UPRIVER DAM HYDROELECTRIC PROJECT: FAILURE AND REHABILITATION

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Introduction

A fault on the Washington Water Power (WWP) 13.8-kV interconnecting tie line to the Upriver Dam Hydroelectric Project caused the protective relaying to shut down and lock out all five generating units in the No. 1 and No. 2 Powerhouses. (See Figure 1.) This prevented operation of the spillway gates, leading to overtopping and breaching of abutments on both sides of the dam and closure embankments on both sides of No. 1 Powerhouse.

The washout left No. 1 Powerhouse tilted upstream with an eroded foundation and minor flooding damage. The No. 2 Powerhouse suffered damage to its electrical components including the generator switchgear and station service transformer, No. 1 Powerhouse tie breaker, exciter cubicles, cable tray system, and other miscellaneous equipment. The switchyard takeoff structure and line potential transformers were also damaged. The 6-MVA, 2.4-4.16-kV, 3-phase transformer which stepped up the No. 1 Powerhouse generation to the No. 2 Powerhouse bus voltage was washed downstream.

Power generated by these plants defrays the cost of power for the pumps which supply water to the City of Spokane (City). It was necessary, therefore, to quickly repair the facilities. The City set up a task force that worked together closely to "fast track" the repairs. The task force was composed of key City personnel familiar with the original project and R. W. Beck and Associates (Beck).

The total cost of repairing the damage and for implementing the recommended enhancement provisions was about $11.5 million. This amount does not account for lost generation or for purchasing replacement power.

As required by the Code of Federal Regulations, the licensee of a hydroelectric project is required to file a Failure Investigation Report with the FERC when an accident occurs at the Licensee's Project. The City's initiative for the investigation of the incident went beyond the requirements of FERC to assure that identifiable shortcomings would be eliminated on reconstruction of the facilities. The City moved swiftly to conduct the investigation and repair the damage. Within two weeks of the accident, Beck was retained to provide the following services:

- Prepare an emergency evaluation and independent failure investigation as required by FERC;
- Conduct feasibility investigations of rehabilitation alternatives; and

- Prepare construction contract documents and provide construction management services for restoring the damaged facilities.

This paper addresses the investigation and rehabilitation of the electric controls and protective systems.

Investigations

Preparation of the "Failure Investigation Report" and additional investigations revealed a number of irregular operating and protective relaying philosophies, the most significant of which was that the protective relaying scheme was designed to shut down and lock out all of the turbine-generator units for any fault in the vicinity of the Upriver hydro plants, including faults on the WWP system and the tie line to WWP. This, coupled with the lack of centralized control, the absence of a reliable standby power source to operate the dam gates and minimal freeboard for the forebay, was virtually a guarantee of the washout that occurred.

The problem of providing power to operate the dam gates was compounded by the requirement that the normal power for the gates came from the No. 1 Powerhouse station service bus, and the only tie to WWP was via the 13.8-kV line breaker at No. 2 Powerhouse. This breaker could only be closed at the breaker cabinet in the switchyard by placing the local-remote switch in "local" and operating the local control switch to "close" position. There were no interlocks or lockout contacts in this close circuit. After this breaker was closed to energize the plant, the 4,160-volt and No. 2 Powerhouse station service 480-volt buses and the No. 1 Powerhouse 2,400-volt and 240-volt buses had to be energized before normal power could be supplied to the dam gate hoist motors. This required closing of the tie between No. 1 and No. 2 Powerhouses via 52T2 and the 6 MVA, 4,160/2,400-volt transformer.

By the time the No. 2 Powerhouse 4,160-volt bus was reenergized, the No. 1 Powerhouse 2,400-volt bus could not be reenergized, because attempts to close 52T2 were unsuccessful. Operators reported hearing "charging" sounds after attempts to close; however, if the breaker was closing into a made-up trip circuit, it is unclear what was tripping the breaker, since 87T2 and 50-2 relays had never been installed. Since 52T2 was torn apart when the cable between the two plants washed out, and the new design did not include this tie, no time was used to further investigate this problem.

