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MEDICINE BOW WTS-4 WIND TURBINE FIELD TESTS

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16. ABSTRACT
This report is on the system fault testing and analysis of test data obtained at the Bureau's Medicine Bow Substation (Medicine Bow, Wyo.) Testing consisted of two 3-phase-to-ground faults for the purpose of evaluating the 4-MW WTS-4 wind turbine and generator interaction with the existing power system during adverse conditions. Testing was performed in conjunction with Hamilton Standard (Div. of United Technologies Corp. Windor Locks, Conn.) engineers who operated the WTS-4 facility during the subject tests.

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MEDICINE BOW WTS-4 WIND TURBINE FIELD TESTS

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Division of Research and Laboratory Services
Engineering and Research Center
Denver, Colorado

January 1985

SI METRIC

UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

ACKNOWLEDGMENTS

The information presented in this report was obtained by Bureau personnel at Western Area Power Administration's Medicine Bow Substation and is being presented to Hamilton Standard for use in the wind-based power generation system impact study Hamilton Standard is performing under EPRI (Electric Power Research Institute) contract. The data presented here are only a small part of that required for the EPRI study. The work was performed according to the jointly developed test procedure presented in Appendix A and covers only that portion of the test plan pertaining to the 3-phase faults.

The research covered by this report was funded by the Bureau of Reclamation's Lower Missouri Region Project Office.

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INTRODUCTION

The purpose of this investigation was in assisting Hamilton Standard (Division of United Technologies, Windsor Locks CT 06096) to obtain performance data regarding the interactions between the Hamilton Standard WTS-4 wind turbine and the power system during adverse system short-circuit conditions. The WTS-4 consists of a 4-MW, 1800-rev/min, 4160-volt synchronous generator connected to a 30-rev/min wind turbine through a 60 to 1 gear box. The gear box is referred to as a soft-shaft coupling in that it is a planetary gear train for which the case is attached to a fixed reference through a spring and damper assembly. The shaft twist between the turbine and generator is obtained by allowing the gear case to rotate a limited amount with respect to a fixed reference. The turbine generator is tied in to the power system through approximately 5 miles (8 km) of 34.5-kV line to the Medicine Bow Substation.

It is understood the *H* constant of the turbine to be rather large compared to that of the generator. The somewhat unconventional system comprising the wind turbine itself, the large turbine *H*[1] factor, and the soft-shaft justified the decision to investigate the interaction between the wind turbine-generator and the existing power system during severe local system fault conditions.

Hamilton Standard requested three 3-phase-to-ground faults, four to eight cycles in duration to be placed on the power system at Medicine Bow Substation. The objective of the proposed test as explained to the Bureau was to determine if the machine would remain synchronized to the system after the clearing of each fault. The likelihood of synchronism being maintained subsequent to fault clearing, with normally expected fault clearing times, seemed good owing to: (1) the large inertia of the wind turbine which would tend to prevent the generator from reaching an excessive overspeed condition for short duration faults, and (2) the soft-shaft and associated damper which would absorb a large portion of the resynchronizing shock when the fault is cleared and thereby minimize the possibility of the generator slipping poles.

Hamilton Standard requested that the Bureau monitor system conditions at the substation during the fault tests and to submit an analysis of the Medicine Bow Substation data, for use in the EPRI study mentioned in the Acknowledgments. One of the purposes of the EPRI study is to investigate wind turbine dynamics during various system conditions.

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[1] The inertia constant *H* is defined as the megajoules of stored energy of a machine at synchronious speed per megavolt-ampere of the machine rating.

TEST SETUP

The tests consisted of two 3-phase-to-ground faults on the 34.5-kV bus between the Hanna line disconnect switch and the Hanna line breaker at Medicine Bow Substation. The Hanna line disconnect remained open to permit the Hanna line to be energized from the far end (fig. 1). The Hanna line breaker was used to close into the "bolted" fault and to clear the fault. Initially, three faults were planned. The duration of the first fault was to be as short as possible – hopefully four cycles. Durations of the second and third faults were to be six and eight cycles, respectively. During pretest preparations (at the site) the interrupting time of the Hanna line breaker was determined to be 4.5 cycles. Fault clearing times of 7.5 and 11.5 cycles were realized on the first two tests. As a result of these slower than desired clearing times, a third fault was not staged.

