).

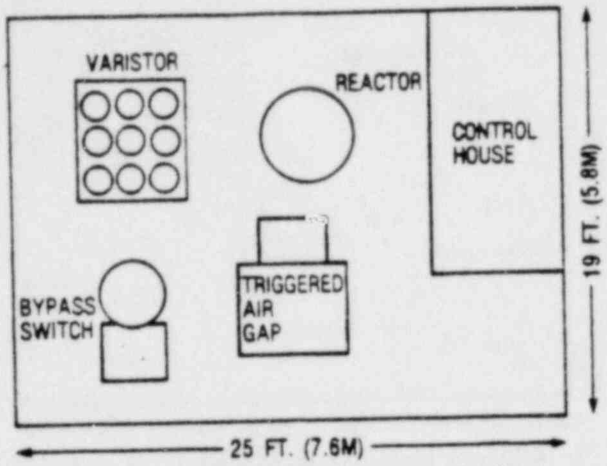

Fig. 8. Plan view of prototype platform.

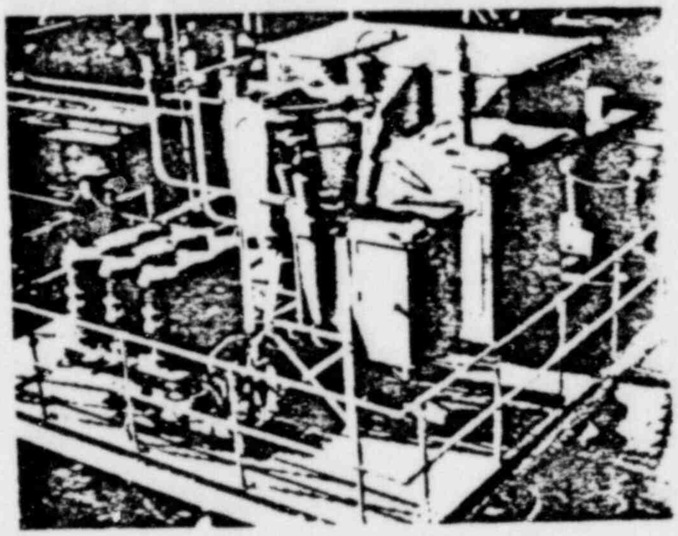

Fig. 9. Prototype installation.

PROTOTYPE SPECIFICATION

Although the prototype installation was made on a 345 kV line, a BPA objective was to demonstrate that the new protection system could be applied on a 500 kV system such as the Pacific NW - SW AC Intertie.[4-8] To that end, equipment specifications and design margins were made comparable to those that would be used for a full scale 500 kV series capacitor bank.

Varistor Specification

The central requirements of the prototype specification concerned the varistor sizing. The BPA specification stated that the varistor thermal capability was to be sufficient withstand the most severe fault sequence internal to the McNary-Ross line; the resulting rating would be comparable to that required for the most severe remote faults on the Intertie. In this way, the North John Day Prototype could closely simulate external line or remote internal line fault duty for the Intertie.

The varistor's protective level was chosen to be 2 p.u. (58 kV crest) on the basis of the operating and swing voltages of the line. Anticipated thermal duty to the varistor was confirmed by use of the EMTP program. Figure 10 summarizes the expected varistor duty for single line to ground faults placed at various locations along the line. It is seen that the fault current magnitude and fault energy varied with the location of the fault, and that these quantities were a

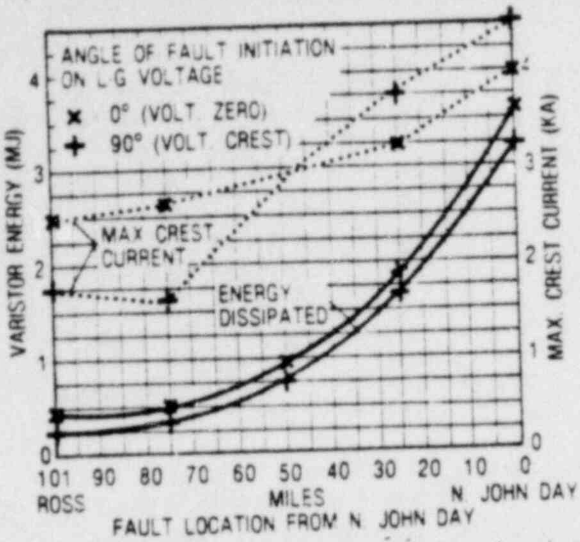

Fig. 10. Calculated varistor duty for 5 cycle single line-to-ground faults at various locations between Ross and North John Day.

maximum when the fault was located next to the bank on the Ross side. The maximum energy absorbed in a 5 cycle, single-line-to-ground fault at the bank was approximately 3.5 MJ and the maximum varistor current was 4.5 kA crest.