Although the 30-kVA gas engine-generator was finally started and used to supply limited power at the Well Electric Building, attempts to obtain power from it to the diversion dam gate hoists were unsuccessful. Thus, the earthen embankments between the powerhouses and between the No. 1 Powerhouse and the Well Electric Building were washed out, as well as part of the embankment between the dam and the No. 2 Powerhouse. Also, the bridge and water pipe crossing downstream of the plants was destroyed.

Beck's Failure Investigation Report included recommended minimum electrical design changes, which needed to be made before the plants could safely be put back in service and changes to optimize the design. The City chose to go with the optimized design recommendation.

The optimized design was predicated on maximum reliability of station service power supply and, therefore, required high-speed, selective clearing of all faults.

To meet the rehabilitation schedule, seven separate contracts were negotiated, as well as use of force account labor. The contracts for electrical work included: Contract No. 3 with installation of electrical duct banks, ground mats, and foundations; Contract No. 4 with releveling of No. 1 Powerhouse generators, installation of spillway gate power and control, installation of four standby generators, installation of generator switchgear in No. 1 Powerhouse, replacement of governors in No. 1 Powerhouse, installation of Switchyard No. 1, installation of site lighting, and electrician and millwright labor as required. Contract No. 5 included supply of the hydro facilities SCADA system equipment. In addition to the contracts, R. W. Beck worked directly with the City's force account staff to repair and modify the No. 2 Powerhouse equipment, control circuits, and protective relay system. Contract No. 6, which is to be prepared by the City, will involve security system improvements.

To provide for reliable and safe operation of the Project, it was decided to separate the powerhouses for power output, protective relaying, and standby station service power. The controls have been redesigned for automation and remote operation via a central hydro facilities SCADA system. A coordinated protective relay system has been redesigned for the overall Project.

<u>No. 2 Powerhouse Rehabilitation</u>

The No. 2 Powerhouse was commissioned in 1984 with automated modern equipment and controls. However, several control and protection problems still remained to be corrected at the time of the accident and, the failure caused damage to some electrical equipment. The disruption exposed the equipment and controls to power surges. (See Figure 3.) The 4,160-volt No. 1 Powerhouse tie cables embedded in the breached closure section were pulled out of tie breaker, 52T2, complete with the current transformers attached. This damaged the circuit breaker cabinet, the Unit No. 4 Excitation Cabinet, the excitation transformer cables, the station service transformer and cables, and the cable tray. The Unit No. 5 turbine servomotor was bent and all the wicket gate shear pins were sheared.

The damaged No. 2 Powerhouse equipment was repaired. Damaged cabinets were straightened rather than replaced. The control and protective systems were thoroughly reviewed and several design deficiencies were identified. The deficiencies were corrected as follows.

The No. 2 Powerhouse generator neutrals were grounded through a distribution transformer and secondary resistor to limit the maximum ground current to approximately 4.2 amperes. Since the machines were bused at generated voltage, this method of grounding did not lend itself to selective clearing of generator ground faults. To provide selective, high-speed clearing of ground faults, the generator grounding was changed to a primary resistor of 2.4 ohms, thus providing high-speed selective clearing of generator ground faults by the generator differential relays. Further, a CT, salvaged from 52T2, was installed in the neutral, and an overcurrent relay connected in its secondary to provide time-delayed, non-selective backup for the generator differential relays.

Ground fault detection for the 4,160-volt bus or 20-MVA bank delta winding for the condition when the generators were off-line and station service was obtained from WWP, was comprised of three 4,200/120-volt P.T.'s connected wye - open delta, with a voltage relay and 75-ohm resistor connected across the open corner of the delta. During rewiring to implement the new design, it was discovered that the relay was not wired to either annunciate a bus ground or to block closing the generators into a bus ground.

This ground detection scheme was changed to a single 4,200/120-volt P.T. connected between phase and ground, with an 1AV51 over and under voltage relay connected across its secondary. This relay picks up an HFA relay, which seals in through a reset pushbutton and opens the close circuits of the generator breakers and annunciates a 4,160-volt bus ground.