INSTRUMENTATION

Parameters Measured

The quantities monitored by Bureau personnel at Medicine Bow Substation were:

On the B&H (Bell & Howell) 519 oscillograph

34.5 kV bus voltage (all three phases)
Hanna breaker fault current (all three phases)
SVU (system verification unit) line current (all three phases)
Hanna breaker trip and close signals
SVU line breaker trip signal
115-kV circuit switcher trip signal

All signals were obtained from the existing PT, CT, and control circuits.

On the Gould-Brush 4-channel strip chart recorder

A phase SVU line current
A phase 34.5 kV bus voltage
Three-phase SVU line watts
Three-phase SVU line vars

All four of these signals were obtained from Bureau furnished standard 0.1 percent accuracy current, voltage, watt, and var transducers.

Calibration

All a-c voltage and current signals were calibrated the day before the test at Medicine Bow Substation. Voltage calibration consisted of injecting a known a-c voltage from a Fluke Programmable A-C Calibrator (Model 5200A) and adjusting the galvo shunt box for a specified oscillograph deflection. The current signals were calibrated in a similar manner except that a Valhalla Scientific voltage-to-current calibrator (Model 2500-E) was inserted between the Fluke Calibrator and the galvo shunt box. High accuracy DVM's (digital voltmeters) were used to verify the voltage and current output of the calibrators.

The current and voltage transducers (Scientific Columbus CT-510-A4 and VT100-A4) were calibrated in the Engineering and Research Center laboratory the week prior to testing and checked at the Medicine Bow Substation the day before the test. The Gould-Brush Strip chart recorder was adjusted to obtain the correct deflection for the specified a-c signal into the voltage and current transducers. The Fluke and Valhalla calibrators and high accuracy DVM's also were used for this calibration.

The watt and var transducers (Scientific Columbus DL3-1K5-2½A2 and DLV3-1K5-2½A2) were calibrated in the laboratory the week before the test with a Scientific Columbus SC-60 calibration standard. The Gould-Brush strip chart recorder watt and var channels were checked the day before the test with the high accuracy DVM's.

All Medicine Bow CT and PT ratios were assumed accurate and were not included in the calibrations.

Auxiliary Current Transformers

Due to the high fault currents involved, it was necessary to install auxiliary step down 50 to 5 CT's between the Hanna fault current line breaker CT circuit and the monitoring equipment. These auxiliary CT's reduced the current an order of magnitude from about 90 amps to 9 amps.

Relaying

The instantaneous overcurrent elements on the Hanna (fault breaker) line breaker ground and phase overcurrent relays were disabled. The Hanna breaker phase overcurrent relay dial settings were increased to 3.5 to provide 15 to 20 cycles of delay in pickup on the faults.

All circuit breaker automatic reclosing at Medicine Bow Substation were removed from service.

An instantaneous overcurrent relay supervised by an auxiliary electromechanical timer was installed to trip the 115-kV circuit switcher and the SVU line breaker approximately 12 cycles into the fault. The purpose of this backup protection system was to clear the switchyard in the event the Hanna Line fault breaker failed.

The actual initiation and clearing of the fault was accomplished with the Bureau's sequence controller. This specially designed device was built for precision sequence control during power system short circuit testing.

BACKUP POWER

An engine-generator was used to provide instrumentation power during the fault tests. This was necessary because Medicine Bow Station service would be lost during each fault.

The sequence controller was battery powered and therefore did not require a backup power supply.

PRESENTATION OF FAULT TEST PROCEDURES FOR ANALYSIS

Two 3-phase-to-ground faults were performed. These tests occurred at 2:50 p.m. and 4:23 p.m. on Wednesday, November 16, 1983. The tests are referred as *test 1* (2:50 p.m.) and *test 2* (4:23 p.m.).

Oscillograph and strip chart data records with labels and calibrations are shown on figures 2 through 5. In addition, a strip chart record of the wind turbine generator being loaded prior to test 2 is shown on figure 6. The polarity of the current and voltage traces on the oscillograph are such that power flow out of the substation is positive.