There were two varistor duty fault sequence scenarios described in the BPA specification. In the first sequence, two single-line-to-ground faults of maximum duty were immediately followed by a system swing of 1500 A rms (1.7 p.u.) and then by line operation at 1.2 p.u. At some later time, line current would be reduced to 1.0 p.u. In the second fault sequence, three successive single-line-to-ground faults were followed by line lockout. In both event scenarios, successive varistor duties were separated by the 30 cycle reclosing time of the line breakers.

Other Specifications

Since it was desired to evaluate the protective system in the configuration that would be offered in a full scale 500 kV installation, a triggered air gap was supplied for the prototype installation. In practice it is unlikely that the gap would be triggered because the varistor was rated to withstand severe faults on the McNary-Ross line. The control circuits for the triggered air gap were specified such that the gap could be triggered over a wide range of currents and energies. This adjustable control feature was beneficial during the field testing. In all other power circuit equipment, BPA specified that minimum continuous current ratings were to be based on an assumed continuous line loading of 1200 A.

Equipment Description

The equipment provided included a varistor, triggered air gap, bypass switch, reactor, control circuit, communication column, platform power supply, and equipment platform. Commercially available components were selected to perform the various electrical functions; however, several pieces of new equipment were required. These new components were extensively tested before being installed. A brief description of the major components is given below.

Varistor

The varistor consists of 18 porcelain housings with each housing containing four columns of disks and with 14 disks per column. The 18 varistor units are all connected in parallel. A bus bar is used to connect the top nine units in parallel with the bottom nine units. By removing the bus bar the top nine varistor units can be removed from the circuit electrically, thus reducing the total energy rating of the varistor by 50%. The voltage-current characteristic for the varistor is shown in Figure 11. The normal operating voltage of the varistor is 20.8 kV rms (1 p.u. of rated capacitor bank voltage), at which it will dissipate 250 watts. The maximum continuous operating voltage is 24.9 kV rms (1.2 p.u.), and the protective level is 58 kV crest (1.97 p.u.) at 10,000 A crest. The varistor has a voltage-time overload rating of 1.39 p.u. for two hours.

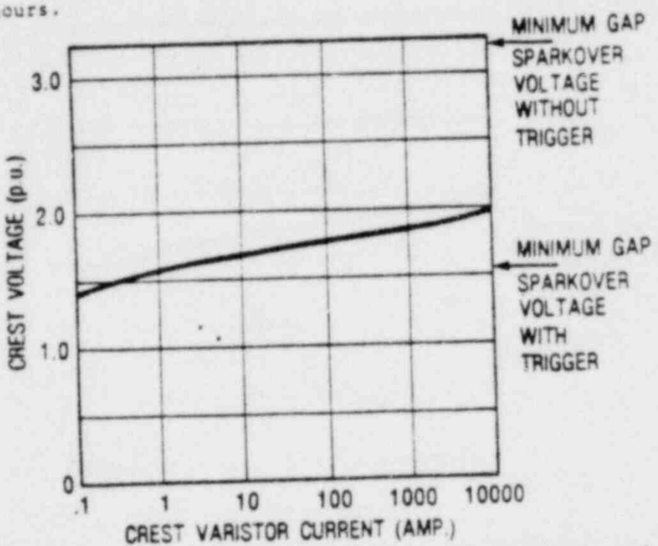

Fig. 11. Varistor voltage-current characteristic and relative levels of gap sparkover.

The energy rating of the total varistor is 12.75 MJ (6.38 MJ with the bus bar disconnected). This rating applies for repeated faults or for a single large fault. In addition, the varistor is capable of absorbing an additional 12.75 MJ of energy after a time delay of one minute following the initial rated energy absorption. The one minute time delay permits the temperature distribution within each disk to equalize.

