Abstract - The U.S. Bureau of Reclamation (USBR) operates the world largest, fully operational hydroelectric facility at Grand Coulee Dam located on the Columbia River in eastern Washington state. Data transmitted for control, protection, and communication between this facility’s Third Powerplant and 500-kv switchyard are essential for the safety and efficient operation of the Bureau’s equipment and the integrity of the connected power system. To accomplish the reliable, high-speed transmission of such data over the relatively long distance between these two locations having unequal ground potential rise (GPR), a fiber optic communication system was installed, tested, and placed into service. The paper discusses the rationale for applying fiber optic technology in this application with emphasis on the related design considerations important in control and protection of this large hydroelectric facility. Brief summaries of hardware used and installation considerations are given. Fundamentals and principles of fiber optic system design are not intended or covered. Discussion of factory and unique field testing, including electromagnetic interference (EMI) induced transient influence and timing tests, is included. Operating experience and projected future use are summarized.

INTRODUCTION

At Grand Coulee Dam, which has an overall installed hydroelectric generating capacity of approximately 6500 MW, the largest block of power is produced by a four-unit Third Powerplant (three 600 MW and three 700 MW units) and transmitted via high voltage, oil-filled cables and overhead transmission lines to the 500-kv switchyard located some 3.4 km (2.1 mi) to the west of and 420 m (1400 ft.) higher in elevation than the powerplant. See Fig. 1. Unit breakers are not provided at the powerplant thus all synchronizing, switching, and emergency circuit breaker tripping is done in the switchyard with the appropriate control, protection, and instrumentation signals being transmitted in 2-way communication between these two locations. Hardwired communication has been exclusively by redundant, but alternately routed, microwave paths. Microwave, rather than a hard-wired communication path, has overcome the problem of transmitting the signals over the long distance between the powerplant and switchyard and the undesirability of conductively connecting these two locations which have significantly different ground potential rise (GPR) during faults. One group of signals traditionally transmitted in this fashion consists of circuit breaker position and path availability indication, and transfer trip commands. The first two signals were time-division multiplexed on both ends of the microwave link with the inputs and outputs being hardwired into the control circuits. The transfer trip signal was not multiplexed.

After some major disruptions of powerplant output due to human error and multiplexer hardware failure it became apparent that the system needed to be upgraded. Ultimately, a fiber optic system was decided upon to meet the present communication needs for these functions and provide potential for future transmission of other kinds of information. Procurement, installation, testing, and training followed with the system being phased into service during 1986 and 1987.

THE REQUIRED SIGNALS

The facility’s control and protection schemes require reliable, high-speed transmission of the following signals between the powerplant and switchyard:

- Breaker Position Indication: See Fig. 1. Proper operation of control and protection circuits in the powerplant requires accurate knowledge of the position (open/closed) of the “A” and “B” breakers in the switchyard. This position information is also needed as an input to the computer-based supervisory control system.
  - Breaker position as detected by the auxiliary switches at the breakers is hardwired into the switchyard control building where it is used as an input to the channel units of the communication equipment. Positive indication of both positions of the breakers (i.e., both “a” and “b” switch contacts) are transmitted. Output relays replicating the breakers’ positions at the powerplant provide contacts for use in the various control and protective circuits as well as for supervisory control input.
- Path Availability Indication: See Fig. 1. Several possible combinations of circuit breaker and disconnect switch positions exist for a given switchyard bay. It is important for the operator or supervisory control system to know, prior to starting a generator, that a path is available to permit connecting that unit either to the switchyard busses or to an outgoing transmission line. “Path Available” is defined as circuit breakers open and functional and disconnect switches closed. Path availability is determined by using complex strings of parallel and series connected hardwired contacts, representing all necessary conditions for path availability, as inputs to the switchyard fiber optic transmitter equipment. Positive indication of both “Path Available” and “Path Not Available” are transmitted. Output relays replicating the path status at the powerplant provide contacts for indication to the operator and the supervisory control system.
Transfer Trip Command: Switchyard or powerplant protective relay actions which warrant full, emergency shutdown of the generator and tripping of the circuit breaker(s) must ultimately accomplish the following actions:

Trip the A or B breaker, or both depending on the switching arrangement at the moment.