One set of generator PT's on each machine was connected wye-wye and the 4,160-volt bus PT's were connected wye-wye. No line-to-ground burdens were connected to any of these PT's, and the grounds were "lifted" on the primaries. There were penciled notes throughout the powerhouse "remove ground in field." There were 120/120-volt isolating transformers between the generator and bus PT's and the automatic synchronizer. The center PT was removed from the wye-wye connected PT sets, and they were reconnected "V Phase", i.e., two PT's connected phase-to-phase, with B phase secondary grounded. The 120/120-volt isolating transformers were also removed. This resulted in five 4,200/120-volt and two 120/120-volt spare potential transformers.

The line relaying was comprised of three instantaneous overcurrent relays, one in each phase. These relays were connected in the secondary of transformer bushing CT's. The existing three-line drawing showed these CT's connected in wye. During startup, when checking CT secondary currents, it was found that they were actually connected in delta. In the meantime, an overcurrent relay, which was connected in the station service transformer neutral, was removed from the station service neutral circuit and reconnected in the residual circuit of the line phase overcurrent relays. The transformer drawings showed all transformer CT's connected in delta, and it was found that the transformer drawings were correct. The line overcurrent relays were reconnected in wye, thus providing sensitive line ground relaying. The line relays, as were all protective relays, were connected to shut down and lockout both turbine generators. These relays and an over and under frequency relay were reconnected to trip only the line breaker (52MB) and to initiate automatic resynchronizing across 52MB upon reenergization of the line by WWP.

The line relaying is now comprised of phase instantaneous and residual ground time, and instantaneous overcurrent and over and under frequency relaying.

The 225-kVA, 4,160-480/277-volt delta-wye station service transformer was fused on the 4,160-volt delta side, with 100E Westinghouse-type CLE fuses, with total clearing time for a bolted minimum, one line-to-ground fault on the 480-volt bus of 30 seconds. The station service transformer 480-volt neutral relay was wired to trip the main transformer lockout relay. The station service transformer fuses were changed to 50E for a bolted, 480-volt bus line-to-ground fault, with minimum generation; total clearing time of one second. A molded case circuit breaker was installed in the 480-volt leads of the station service transformer, with phase and ground sensing and tripping to provide the secondary ground fault protection removed by deletion of the neutral relay.

A short-circuit study was prepared in cooperation with Washington Water Power Engineers and was used in the preparation of protective relay settings. No attempt was made to coordinate the line relays with WWP's beacon substation relays. The philosophy is to separate from WWP instantaneously for any local system problem and to resynchronize when the problem is corrected.

The City requested that Beck supervise their technician in testing and setting the relays. The relays were tested and set by City and R. W. Beck personnel, using a Multiamp relay test set. During testing, several relays were found to be inoperative. In all cases, it was possible to make them operative, either by adjustments or resoldering internal connections. Also during testing, several trip circuits shown on the drawings were found not connected, and the relay designated 81/O (overfrequency) was in fact, a GE static underfrequency relay. Since it was set to trip for frequency in excess of 60.6 Hz, it was sending a continuous trip signal at normal system frequency and the trip circuit had been disconnected. A new electro-mechanical over and underfrequency relay was installed in place of the static underfrequency relay and connected to trip the line breaker and initiate resynch upon return of line voltage.

The generator relaying consists of voltage controlled time overcurrent, negative sequence overcurrent, and loss of excitation, in addition to generator differential and backup generator neutral ground relaying.

As mentioned earlier, the line breaker (52MB) had neither control or status indication in the powerhouse control room. A breaker control switch and red and green indicating lights were salvaged from 52T2 panel and located on the main control switchboards. The close circuit from this switch was routed through normally closed contacts of the transformer lockout relay, and a "b" switch from each of the generator circuit breakers in series so that the breaker can be safely closed without operation of the synch switch to restore station service rapidly if the generator breakers are open, and the main transformer is not faulted. A three-position mode selector switch, a synch switch, a synchroscope, and incoming and running voltmeters were mounted near the 52MB control switch. The three positions of the mode selector switch are "manual," "Auto," and "Remote." In manual, the incoming and running voltmeters and scope are energized, and a contact is closed in parallel with the 52G "b" switches to permit manual synchronizing. With the switch in Auto, the autosynchronizer is picked up approximately 2 minutes after the line is reenergized from WWP after a trip by the line over currents or frequency relay.