Laboratory testing of the varistor was performed to confirm its electrical, thermal, and mechanical performance. A typical test circuit and oscillogram is shown in Figure 12. In this test the Ross-McNary line, the North John Day capacitor bank, and the varistor were modeled with scale factors of 1/9 for current, 1/6.81 for voltage, and 1/63 for energy. The short circuit current in this test corresponded to a system fault current of approximately 2.4 kA rms available. The model varistor absorbed 222 KJ (13.99 MJ equivalent for the full scale varistor) and provided a maximum protective level of 8.42 kV crest (57.36 kV or 1.95 p.u.) at a maximum varistor current of 620 A (5580A) crest. A subsequent section will show that the waveforms obtained in actual field tests are very similar to those obtained in the laboratory.

Triggered Air Gap

The triggered air gap contains three carbon electrodes. The center electrode is impulsed by the control circuits to cause the gap to fire. The important features of the gap are no sparkover except by control action and no mechanical motion involved in its operation.

The gap design was made to take advantage of the voltage limiting function of the varistor. The gap sparkover voltage without a trigger impulse was made

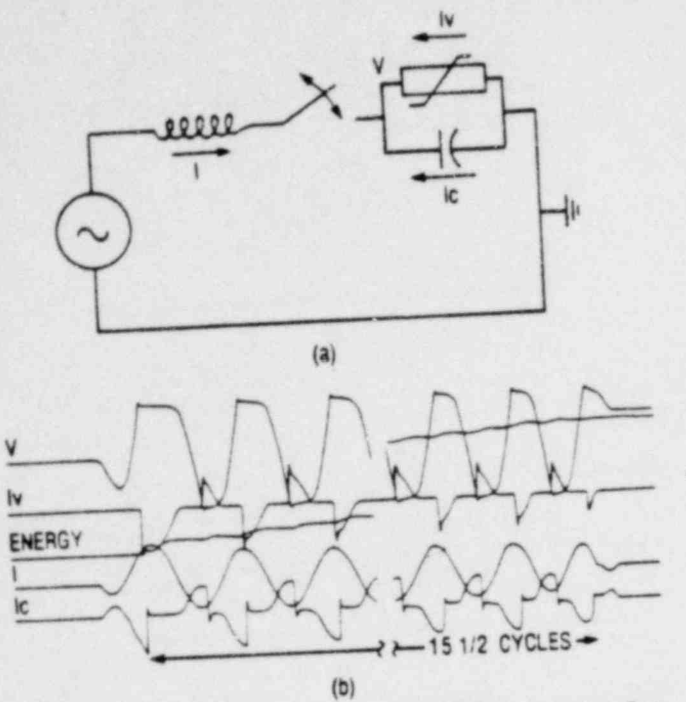

Fig. 12. a) Equivalent of laboratory circuit for varistor fault conduction test.
b) Test waveforms for circuit of Fig. 12a.

higher than the varistor protective level so that the gap could not spark over spontaneously during a fault. Further, the gap was designed so that it would not spark over, even with a trigger impulse, when there was no fault on the line. This eliminated the possibility of gap conduction during normal line operation. Thus, the only way in which the gap could spark over was during line fault conditions. The relationship of these voltages to the North John Day Varistor volt-ampere characteristic is shown in Figure 11. The gap was designed and laboratory tested to carry 7000 A rms for 10 cycles, and then to withstand 65 kV crest (2.2 p.u.) 30 cycles after the arc had been extinguished. Since the varistor limited the maximum gap voltage to 2 p.u. (as shown in Figure 12), transient voltages caused by line reclosing would be below the sparkover level of the gap.

Triggered Gap Control Circuits

The control circuits include a thermal analog circuit and a high voltage pulse generator. The thermal analog circuit monitors the total varistor energy absorption and the rate of varistor energy absorption. If either of these design limits is exceeded the thermal analog generates trigger signals to cause the pulse generator to operate. The energy absorption limit is determined by the thermal capacity of the zinc oxide material; the energy rate limit is determined from the magnitude of the varistor fault currents possible in a specific application.