The SVU line loading just prior to each test was about 2.8 MW (test 1) and 3.7 MW (test 2). The test load levels were preselected by Hamilton Standard staff. The target load values are believed to have been 3 MW for test 1 and 4 MW for test 2. It should be noted that the Medicine Bow Substation SVU line power will be slightly different from the Hamilton Standard generator terminal value due to the local load at the test facility. The same holds true for the VAR measurements.

The first fault lasted 7.5 cycles and the second 11.5 cycles. In both instances, the breaker was tripped as soon as the breaker mechanical close sequence was complete. There is not an apparent reason for the four-cycle difference in breaker cleaning time and this may be normal for this type of oil breaker. The breaker was timed earlier in the day and found to be consistent in both the trip and close operations. The time for close coil energization to mechanical contact closure was 12 cycles. The time from trip initiation to mechanical contact parting was 4.5 cycles.

As can be seen from the fault current oscillograph traces, there is a distortion in the first few cycles of fault current. This is in all probability due to CT related problems. There were about 90 amps flowing in the Medicine Bow 5 amp CT secondary. In addition, there was an added burden from the Bureau's auxiliary CT's and monitoring equipment.

The records presented on figures 2 through 6 are marked with labels, calibrations, and actual measurements. All measurements and calibration were taken from the original oscillograph and strip chart records.

The response time of the current and voltage transducers was somewhat less than ideal for the short fault times involved and, therefore, the outputs are somewhat meaningless during the fault.

The var and watt transducer data are invalid during the fault because of the loss of the bus voltage during the short circuit period.

The frequency measurements obtained from the SVU line current oscillograph traces are rather crude. These measurements consist of a simple period measurement that is converted to a frequency. Each arrow points to the cycle for which the corresponding period was measured. Measurements were made on the original records using a Gerber variable scale that was set to one per unit period on the 60-Hz post fault voltage waveforms. The oscillograph paper speed is controlled by means of a servoloop controlled d-c motor and therefore is unaffected by the frequency variations from the engine generator power supply. In addition, a cross check was made by checking the frequency of the fault current oscillograph traces.

The PT A-phase bus voltage was 72.06 volts prior to *test 1* and 72.00 volts prior to *test 2*. Measurements were made on the 19900/67 ratio A-phase PT circuit using a high accuracy DVM.

RELAY OPERATION

During both tests, targets appeared on the blocked Hanna phase overcurrent relay instantaneous units at Medicine Bow Substation. This was to be expected and was the reason why these units were blocked. In addition, the A and C phase overcurrent instantaneous units picked up at the SVU facility and tripped the SVU generator breaker approximately seven cycles into the first fault. It is believed personnel at the SVU facility blocked these units to eliminate the problem during subsequent tests. On the second fault the WTS-4 computer control equipment tripped the unit offline on "frequency out of range" and "overspeed" conditions. Again, the trip occurred approximately seven cycles into the fault.

The SVU facility relay data sheets indicate that the phase overcurrent relay instantaneous units are set for 22 amperes (5280 A, primary) = 150 percent of the relay rms symmetrical subtransient current for a zero-arcing-resistance 3-phase fault on the Medicine Bow Substation 34.5-kV bus. This setting was recommended by PTI (Power Technologies, Inc.) and the Bureau concurred. The values of the SVU 34.5-kV line phase currents measured during the first staged 3-phase fault indicate that the current in each of the instantaneous units would have had a value in the order of 17 amperes rms or less. The instantaneous units set as indicated should not have operated. These units should be bench tested to verify pickup level. It should be confirmed that the CT's being used are connected in wye for a 1200 to 5 amphere ratio and performing within specified accuracy tolerances.