Trip the generator exciter breakers.

Drop the governor shutdown solenoid to close the gates.

Transfer trip commands can be initiated from either the powerplant or switchyard in response to local relay action. Reliable, high-speed transmission of transfer trip commands is critical because:

1. With no unit breaker at the powerplant, faults between the powerplant and switchyard can be fed with fault current from either direction. Rapid elimination of the fault current from both ends is essential.

2. The large size of these generators can have a serious effect on power system stability if high-speed clearing of faults is not accomplished. The one-to-three cycle breaker tripping time is effective in reducing these stability problems once the transfer trip signal is received.

The transfer trip command was originally transmitted exclusively by the microwave system. The fiber optic system now provides a permanent path for this signal parallel to the microwave path. The fiber optic system now provides a permanent path for this signal parallel to the microwave path. The transfer trip command is now connected as an input to the fiber optic transmitter equipment while output relays on the receiver and replicate the transfer trip command providing contacts for use in the appropriate protection circuit. Because the multiplexing rate of the fiber optic equipment is so high, speed is not sacrificed by routing the transfer trip command through it. Fiber optic system redundancy provides adequate reliability.

COMMUNICATION CONSIDERATIONS

Conventional hard-wired, electrical transmission of signals between the powerplant and switchyard is not possible because:

1. The relatively long distance of approximately 5 km. (3.1 mi) (surface route) which separates the two can cause voltage drop problems.

2. A large difference in GPR makes it undesirable to interconnect these two parts of the facility with conductive control cable.

A direct microwave path and a parallel combination microwave/hardwired path (for redundancy) has been used for years to overcome these difficulties. It was recognized, however, that fiber optic communication systems were also capable of overcoming these problems and their successful use in similar power station applications was encouraging.

A NEEDED CHANGE

As the six Third Powerplant units were completed and brought on-line during the 1970's and 1980s it became obvious that communication path changes must be made. Four major reasons were:

1. The time division multiplexer equipment was aging and spare parts were not readily available since the original manufacturer had gone out of business. Continued reliable operation of the equipment could, therefore, not be guaranteed.

2. Accidental shutdowns of the multiplexer system with resulting loss of generation (due to the fail-safe design of the external control circuits) pointed up the need for additional redundancy and security that could not be achieved with the existing equipment.

3. Troublesome microwave system noise which occasionally caused loss of signal suggested that an alternate, non-microwave path would be desirable for redundancy.
4. As the facility was completed and more remote control and indication was anticipated a more flexible, expandable system was needed.

Replacement of the existing multiplexer equipment with more up to date, expanded multiplexer equipment was considered along with microwave improvements which were needed in any case. However, it was recognized that a fiber optic system would be immune to noise and cross-talk typically associated with microwave equipment. Also, the intrinsically shielded route (e.g. dam galleries and buried conduit) makes the fiber link more secure from adverse weather and potential sabotage. The fiber link itself would also retain the needed electrical isolation between the powerplant and switchyard.

Therefore, based on the need to have an alternate, non-microwave path and expansion potential plus favorable cost comparisons with the alternatives, a fiber optic system was chosen. It was decided that such a system was capable of overcoming the problems of the existing system, providing electrical isolation between the two ends, and permitting future expansion. As a significant side benefit, experience in the design, application, installation, and operation of such equipment would be gained for future Bureau installations.

**DESIGN CONSIDERATIONS**

Early in the design stages it was determined that the fiber optic system would have to meet the following criteria:

1. **Speed:** System speed is critical particularly for the transfer trip function so that faults are cleared quickly and power system stability is maintained. The multiplexer/microwave system was measured to determine the time required for an output replica relay on the receiver end to energize after an input on the transmitter end was keyed. This one-way signal propagation time was nominally 20 msec. The fiber optic system was specified to meet or exceed this speed and tests were required to verify it.