Current transformers are used to sense the varistor current. The varistor current is used to develop an electrical analog of the energy absorption. Redundant circuitry is used so that high reliability can be assured.

The high voltage pulse generator uses two independent circuits to supply high voltage impulses through a pulse transformer to the center electrode of the triggered air gap. The generator provides impulses only when triggered by the thermal analog circuit. The pulse generator operates from a 125 V DC platform supply.

Bypass Switch

A standard 38 kV oil circuit breaker is mounted on the platform to serve as the bypass switch. The three breaker poles are connected in parallel to increase the continuous current rating of the breaker beyond the 1200 A rating of a single pole. The breaker has a closing time of 9 cycles and operates from the 125 V DC platform supply.

The bypass switch was designed to be operated either manually by an operator command or automatically by platform relays. The platform relays cause automatic bypass switch closure only if:

1) The triggered air gap conducts longer than 10 cycles.
2) The platform battery voltage drops below a design limit.
3) The varistor conducts current beyond the length of the selected design fault sequence.
4) Certain platform contingencies occur including capacitor differential current relay operation.

The existence of any of these four situations would indicate severe system and/or platform difficulties. Closing the bypass switch in any of these situations would provide absolute protection of the capacitors and protective components, and the relaying was designed to lock the bypass switch in the closed position until manually opened by an operator at the substation. Equipment was not available to permit remote operation of the North John Day substation, although the protective system could be designed for supervisory operation.

The operation of the prototype bypass switch is on a three-phase basis with the existing switches of the bank with interphase control provided by ground level relaying. On a three-phase installation of the new protective system, the operation of the bypass switches would similarly be on a three-phase basis.

Current Limiting Reactor

A standard epoxy encapsulated reactor is used to limit the capacitor discharge current due to gap sparkover or bypass switch closing. The reactor is connected in series with the gap and the bypass switch as shown in Figure 6. A 1.06 mH, 1200 A rated current reactor is used.

Communication Column

A fiber optic coupled communication was developed for the BPA installation. The function of the column was to relay information between the equipment platform and ground level.

The communication column consists of the fiber optic cable, its porcelain housing and electronic interface circuits at ground level and platform. The column is designed to provide a number of digital functions (three going up and four going down) between ground level and the platform. The digital functions are used to operate the bypass switch, to indicate the position of the bypass switch, to indicate platform lockout, and to indicate battery voltage (normal/low).

The sealed porcelain housing insures a controlled environment for the fiber optic cable and maintains its voltage withstand capability.

The communication electronics requires 125 V DC supply at ground level and on the platform.

Platform Power Supply

Platform power is provided by 125 V, 50 ampere hour lead-calcium batteries, and battery voltage is maintained by a charger which operates from line current. Battery charge can be maintained for line currents as low as 300 A rms. The battery is rated to sustain operation of the protective system for seven days without requiring charging energy. This ability was demonstrated in the field experience with the prototype. Identical platform power supplies have been successfully used in earlier series capacitor installations.

FIELD TESTS

A program of staged fault tests was conducted at North John Day to evaluate the performance of the prototype installation. The first series of tests was conducted April 4 and 5 and a second series was conducted on May 5, 1979.

Instrumentation:

Current transformers and resistor voltage dividers were installed to measure the following quantities at, platform potential: (See Figure 13)

- Capacitor current - I_C
- Line Current - I_L
- Triggered Air Gap - I_G
- Bypass Switch Current - I_S
- Varistor Current - I_V
- Triggered Air Gap Voltage - V_G
- Varistor Capacitor Voltage - V_V

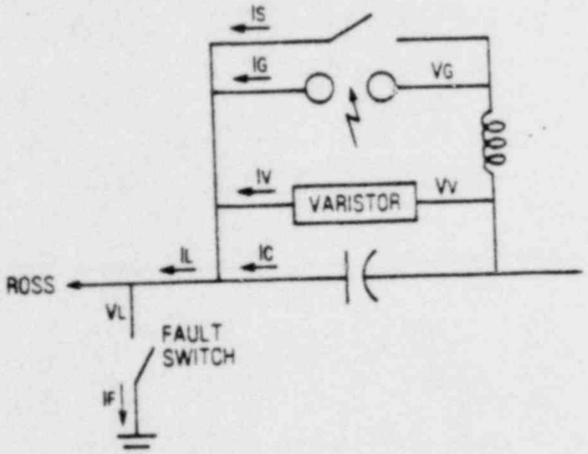

Fig. 13. Quantities measured during field test.