STABILITY EVALUATION

A review of the test records indicates that the WTS-4 frequency at the end of seven cycles reached 63 Hz during *test 1* and 67 Hz during *test 2*. The increased loading during *test 2* would be the primary reason for the higher overspeed condition in test 2. In test 1, the generator most likely would have been able to regain synchronism with the system had the generator not been tripped offline by the overcurrent relay instantaneous units. During the full load rejection of test 2, the machine may have been able to regain synchronism with the system if the fault had been cleared in less than seven or eight cycles. These statements should not be taken as authoritative; they are based on a very crude analysis and measurement of the angle between the WTS-4 and the system during the fault period. Many simplifying assumptions and approximations were made and considerations were not given to the machine dynamics with its special spring-damper type shaft and large turbine H factor. Also, it should be noted that test 2 was not the worst case since the system would have the smallest stability margin when the machine is absorbing vars. The subject stability evaluation is presented in appendix B.

The result of this analysis is rather unusual in that even though the turbine has a rather large H constant, the unit performs like one having a much smaller H constant. Primarily, this is due to the soft shaft that essentially isolates the turbine inertia from the generator inertia.

REFERENCES

Power System Stability, Selden B. Crary, John Wiley & Sons Inc. New York, vols. 1 & 2, 1947.

Electrical Transmission and Distribution Reference Book, Westinghouse Electric Corp., Central Stations Engineers, East Pittsburgh, Penn., 4th ed., 4th printing.

