IEEE Transactions on Power Delivery ,Vol. 6, No. 3, July 1991

EXPERIENCES WITH PARALLEL EHV PHASE SHIFTING TRANSFORMERS

by

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Abstract

Unscheduled power flow is a major concern in interconnected power systems. Phase shifting transformers (PSTs) are one method used to control unscheduled power flow. This paper discusses the application, protection, commissioning, and initial operating history of two sets of parallel, 300-MVA, 345-kV, PSTs. The four Western Area Power Administration (WAPA) PSTs were energized in 1989 and are located in northwestern New Mexico in Shiprock and Waterflow Substations. The installations are unique because two PSTs, using a series no-load and load tap changer (LTC) design, are operated in parallel at each location.

Introduction

A PST increases or decreases the electrical voltage phase-angle relationship of a circuit with respect to another. This shift in the phase-angle relationship allows control of the real power flow between the circuits. There are various methods of shifting the phase-angle relationship in an interconnected system using transformers. The standard delta-wye transformer provides a fixed 30^{o} shift. A hexagonal transformer connection [1] allows for multiple phase-angle shifts, but the transformer must be de-energized to vary the angle through a no-load tap changer. If the power flow control requirements are seasonal, the hexagonal connection may be adequate, but where hourly or daily adjustments are required, a method of varying the angle while the transformer is loaded is required. This can be accomplished through the use of a PST that utilizes a series and an exciting winding with a LTC, as shown in Figure 1.

The LTC, PST design consists of a series unit and an exciting unit - two separate transformer units connected by a special throat connection. The terminals of the series unit primary windings (marked S and L) are connected to the power system while the midpoints are connected to the primary windings of the exciting unit. The secondaries of the series units are connected in Delta and are interconnected with the secondaries of the exciting unit containing the taps. As the tap positions are changed, a proportional quadrature voltage (V_{SL}) is introduced into the series winding, producing a phase-angle shift between the source and load (input and output) terminals. The phase shift equals 2 Arcsine of $V_{SL}/2V$, where V is the magnitude of the line-to-neutral system voltage at the source and load (S and L) terminals. The LTC design provides a maximum, continuously variable, angle of approximately +/- 25 degrees. The angle of regulation can be considerably increased using a combination of no-load tap changers (NLTC) and load tap changers [2]. The NLTC provides a large fixed shift that can take care of large seasonal variations of power flow.

This paper discusses the application, protection, commissioning and initial operating history of two sets of parallel PSTs using NLTC and LTCs.

91 WM 020-8 PWRD A paper recommended and approved by the IEEE Transformers Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1991 Winter Meeting, New York, New York, February 3-7, 1991. Manuscript submitted August 28, 1990; made available for printing December 11, 1990.

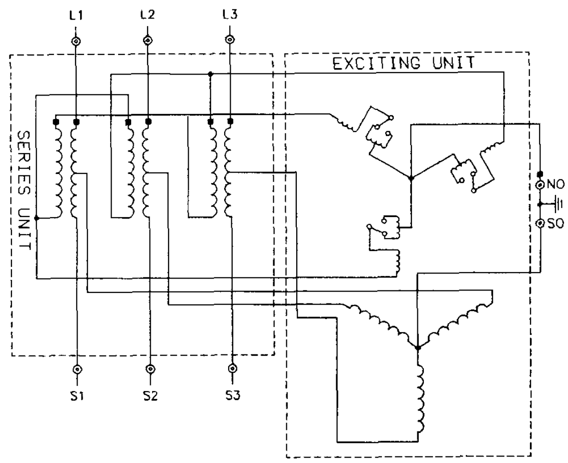

FIGURE 1. PHASE-SHIFTING TRANSFORMER WITH LOAD-TAP CHANGER

Application

The bulk power system in the western United States, coordinated by the Western Systems Coordinating Council (WSCC), has a unique characteristic because a large transmission network has developed that is sparse in the center and encircles the region in a large loop. When large amounts of power are being transferred through the WSCC system, the power takes the path of least impedance which may not be a scheduled path. In the WSCC system, unscheduled power flow has become a major problem and has acquired the special name of "loop flow."