Varistor energy dissipation was derived by analog multiplication and integration of varistor voltage and current signals. All of the above signals were recorded at platform level by an oscillograph powered from a gasoline generator and initiated from ground by a light beam and photo relay. In addition, a ground level fault current (I_F) and C phase line voltage (V_L) were recorded at ground level.

Procedure and Results

All faults were applied from C phase to ground using a special high-speed SF_6 fault initiating switch. The switch was located at North John Day on the Ross side of the line and was controlled synchronously to maximize the total fault current. For the tests where arcing faults were required the fault initiating switch was connected to the line via a fuse wire. For bolted faults the switch was connected to the line with heavy cable. The procedure and results for each of the 6 tests are discussed in the following:

Test 1: This test was an instrumentation check and no faults were involved. The capacitor bank was inserted while the line carried a load current of approximately 300 A.

Test 2: The purpose of this test was to verify operation of the gap when triggered by the thermal analog under fault conditions, and to demonstrate proper closure of the bypass breaker for excess gap conduction time. Minimum current and energy levels were set on the thermal analog and minimum delay was set on the gap conduction timer. This allowed complete protective system operation within the anticipated fault duration.

The line was open at Ross and fed radially from McNary. The fault switch was closed to establish a bolted fault which was cleared in four cycles by the McNary breaker.

The thermal analog fired the gap successfully at the appropriate varistor current level. After two cycles of conduction the arc in the gap transferred from the arcing contacts to the gap enclosure, bypassing the gap current transformers. Loss of the current transformer signal to the triggered air gap conduction timer prevented the bypass breaker from closing. Additional insulation barriers were added after the test on the inside of the gap enclosure to correct the problem.

Test 3: The purpose of this test was to demonstrate the dielectric recovery capability of the trigger air gap after discharging the capacitor and conducting fault current. The thermal analog current and energy levels were left at the minimum settings. The line was closed at both ends resulting in a load current of about 400 A.

An arcing fault was established by closing the fault switch at North John Day. The gap fired and conducted a peak capacitor ring down current of 18.6 kA, superimposed on a symmetrical rms line current of 1950 A. The additional barrier insulation successfully prevented arc transfer to the gap enclosure. The fault was cleared in 4 cycles and McNary and Ross reclosed at 44 cycles and 67 cycles respectively after fault initiation. The gap successfully withstood a peak voltage of 36.4 kV crest (1.24 p.u.) after reclosure.

Test 4: The purpose of this test was to verify both the short-time energy rating and the voltage limiting function of the varistor. Half of the 18 parallel varistor units were disconnected for this test to facilitate testing the remaining nine to their design energy rating (6.38 MJ).

With the line open at Ross and energized from McNary, a bolted C phase-to-ground fault was established at North John Day by closing the fault switch. After 4 cycles the McNary breaker cleared the fault, reclosed back into the fault 39 cycles later, cleared again in 4 cycles and then remained open.

The oscillogram from Test 4 is shown in Figure 14. The distortion of the varistor-capacitor voltage trace was caused by an amplifier ground problem. Note, however, that the gap voltage should be virtually identical to capacitor voltage whenever the gap is not conducting. Thus, the gap voltage trace may be used to infer the varistor-capacitor voltage. The current and voltage waveforms from the test are nearly identical to those from the simulation studies and laboratory tests. During the fault the varistor conducted a peak current of 3600 A and limited capacitor voltage to 55 kV (1.9 per unit). Since only half of the parallel varistor units were connected, this corresponds to 7200 A peak current for the total varistor.

The varistor conducted for approximately 7 cycles during the two faults, dissipating 6.0 MJ or nearly [illegible] per cent of the 6.38 MJ rating for the half varistor. The thermal analog which had been set at 6 MJ operated and fired the triggered air gap bypassing the bank during the last cycle of fault current demonstrating successful operation of the varistor thermal protection function.