The autosynchronizer was found to close the breakers, at times, immediately upon being energized, without checking synchronism. At other times, the close pulse was of insufficient duration to close the breaker. The first problem was solved by inserting a timer in the close circuit to keep it open until the synchronizer had been energized for a time adjustable from 0.5 to 10 seconds. The second problem was corrected by picking up a high-speed relay with the close pulse and sealing it in through a breaker "b" switch.

As redesigned under normal operation, the only way normal station service can be lost is for a main transformer, or 4,160-volt bus fault, or failure of the station service transformer. For all generator or line faults, only the faulted generator or line breaker will be tripped, and the unfaulted equipment will remain in service.

In the event where normal station service is lost, a 287-kVA diesel engine-generator will start automatically, and when it attains rated speed and voltage, an automatic transfer switch will transfer the station service loads to it. This transfer occurs within 10 to 15 seconds after loss of normal station service. If station service is interrupted for one minute, a 75-kVA diesel engine-generator will start automatically at the south end of the dam, and the dam loads will be transferred automatically to this 75-kVA machine. If this second standby diesel fails, a propane-fueled engine-generator, located on top of the dam, can be started and used to raise one gate at a time. The 75-kVA diesel engine-generator has the capability to operate two gates simultaneously.

Each time power to the dam is interrupted, an audible and visual alarm occurs in the central control room at the Well Electric Building. The audible alarm can be reset by the operator, but the visual alarm remains until power to the dam is restored, at which time it resets automatically.

The foregoing design modifications for No. 2 Powerhouse were effected by preparation of sketches in Beck's Seattle office, which were used by the City's mechanic to implement the design changes. Beck's engineers worked directly with the City's mechanics to complete the necessary installation, wiring, and checkout of the No. 2 Powerhouse design changes.

No. 2 Powerhouse was returned to commercial operation on January 4, 1987, three and one-half days later than scheduled.

No. 1 Powerhouse Rehabilitation

No. 1 Powerhouse underwent considerable automating and equipment upgrading. (See Figure 2.) The City took advantage of the opportunity by replacing 1936 vintage electrical and mechanical equipment with new state-of-the-art equipment. The three existing generator oil-circuit breakers were replaced with indoor metal-clad 5-kV switchgear with three 4.16-kV, 1,200-ampere air circuit breakers with 250-MVA short-circuit duty. The oil-filled station service transformer bank was replaced with a 75-kVA, 3-phase, 2,400-120/240-volt dry-type station service transformer and a 2,400-volt fused disconnect switch connected to the 2,400-volt generator bus. The existing transfer switch was replaced with a new automatic transfer switch. A new 240/120-volt, 3-phase station service switchboard and a new 125-volt dc panelboard were also installed. The following is a description of the rehabilitation.

AC one line and three line and detailed DC control and protection schematic diagrams and equipment specifications for the new No. 1 Powerhouse control and protection switchgear were designed and prepared by Beck's Seattle office. General Electric relays and a Beckwith autosynchronizer were specified so that spare parts could be common to both plants since No. 2 Powerhouse utilized equipment of these manufacturers. However, because General Electric could not meet delivery dates, Basler solid state relays were used at the powerhouse. Since the transformer at the No. 1 Switchyard was provided by Westinghouse, the No. 1 Switchyard relays are Westinghouse, except for the 2,400-volt bus ground detector, which is G.E. 1AV.

The No. 1 Switchyard is comprised of a 15-kV vacuum circuit breaker, a 7.5-MVA, 13.8/2.4-kV transformer, two 2.4-kV feeders, and a 2.4-kV tie breaker to connect the No. 1 Switchyard to the No. 1 Powerhouse 2.4-kV bus.

The transformer is wye on the 13.8-kV side and delta on the 2.4-kV side. The high side connects to a tap on the Washington Water Power 13.8-kV Upriver Hydro-Beacon substation line through the 15-kV vacuum breaker.

The 13.8-kV line and 2.4-kV feeder relaying is comprised of three time and instantaneous phase and a time and instantaneous residual ground-over-current relay.