WAPA operates a transmission system which includes over 16,500 miles of high voltage transmission lines in 15 western states. In southwestern Colorado the Curecanti-Shiprock 230-kV line has historically been severely impacted by loop flow. To lessen the impact, the line is to be uprated to 345-kV in the future. The parallel 345-kV Long Hollow - San Juan line, energized in 1988, provides additional capacity to accommodate loop flow, but even with the additions, studies showed that 50 - 75 percent of the scheduling capacity over the two lines could still be consumed by loop flow in the fall and winter.

In 1986, it was decided that PSTs would be installed on the two lines to enable WAPA to limit loop flow and effectively utilize the system's transfer capabilities. PSTs were required on both lines because a single PST would have forced power to flow on the parallel unregulated line. 600-MVA duties were required for each installation. The PSTs would be installed at the existing Shiprock Substation and at a new substation, Waterflow Substation, which is 1/2 mile north of the existing San Juan Generating Station (Figure 2). 345-kV PSTs would be installed at both substations, although the Shiprock installation would initially be operated at 230-kV. The 230-kV operation of the Shiprock PSTs reduces the MVA capacity, by the ratio of the voltages, to 67% of the original rating, however the full phase shift range is maintained.

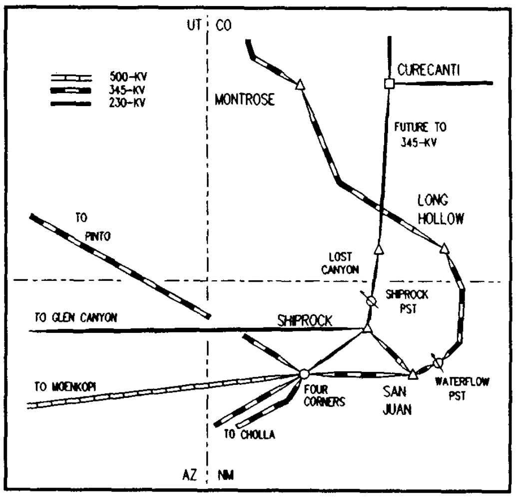

FIGURE 2 - SYSTEM DIAGRAM SHOWING PARALLEL PST LOCATIONS

The characteristic loop flow over the two WAPA lines is seasonal in nature and also is affected by generation patterns. The cost differential of purchased power can be significantly impacted by the scheduling capability available on the two lines. It was important, to allow maximum utilization of the two lines, that the PSTs have the capability to be adjusted while carrying load. In addition, the direction of loop flow changes during the year so that the PSTs must also be capable of up to a 60^{0} positive (advance) phase shift as well as a 30^{0} negative (retard) phase shift.

Phase Shifting Transformer Requirements

WAPA has operated PSTs with LTCs for over 15 years without any major problems. Presently the largest PST in WAPA's system is a 500 MVA, 230-kV unit with + 47, - 34 degree regulation located at Liberty Substation in Arizona. The PSTs at Waterflow and Shiprock were to be 600 MVA, 345-kV, and would have been two of the largest PSTs with LTC ever built. The physical size of a single 600 MVA PST raised transportation concerns. System reliability was another concern since the loss of one PST would render the other PST ineffective in controlling loop flow. Therefore, it was decided to install two parallel 300 MVA PSTs at each location.

The required phase-angle shifting range, determined by system studies, was -30 to 60 degrees. Three different shift ranges; +60 to 0 degrees, 30 to -30 degrees, and 0 to -60 degrees were specified. The lower -60 to 0 degree range is available by simply reversing the internal connections on the 60 to 0 degree tap at minimal additional expense. The shift range is selected by de-energizing the transformers and changing the position of a no-load tap changer. Once the desired range has been set, the LTC can be used to adjust the angle. The PSTs were specified to supply the rated 300 MVA at maximum phase shift with 180/240/300 MVA, OA/FOA/FOA cooling stages.