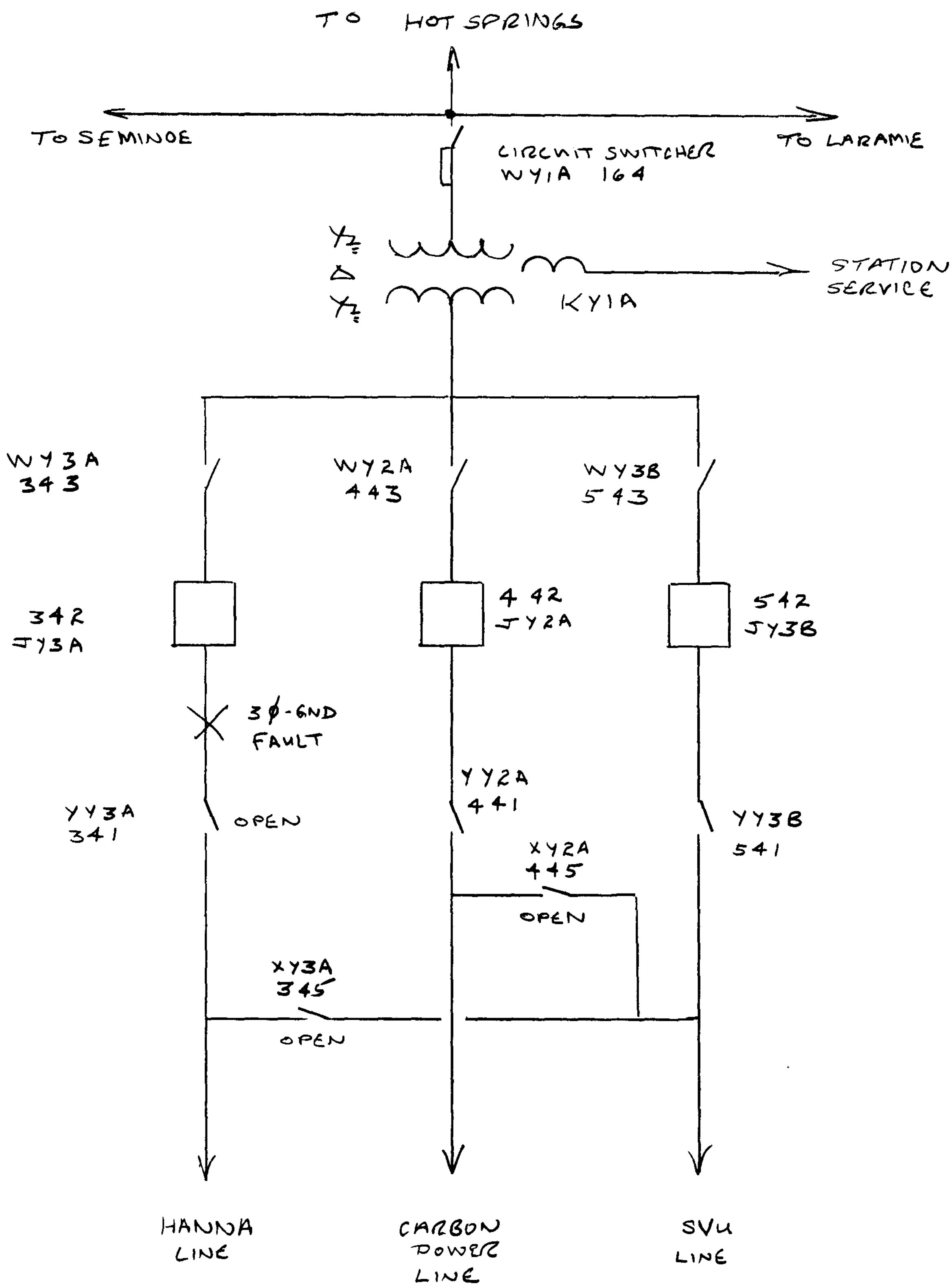


Figure 1. – System configuration.