2. **Redundancy:** Redundancy in the system is important in providing the required level of reliability. Therefore, the fiber optic system was required to match or exceed the level of redundancy of the existing multiplexer/microwave system. See Fig. 2. Significant redundancy features of the installed system include:
   a. Each signal is transmitted simultaneously by each of the two separate and independent systems. This redundancy permits continued operation even with one system down due to failure or out of service for maintenance.
   b. Each system has its own 5-fiber cable as its optical link thus loss of one cable does not cause failure of the system.
   c. Each system uses fail-over circuitry to detect a failed fiber or communication system hardware failure and transfers the signal to another fiber.

3. **Immunity to EMI Induced Transients:** Since the capability of the fiber optic light path itself to be immune to power system induced EMI is well known [1],[2], the major area of concern was the ability of the input hardware of the transmitter equipment to suppress or withstand EMI induced transients on the hardwired input circuits. This was considered important because this type of hardware was generally designed for telephone type applications and was not normally found in power station environments where EMI is prevalent. This was of particular concern in the switchyard where input circuits were long (sometimes in excess of 1300 m (4400 ft.) round trip) and routed throughout the yard in the vicinity of the 500-kv buswork and equipment.

Exact magnitudes and types of transients generated in the control cable conductors during switching operations and faults were not known so a conservative design of the system's transient suppression capability was specified. Factory and field tests were required to verify this capability and make measurements of the actual transients experienced in the yard.

4. **Flexibility:** Although the immediate need was to provide a communication path for the control and protection signals discussed above, it was deemed important to require the system to be capable of handling additional data by providing sufficient numbers of channels and fibers to efficiently transmit future control, protection, and communication signals.

**HARDWARE**

See Fig. 2. The fiber optic system hardware comprises two separate systems (operating in parallel) and two separate fiber optic cables connecting these systems.

Each system consists of one terminal at each end of its fiber link containing common power supply and alarm equipment and the following:

1. Communications equipment and two optical transmitters (LED (light emitting diode) type, transmission rate: 3,000 Bps/sec), two optical receivers (APD (avalanche photo-diode) type), and two automatic protection switches (with alarm) to switch fibers on a failed fiber or communication system hardware failure.

2. A 24-channel multiplexer which interfaces to the channel units comprised as follows:
   a. Nine transmitting (receiving) channel units and two receiving (transmitting) channel units at the switchyard (powerplant) terminal. Each channel unit has eight inputs or eight outputs.
   b. One voice frequency telephone channel unit at each terminal.
   c. Space for twelve additional ON/OFF or voice frequency transmit or receive channel units at each terminal.

Each 5-fiber cable is approximately 5 km (3.1) long and consists of graded-index multimode type fiber (approx. 4 db/km loss) connected by 4 splices (approx. 0.58 db/splice loss; average). The total measured loss of the installed cable including splices and end connectors is approx. 22.14 db, average.

**INSTALLATION**

Installation of the fiber optic equipment was performed under a contract separate from that for providing the hardware. The terminal equipment at the powerplant was installed adjacent to other communication and microwave equipment and the terminal...
equipment at the switchyard was installed in the protective equipment lineup in the control building.

The fiber optic cables were installed in a combination of cable trays and conduit from the Third Powerplant, through the galleries of the dam, passing through the 115 kV switchyard and on to the 500 kV switchyard. The route includes a 50 m. (163 ft.) vertical drop where the cables are supported at 3.3 m. (10 ft.) intervals.

Four splices in each 5-fiber cable were made and tested along the route. All splices are accessible for inspection.

**Testing**

In addition to routine factory and field functional testing, the system was required to undergo special tests to confirm its ability to perform correctly in the presence of EMI induced transients, particularly in the switchyard where one and three cycle 500-kv circuit breakers are operated for switching and fault interrupting.