The LTC was a concern in the transformer design, since high reliability is a critical. The LTC contacts were required, by the specification, to perform 250,000 operations under full load without requiring replacement or rebuilding, and 60,000 operation before changing of the oil. The PST manufacturer used a resistor type LTC which utilizes a diverter switch in a separate oil chamber for the arcing contacts. This design has a proven operating record and has a recommended servicing interval of 20,000 operation before an inspection is required, 80,000 operations before oil change, and the contacts' life expectancy is in excess of 250,000 operations.

WAPA's standard basic lightning impulse insulation level (BIL) at 345-kV is 900-kV for internal insulation and 1050-kV for the bushings. Because of the complexity of these transformers and the high degree of reliability required, a 1050-kV BIL was specified for the internal insulation. The PST successfully completed all the standard ANSI C57.12.00 tests and the following special tests: insulation power factor, impulse, corona, and switching impulse. The only testing problem encountered was in the heat run tests. The first transformer failed the test twice, and the manufacturer found a problem with the flux density in a corner portion of the core which was overheating and causing high gas readings in the oil. Modification were made to the transformer core to eliminate the problem, and all four units subsequently passed the heat run tests.

Switching Arrangement and Substation Design

Previous PST installations in WAPA's system consist of a single PST with one bypass load break device and one load break and one isolating disconnect device in series with the transformer. In this configuration the series load break switch is used to energize and de-energize the PST. The disconnect switch is used to isolate the PST after the parallel bypass switch is closed. The line breakers are used to clear the line and PST for faults along the line, or in the transformer.

This arrangement has functioned reliably over the years but contains some operational drawbacks. The main problem is that the PST must be bypassed when a line fault occurs. The line is then re-energized, the LTC adjusted to the zero tap position, the PST is inserted back into the line, and then the taps adjusted to obtain the required regulation angle. Another drawback is the lack of a local breaker on each side of the PST for fault clearing and isolation. A Direct Transfer Trip (DTT) signal is utilized to trip the remote line breaker for PST faults. If the communications channel were to fail, the remote line end protection would not detect a low level fault until it evolved into a major fault, thereby allowing significant additional damage to the PST.

The parallel PST installations use the switching arrangement shown in Figure 3. Instead of using 345-kV load-break devices, live tank circuit breakers without free standing current transformers were used. The price differential between using load break devices verses breakers was only on the order of 10%, and the breakers provide much greater operational flexibility and local transformer protection. The breakers allow the line to be re-energized without bypassing the PST and adjusting the angle to zero before re-inserting. The configuration also permits the operators to adjust the angle across the breaker using the PST before closing to minimize the angle between the two sides of the breakers. In the past this has been a problem on the Shiprock - Curecanti line because the line ties generation in western Colorado to that of the Four Corners area of northwestern New Mexico.

Control and Protection

Utilizing parallel PSTs to reduce physical size and increase reliability resulted in a more complicated control system. The LTC controls on each PST had to be tied together so that the two LTCs would remain in step. If the taps become mismatched, large circulating currents between the two transformers result. To keep the LTCs in step, the manufacturer used a master/follower arrangement where one transformer is specified the master and the other the follower. As the master changes taps, the follower is one tap behind until the master reaches the desired tap, at which point the follower catches up and both LTCs are on the same tap. This requires the PST to be capable of carrying full load plus the circulating current resulting from a one tap mismatch. The control logic allows either transformer to be the master or the follower and provides an independent mode.