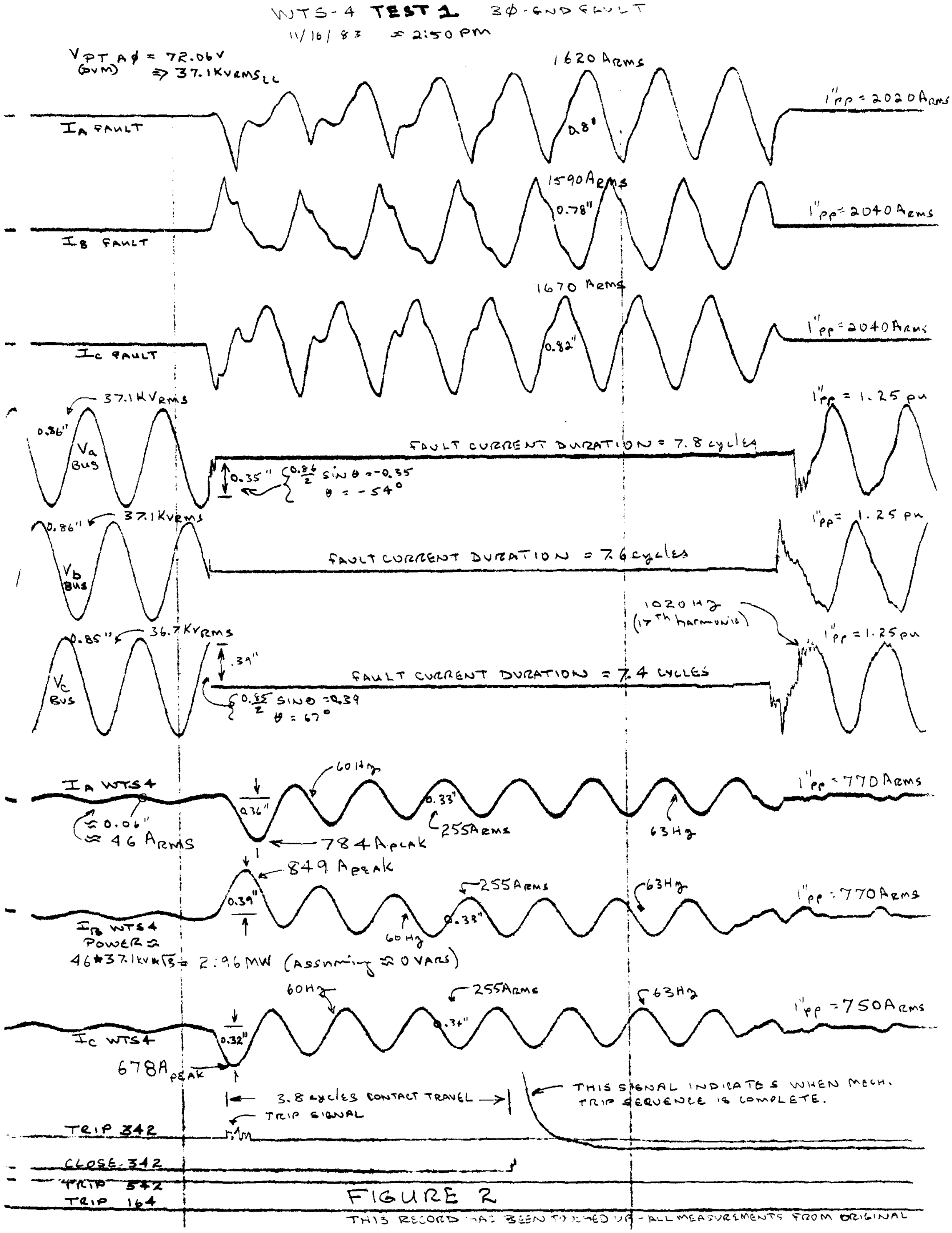


Figure 2. – Test 1 oscillograph record

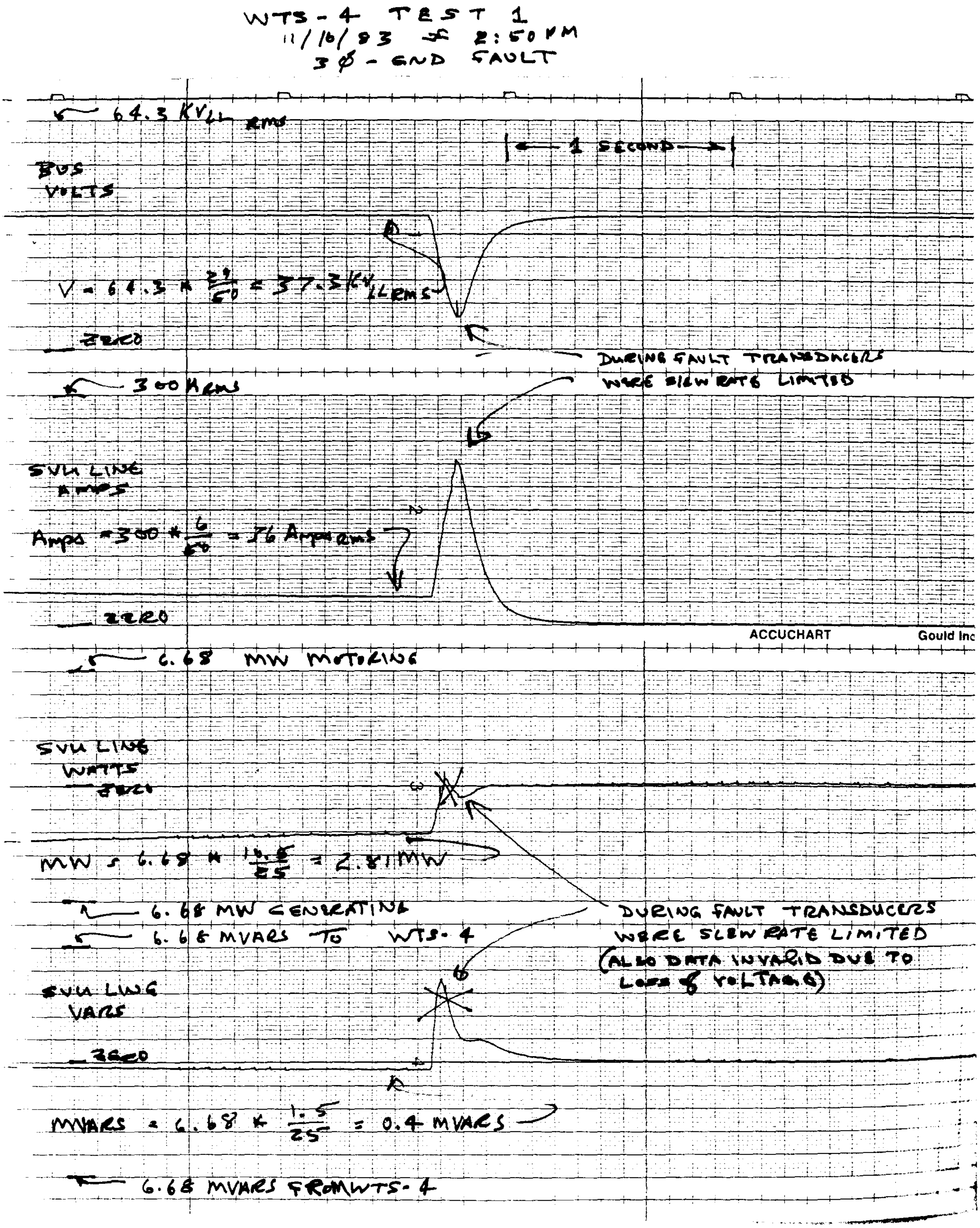