After Test 4 the bank was returned to service with the complete varistor reconnected. On April 12 a tower failure between North John Day and Ross resulted in two

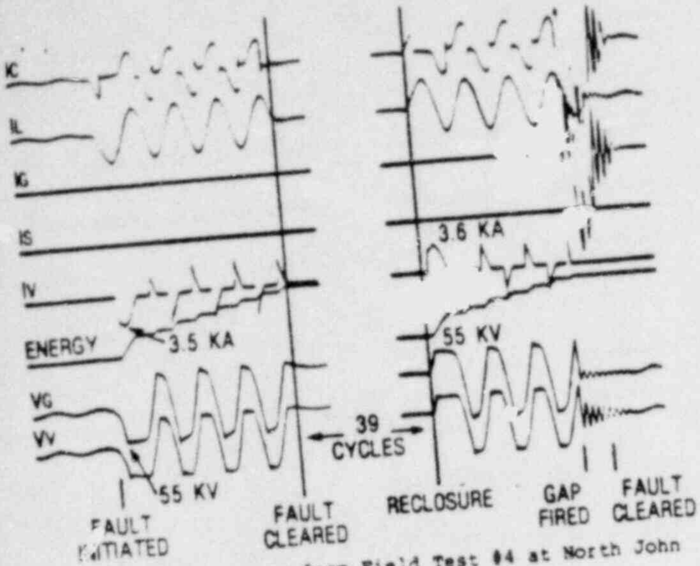

Fig. 14. Oscillogram from Field Test #4 at North John Day.

suc essive faults (one-single-phase, one three-phase) involving the C phase prototype.

Tests 5 and 6: On May 5th two additional fault tests were conducted at North John Day. Test 5 was a repeat of Test 4 except that all 18 of the parallel varistor units were connected. One varistor unit of the upper 9 units failed as a short circuit during the first half-cycle of fault current. The abnormal varistor current was detected by the platform control circuit causing the bypass switch to automatically close. Evidence from the test records suggests that the varistor unit had actually failed during the tower failure faults. This varistor unit was one of the nine that had been disconnected during Test 4. The failed unit was replaced within an hour and the complete varistor successfully retested in Test 6. St dy of the varistor unit removed from the assembly r ealed that a disk had failed. This has led to the dev lopment of an improved quality assurance procedure for isks used in varistor applications.

Long-term Evaluation

The operation of the protective system since the May field tests has been completely satisfactory. During the remainder of 1979 there has been one natural line fault that caused the varistor to conduct. The prototype installation will remain in service through April 1981 for long-term performance evaluation. A BPA developed energy monitor system[9] was installed during the field tests and will remain in service during the evaluation period. An analog signal representing varistor current is transmitted to the microprocessor based energy monitor at ground level over a 5 kHz bandwidth fiberoptic link independent of the signal column of the protective system. The microprocessor based system operating in real time calculates cumulative varistor energy dissipation and provides a permanent record of varistor energy dissipation and peak varistor current with date and time whenever the varistor conducts fault current.

When the prototype is removed from service selected varistor units will be subjected to a series of laboratory tests. Comparison of the test results with the results of identical tests performed prior to energizatio will pro e a check of varistor long-term stability.

CONCLUSIONS

1. A new series capacitor protective system based on a zinc oxide varistor has been developed. This system includes a triggered air gap and control circuit that can protect against excessive varistor duty.
2. The zinc oxide varistor provides instantaneous reinsertion of the capacitors for external line faults. This can result in a substantial increase in power system transient stability and power transfer. This reinsertion is inherently automatic and dependable.
3. The new system eliminates mechanical motion during the normal protective operation. This plus its basic simplicity result in a design of superior reliability.
4. Field prototype equipment has been built, installed and field tested. The prototype has been successful with longer term field evaluation continuing.

APPENDIX I

EFFECT ON SYSTEM STABILITY

As mentioned, for an external line fault the series capacitors in the unfaulted line are effectively reinserted by the varistor immediately after the fault is cleared. This is at a time when the capacitors are most effective in enhancing system stability. This performance is to be compared with conventional protection systems where, generally, there is delayed reinsertion of the bypassed capacitors. The significance of the varistor action was examined for the 500 kV, 480 Km (300 mi) transmission circuit shown in Figure 15a. The equivalent rating of the generation and its transformers were both 1500 MVA. The interia constant for the generator was assumed to be 2.28 megawatt seconds per MVA of rating. Each transmission line section was assumed to be 50% series compensated.