Figure 3 shows the protective relaying used for a PST. Devices shown in dashed lines were added after the initial installation and are discussed in the following sections on installation, commissioning and operating history. The following list describes the function of each device:

- 87A Transformer differential relay.
- 87B Transformer differential relay.
- 51GA Exciting transformer primary ground backup.
- 51GB LTC and Exciting transformer secondary ground backup.
- 26Q Oil temperature relay.
- 49 Winding hotspot temperature relay.
- 63PR Gas pressure relief relay.
- 63SP Sudden pressure relay.
- 71Q Oil level relay.
- 63LTC Sudden pressure relay in the load tap changer compartment.
- 51P Phase overcurrent used for overload protection.
- 59 Overvoltage relay.
- 50/68 Inrush detection relay.

Note: There is a 26Q, 49, 63PR, 63SP, and 71Q located on the series as well as the exciting unit.

Two sets of differential relays are required to adequately protect the PST. The two differential relays have CTs in each phase of the neutral end of the exciter unit windings in addition to the CTs on the source and load terminals. This configuration eliminates the unbalancing effect tap changing would otherwise create on a differential circuit. Relay 87A provides overall protection of the series and exciting unit primary windings. The second differential relay, 87B protects the secondary windings of the series and exciting units. Since the exciting unit secondary windings are Wye connected, they cannot supply zero sequence current for external ground faults [3]. Therefore, the current transformers can be connected in either delta or wye. A delta connection was chosen because it provides more sensitivity. Two overcurrent relays, 51GA and 51GB were placed in the neutral to protect for internal ground faults in the PSTs and are supervised by the 50/68 relays (which were added later) to prevent operation during transformer energization. The 51P relay protects for overloads caused by system conditions, or if the LTC on the two PSTs loses step resulting in large circulating currents between the transformers. There is a sudden pressure relay and oil level relay in each transformer tank and three additional sudden pressure relays, one in each diverter switch compartment. A sixth sudden pressure relay, in the LTC compartment, was added after the initial installation. The 59 overvoltage relay is a volts per hertz relay that provides overvoltage protection for the PST. The volts per hertz relay was used because it provides more setting flexibility than a standard overvoltage relay, allowing the protection to be matched with the PST overvoltage capability.

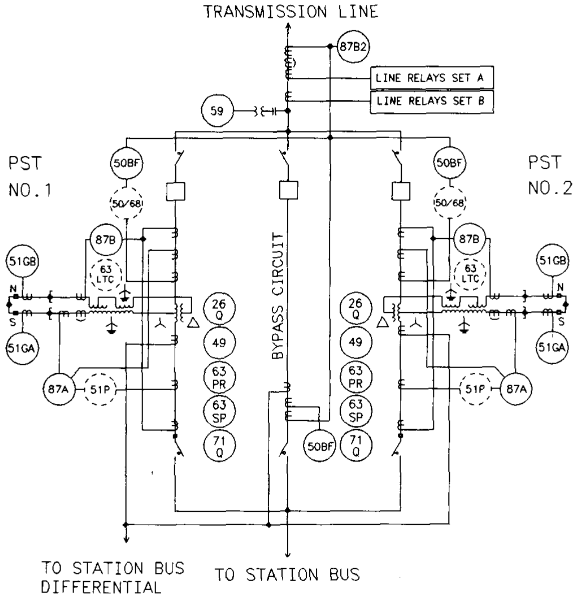

FIGURE 3. PARALLEL PST SWITCHING AND PROTECTION.

The Shiprock Substation installation utilized a differential relay between the station bus and the PSTs. A separate free standing CT was added in the bypass circuit to allow the bus differential relays to remain in service under all switching conditions. The Waterflow installation was slightly different because the substation is located 1/2 mile away from the San Juan Generating Station. Instead of placing a breaker on the San Juan side of the PSTs, redundant current differential relays over separate fiber optic cables were used and the 1/2 mile of line treated as a long bus. The fiber optic cables also transmit dual direct transfer trip (DTT) signals to the San Juan breakers if a PST protective relay action occurs. In addition, a separate impedance relay was placed at San Juan, reaching through the PSTs, to act as an independent backup. The transmission line relays were placed on the line side of the PSTs at both locations using free standing CTs so that the varying impedance and angle introduced by the PST would not affect the reach of the relays.