The transformer and the cable between the switchyard and powerhouse are protected by Westinghouse-type CA current differential relays. 2.4-kV bus ground detection is provided by a 2,400/120-volt potential transformer connected between a phase and ground. A 575-ohm resistor and a 1AV over and under voltage relay are connected across the P.T. secondary.

A ground on the 2.4-kV bus is annunciated at the powerhouse, and if the tie breaker at the switchyard is open, it's close circuit is interrupted; if it is closed, the close circuits of the generator breakers are interrupted.

The generator neutrals are grounded directly with no intentional impedance between their neutrals and ground. Since they have been in service like this since 1936, it was decided the extra expenditure for neutral impedance would be difficult to justify. As it turned out, a 2.4-kV powerhouse bus surge arrester failed during startup, resulting in a line-to-ground fault on the 2.4-kV bus with a generator on-line. The generator came through the ordeal unscathed.

The generator protection is comprised of current differential voltage controlled overcurrent, negative sequence current, and loss of excitation.

During rehabilitation deliberations, it was decided to replace the turbine governors with modern electronic PID governors. The contract was awarded to Digitek, Incorporated, who supplied their microprocessor-based IGC 2000 (integrated generator control) system for each of the three units. This equipment combines governing, startup, and shutdown sequencing, automatic synchronizing and certain protective relay functions. Digitek also supplied the control and protection switchboards and automated the existing Basler automatic voltage regulator controls.

The new No. 1 Powerhouse design provides automatic resynchronizing after clearance of 13.8-kV system faults by the line relays and reenergization of the line by WWP. In addition, the IGC 2000 system automatically returns the turbine-generators to pre-trip loading after resynchronizing.

The No. 1 Powerhouse was returned to commercial operation April 30, 1987, precisely on schedule.

Both plants were tested simultaneously to prove that they could reject full load, return to operation at synchronous speed, no load, and automatically resynchronize after temporary loss of the tie to WWP without interruption of normal station service supply. The test consisted of opening the Beacon Substation end of the 13.8-kV line to WWP when all 5 turbine-generators were operating at maximum output for the existing head (approximately 80% of rated megawatts). Both 13.8-kV line breakers were tripped by the overfrequency relays. When the line was dead, WWP's breaker was reclosed. When the line was reenergized, the plants automatically resynchronized after approximately three minutes, thus proving the plants operate as designed.

SCADA System

Originally, the hydro facilities had no centralized control. A SCADA system was designed with three remote terminal units and a master to provide control of No. 1 Powerhouse, No. 2 Powerhouse, Switchyard No. 1, Switchyard No. 2, and the dam spillway gates from the Control Center in the

Well Electric Building. The SCADA system presently being installed, will provide the operator with all necessary controls, indication, and status to operate the hydroelectric facilities safely during emergency conditions.

Summary

The failure occurred on May 20, 1986, and a tremendous coordination effort of all involved - the City, the consultants, the contractors, and the regulatory agencies, made it possible to restore the project in less than nine months. All this could not have been achieved if proper and timely funding had not been provided by the State and Federal Emergency Management Agencies.

The deficiencies identified in the system project-wise have been addressed and corrected. The project now is considered a highly satisfactory one with important safety features. The insurance agency which paid a major share of the rehabilitation cost, noted all the safety features built-in and considered it satisfactory to the extent that they renewed the policy without any hesitation.