Figure 3. – Test 1 strip chart recorder record

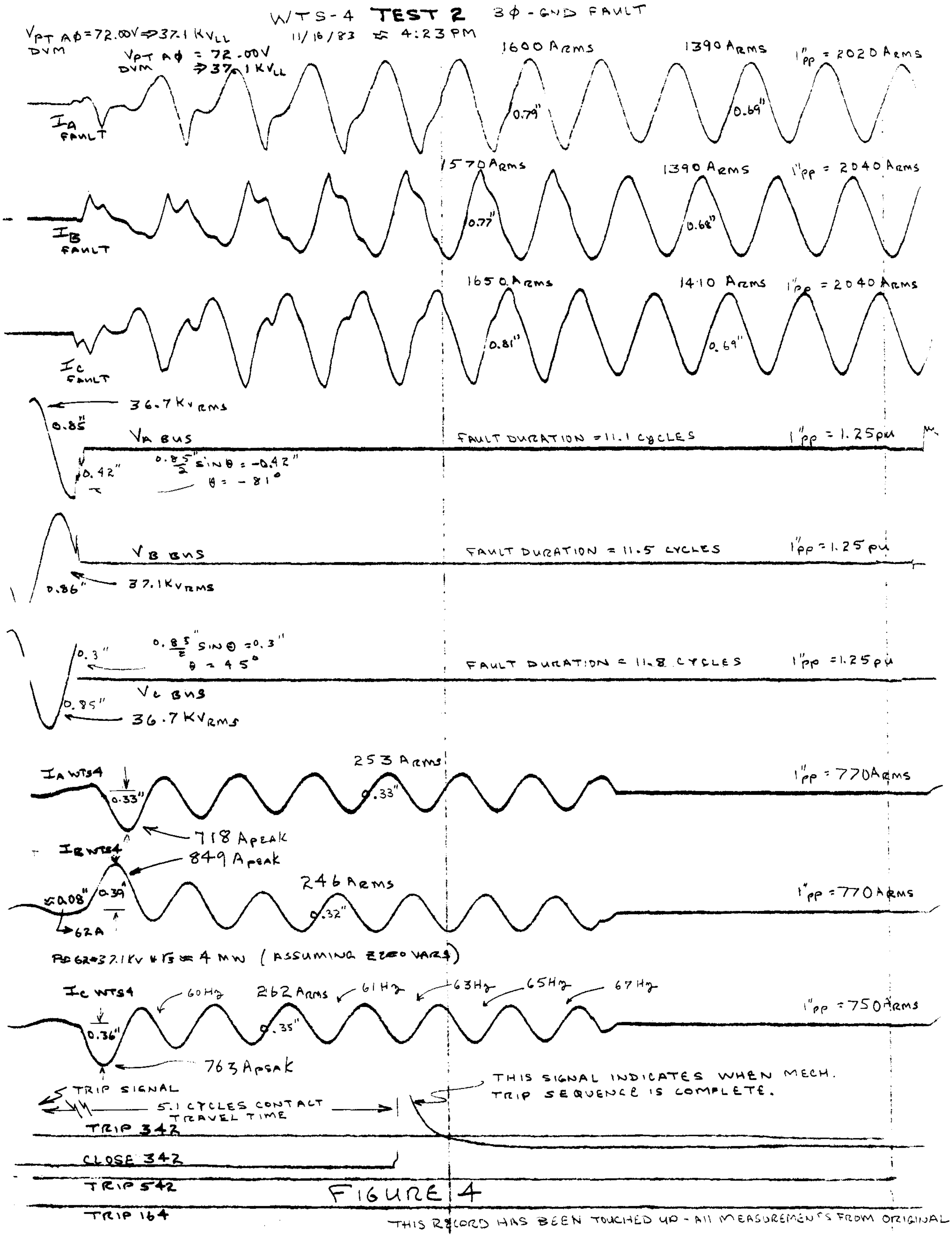