PST Installation and Commissioning

The time from project approval to energization was approximately 3 years for both installations. The manufacturer shipped all four PST units within 18 months of placing the order. To expedite installation, the manufacturer was contracted to assemble and install the PSTs. This was a major task because each transformer consists of two large tanks, one containing the series unit and one the exciting unit, which must be connected together through special throat openings in each tank. In addition, the LTC, bushings, arresters, radiators, and other miscellaneous items were all installed as part of the package.

The PST installations were commissioned in the fall of 1989. The units were initially energized with one breaker open for several hours before being fully closed in. Once the PSTs were fully energized, they were loaded in increments with temperature rises recorded at each load level. The parallel lines and PSTs at each substation allowed the units to be load tested without adversely affecting power flow through the system. The parallel PSTs at each substation were adjusted to create circulating current on the two parallel lines. This unbalanced operation loaded the PSTs without adversely affecting the power system.

Commissioning of the units went well with the exception of a problem with the 51GA ground overcurrent relay in the neutral of the exciter unit primary winding. The 51GA, which is intended for sensitive ground fault protection, often tripped on inrush current during energization. The relay had a short time tripping characteristic without an instantaneous overcurrent element, as recommended by the PST manufacturer. However, the net inrush current in the neutral was sufficient to operate the relay during energization. Attempts to use slower time settings and higher current taps worked for the Shiprock 230-kV PSTs, but failed to prevent energization misoperations on the Waterflow 345-kV PSTs. As a temporary measure, a 15-second delay timer was added to block the neutral ground relays during energization. The energization delay timer enabled the relays to retain fast, sensitive settings while a permanent solution to the inrush problem was studied.

Operating History

The two PST installations performed power flow control operations as expected and allowed WAPA to control unscheduled loop flow through the two transmission lines.

One problem that occurred during operation was a sustained tap mismatch between the LTCs on parallel PSTs. The sustained mismatch caused the control system to bypass and lockout the PSTs. The control logic is designed to allow a one tap mismatch, but opens the PST breakers if a two tap mismatch occurs. Measurements indicate that a one tap mismatch produces approximately 100 amperes (at 345-kV) of circulating current and a two tap mismatch 200 amperes of circulating current. The cause of the sustained mismatch is unknown, but the intermittent nature indicates that there may be a bad relay or contact in the controls.

Energization inrush currents remained a problem, even with the delay timers added during commissioning. The delay timers enabled a single PST to be energized, but when the parallel PST was energized, the first PST would often trip due to sympathetic inrush current in the neutral relays. Tests were conducted, replacing the existing, solid state, short time ground overcurrent relays with electromechanical, extremely inverse time relays, but the new relays also operated on the inrush currents and were removed. Because of the sympathetic inrush problem, as a temporary measure, the 51GA and 51GB overcurrent relay settings were de-sensitized. The slower settings, in addition to the delay timers, allowed the PSTs to be energized without the neutral relays operating on inrush or sympathetic inrush currents.

To obtain a permanent solution to the inrush problems, harmonic restrained overcurrent relays and transformer inrush detection relays were ordered for evaluation. The transformer inrush detection relay is a new type of device that detects the zero current period in the magnetizing inrush current waveform and initiates blocking. The relay will not block if a fault occurs during inrush since the zero current period does not exist. Because the inrush detection relays are new devices, WAPA did not receive them until the summer of 1990. The harmonic restrained overcurrent and the inrush detection relays were tested, and it was decided to use the inrush detection relays to block operation of both the existing 51GA and 51GB neutral overcurrent relays during inrush. During testing, the inrush detection relays provided a positive indication that they were functioning properly by blocking on inrush. The harmonic restrained overcurrent relay was much harder to evaluate since it is designed to not operate during inrush. One inrush detection relay is presently being installed for each PST. The relays, designated as a device 50/68, are located as shown in Figure 3. With the 50/68 relays installed, the delay timers were removed and the original, sensitive, settings were used on the 51GA and 51GB relays.