Since it was assumed that the fiber link itself would be immune to EMI, the testing concentrated on the ability of the transmit channel unit to suppress or withstand the transients induced in the hardwired input circuits as discussed in "Design Considerations," above. Additional tests were needed to verify that the speed of operation would meet or exceed that required for safe, effective transfer tripping, also discussed in "Design Considerations," above.

Two levels of testing were designed to provide assurance of the equipment's capabilities: factory testing by the equipment supply contractor and field testing by the Bureau.

**Factory Testing**

Prior to shipment of the equipment the contractor performed the ANSI/IEEE Surge Withstand Capability (SWC) Test [3] on all input and output circuits. All inputs and outputs successfully passed this test. Factory timing tests were performed which demonstrated a nominal one-way signal propagation time of 18 msec which was deemed acceptable.

**Field Testing**

A series of field tests conducted in the 500-kv switchyard was designed by the Bureau to verify correct operation of the system in situ and provide an opportunity to measure the electrical effects of switching actions and faults (short circuits).

The tests were performed with the fiber optic system fully operational except that the output circuitry was disconnected so as to not cause unwarranted control actions. Measurements were taken of the transients generated in the input control circuits and the system was carefully monitored for misoperation during the following tests:

1. Arcing disconnect switch test in which a 3-phase, 500-kv motor operated, air-break disconnect switch was opened and closed on a hot bus (no load current present).

2. Bus grounding test during which a 500-kv bus (which was deenergized but still somewhat "hot" from inductive effects) was grounded, causing arcing.

No induced voltage was detected during these two tests.

3. Two single-phase-to-ground tests during which fully energized phases of the 500-kv bus were intentionally shunted to ground causing arcing until the circuit breakers cleared the fault. Fault currents of 43,200 amperes for 1.5 cycles and 50,700 amperes for 1.4 cycles (peak values) were experienced and GPRs were measured at 5600 and 6500 volts respectively, during these tests. However, measured control circuit transients were negligibly small (the largest coupled voltage was 9 volts, crest resembling a sine wave at a 4 kHz frequency) and no misoperation of the fiber optics system was caused by these transients.

Speed tests were again performed with nominal one-way signal propagation time of 16.3 msec which was deemed satisfactory.
TO TRAINING

Historically, the Bureau has performed in-house operation and maintenance of almost all equipment in its facilities. Achieving this for the fiber optic equipment required that Grand Coulee project forces be trained in all facets of operation and maintenance with no previous practical experience with such equipment. Project forces were trained by the equipment manufacturer in operation, trouble shooting, testing, and repair procedures including performing optic fiber splices in the field.

OPERATING EXPERIENCE

The system is being phased into service during 1986 and 1987 to operate in parallel with the still functioning multiplexer/microwave system until reasonable operating and maintenance experience can be obtained.

In the early stages of operation some misoperations were detected: electrical transients generated by the deenergization of output replica relay coils were causing malfunctions in the receiver equipment and subsequently other output channels were operating erroneously. This was corrected by installing surge suppressors on the relay coils. In addition, some minor failures in the fiber optic hardware were discovered and corrected by the manufacturer. Subsequent operation has proved the system reliable and the multiplexer/microwave system will be removed from service in 1988 leaving the fiber optic system as the single communication path for this data. To date additional data or signals have not been added to the system, however possible future uses may include remote telemetering of electrical quantities, remote synchronizing, remote annunciation of alarms, and facility security signals.

CONCLUSIONS

Fiber optic communication systems are becoming increasingly more common in power station environments as this technology emerges and the power industry recognizes its value [4],[5],[6]. The use of such a system at Grand Coulee has demonstrated its usefulness in providing a secure, high-speed path for the transmission of control, protection, and communication signals in a power station environment. Redundancy has been a key factor in providing the reliability required while unique testing has provided assurances that input circuit transients will not cause misoperation or damage equipment. The desired system speed was achieved and proven.

System design has provided the means for future expansion of the number and type of signals being transmitted.

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REFERENCES


BIOGRAPHIES

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