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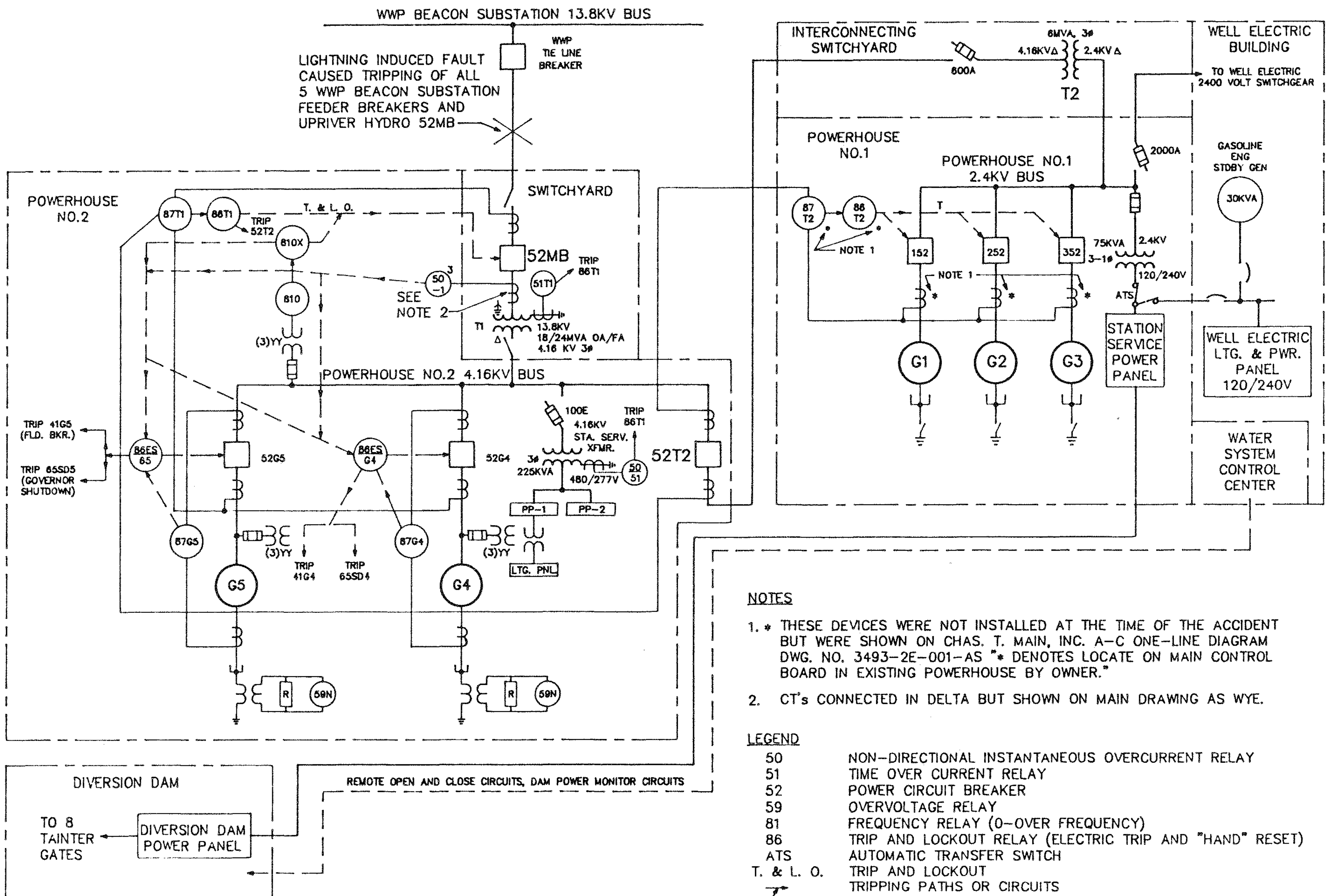

NOTES

1. * THESE DEVICES WERE NOT INSTALLED AT THE TIME OF THE ACCIDENT BUT WERE SHOWN ON CHAS. T. MAIN, INC. A-C ONE-LINE DIAGRAM DWG. NO. 3493-2E-001-AS "* DENOTES LOCATE ON MAIN CONTROL BOARD IN EXISTING POWERHOUSE BY OWNER."

2. CT's CONNECTED IN DELTA BUT SHOWN ON MAIN DRAWING AS WYE.

LEGEND

50	NON-DIRECTIONAL INSTANTANEOUS OVERCURRENT RELAY
51	TIME OVER CURRENT RELAY
52	POWER CIRCUIT BREAKER
59	OVERVOLTAGE RELAY
81	FREQUENCY RELAY (O-OVER FREQUENCY)
86	TRIP AND LOCKOUT RELAY (ELECTRIC TRIP AND "HAND" RESET)
ATS	AUTOMATIC TRANSFER SWITCH
T. & L. O.	TRIP AND LOCKOUT
(arrow symbol)	TRIPPING PATHS OR CIRCUITS