In April of 1990, before the harmonic detection relays were installed, a fault occurred in one of the two PSTs at Waterflow Substation. The fault occurred shortly after the two PSTs were placed in the neutral (zero degree shift) tap position. Initial indications were that a fault occurred in the load tap changer compartment. The only PST relay to operate was the 51GB relay. The relay, which had been de-sensitized due to sympathetic inrush problems, operated in 24-cycles.

Initially, it was unclear why the sudden pressure relays and transformer differential relays did not operate. Although there were five sudden pressure relays on the PST, there was no sudden pressure relay in the faulted LTC main compartment. Pressure build up in the series tank, the exciter tank, or the three diverter switch columns was not sufficient to operate the sudden pressure relays. To improve protection, sudden pressure relays were added to the LTC main compartments in all four of the PSTs.

Field inspections later determined that the fault was caused by two taps in the phase C load tap changer shorting together. Because the PST was in the neutral tap, the LTC was internally bypassed when the fault occurred. For this condition, fault current circulated in the shorted phase C LTC as shown in Figure 4. The magnitudes of the fault currents were determined from analysis of digital fault recorder data. Because of the nature of the fault and the neutral tap operating position, there was no differ ence current to cause the transformer differential relays to operate. The only relay to see the fault was the desensitized 51GB relay. If this relay had had the original, sensitive settings, it would have operated in 3 cycles instead of 24 cycles.

Investigations indicated that the damage due to the fault was limited to the LTC compartment. The LTC was repaired, the compartment cleaned, and the PST was energized less than three months after the fault occurred. During the time the PST was being repaired, the remaining three PSTs were still operating to control unscheduled loop flow through the area.

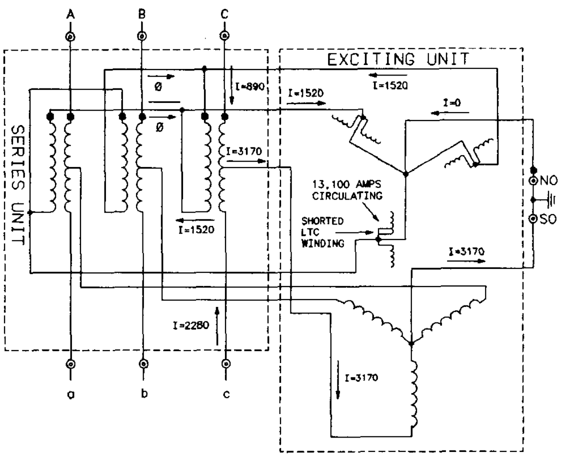

FIGURE 4. FAULT CURRENTS IN THE PHASE-SHIFTING TRANSFORMER

Conclusions

Four large 345-kV, 300-MVA phase shifting transformers have been installed on two critical lines in western Colorado. The parallel application of these large PSTs has been a first for WAPA; and except for some minor commissioning problems, the installation and commissioning went smoothly. A fault in the main LTC compartment later removed one unit from service, but the installation of parallel units at each location allowed for continued operation and control of the power flow on the two lines.

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Biographies

Joel K. Bladow was born in Moorhead, Minnesota on March 5, 1959. He received a B.S. degree in electrical engineering (power option) from North Dakota State University in 1981 and a M.S. degree in electrical engineering from North Dakota State University in 1982. Mr. Bladow joined the Western Area Power Administration in 1983 under the Substation Controls Branch. In 1984 he transferred to the Technical Branch where he was involved with various Electromagnetic Transient Analysis Program (EMTP) studies, the application and setting protective relays for transmission lines and substations, performing short circuit studies, and providing major electrical equipment specifications requirements. Mr. Bladow is presently in the Substation Electrical Branch at Western. Mr. Bladow is a member of CIGRE, IEEE, the IEEE Switching Surge Working Group and is a registered professional engineer in Colorado.

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