The relative angular swing of the generator for a fault was calculated for a conventional series capacitor protection system with complete bypass and delayed reinsertion and for the new varistor series capacitor protection system. The calculations were

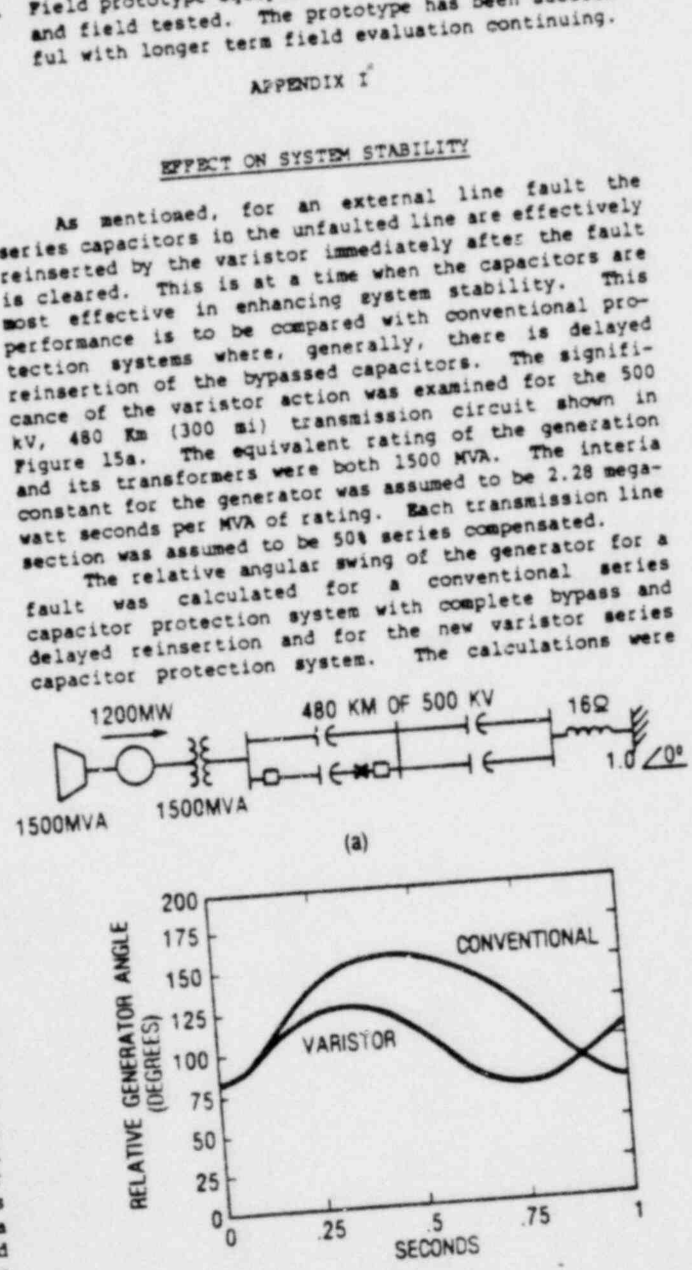

Fig. 15. a) 500 kV system for transient stability analysis.

b) Generator internal angle swings for the circuit and fault shown in Fig. 15a for conventional and for varistor series capacitor protection systems.

made using the EMTP program and with the machine modeled as a constant voltage behind transient reactance. The prefault power generation was assumed to be 1200 MW. The fault modeled was a three-phase-to-ground fault at the location indicated. The faulted line was cleared in 5 cycles and not reclosed. For the conventional protection system, it was assumed that all of the capacitors bypassed upon fault initiation. The reinsertion delay after fault clearing was assumed to be 5 cycles. The varistor was assumed to have a protective level of 2.5 pu on a capacitor rated at 1600 rms.

The results of the simulations are shown in Figure 15b. The angular swing of the generator rotor for the varistor protection system is considerably less than for the conventional protection system. This reduced swing indicates a considerable improvement in transient stability due to the instantaneous reinsertion of the series capacitors by the varistor. This stability enhancement can be translated into increased power transfer, in some cases by as much as 40%, or into reduced compensation for the same power transfer.

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