FIGURE 1 — PROJECT ONE-LINE DIAGRAM AS FOUND FOLLOWING FAILURE

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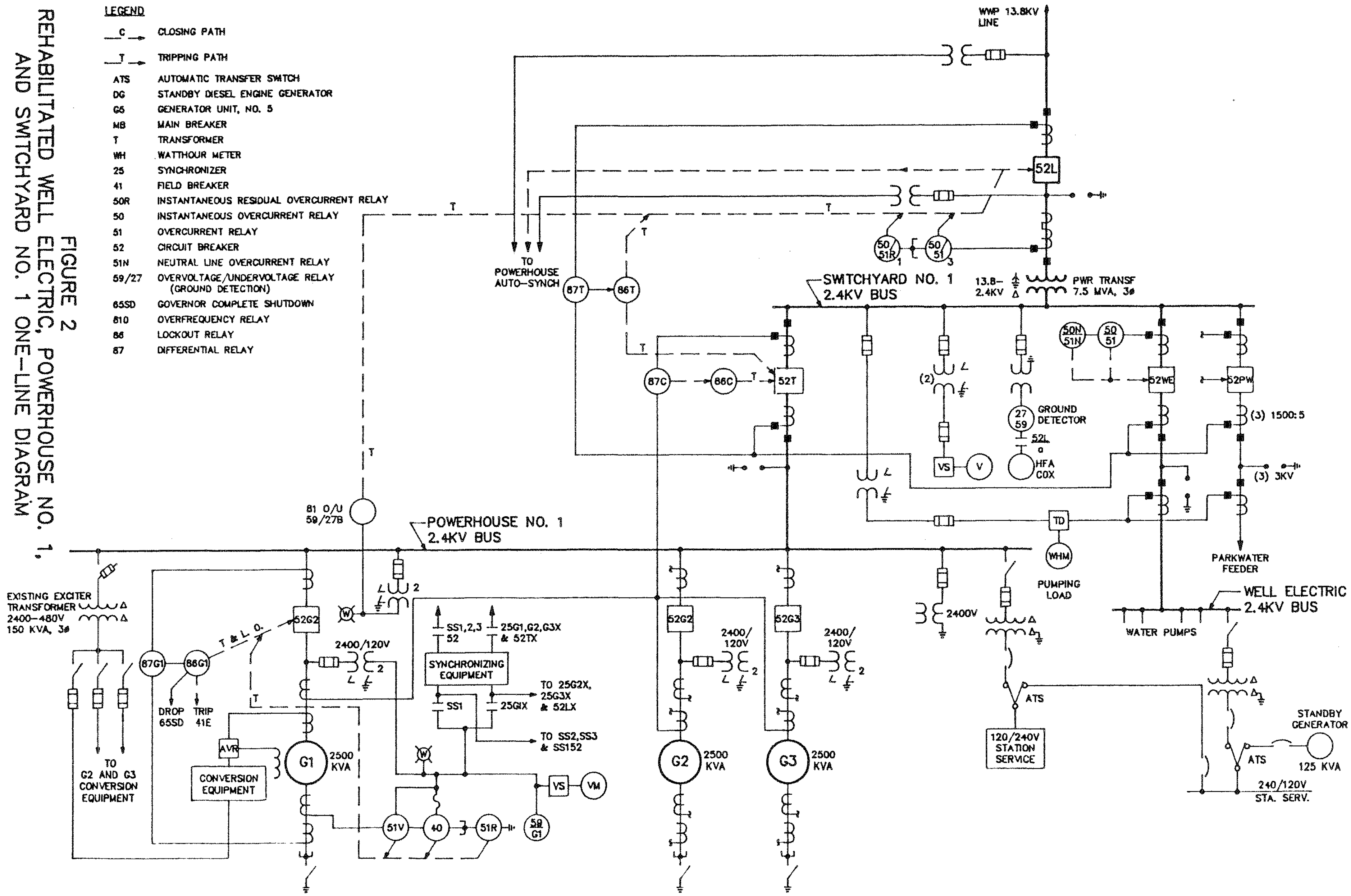

FIGURE 2
REHABILITATED WELL ELECTRIC, POWERHOUSE NO. 1, AND SWITCHYARD NO. 1 ONE-LINE DIAGRAM

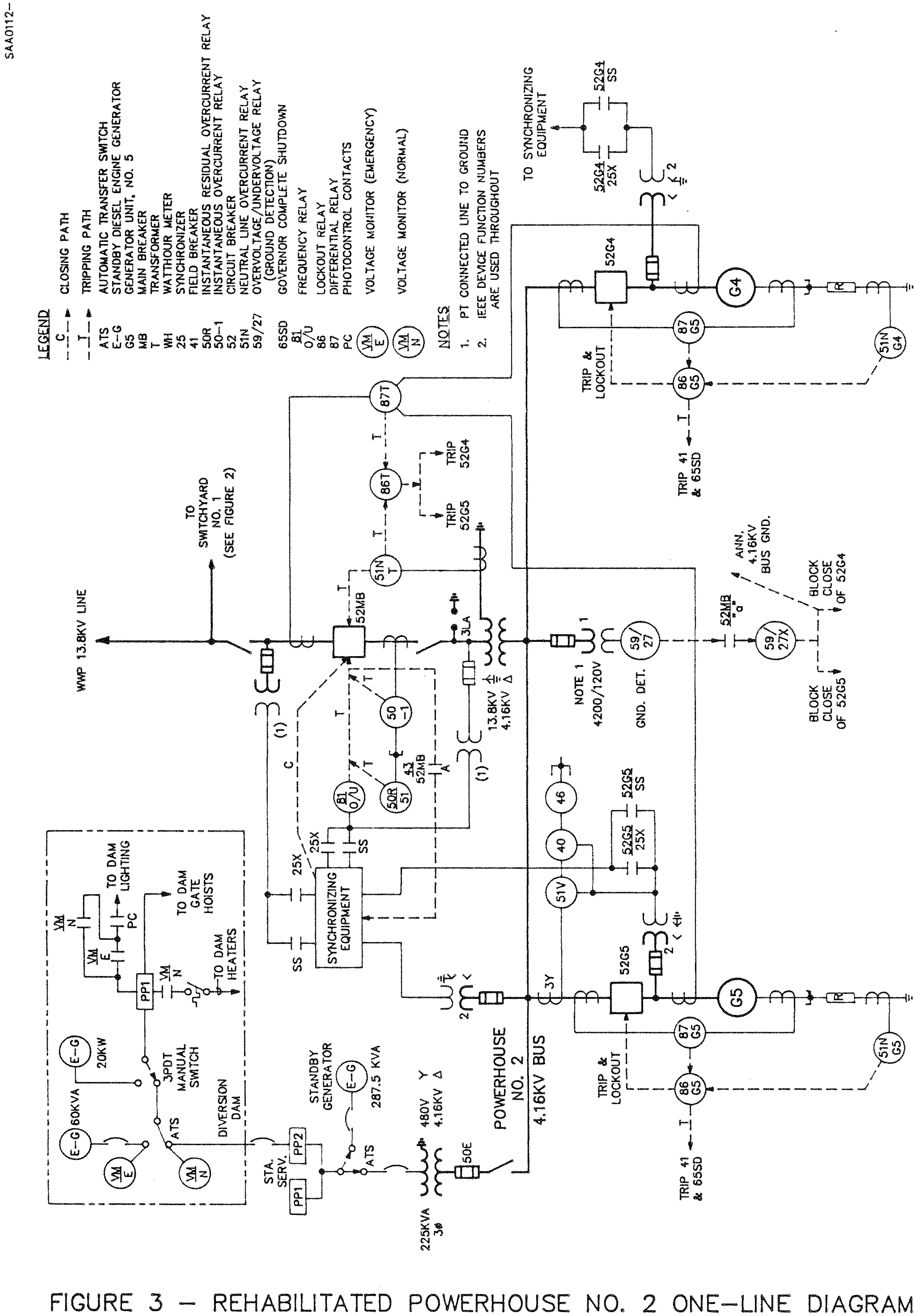

FIGURE 3 – REHABILITATED POWERHOUSE NO. 2 ONE-LINE DIAGRAM