Figure 4. – Test 2 oscillograph record

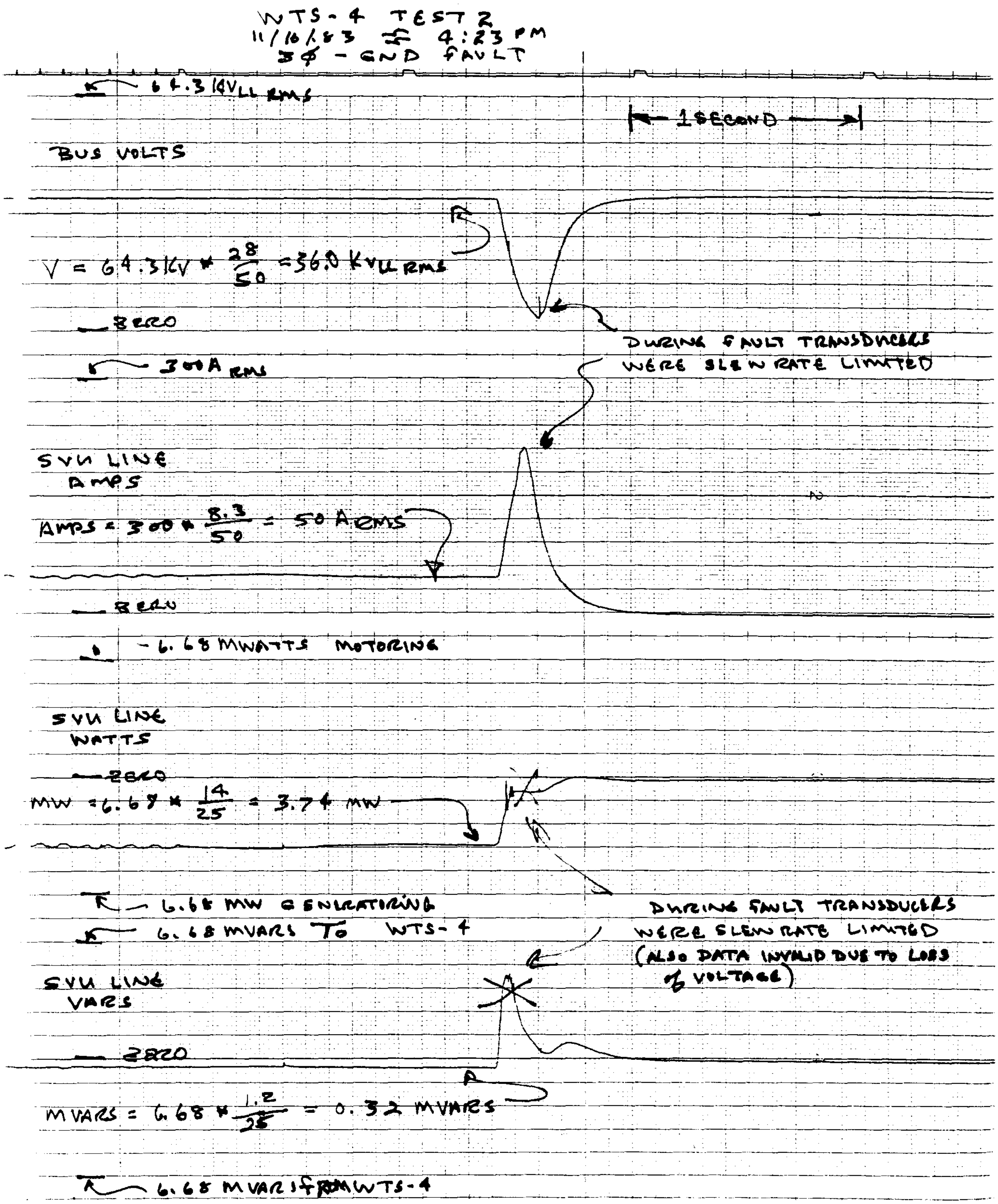


Figure 5. – Test 2 strip chart recorder record

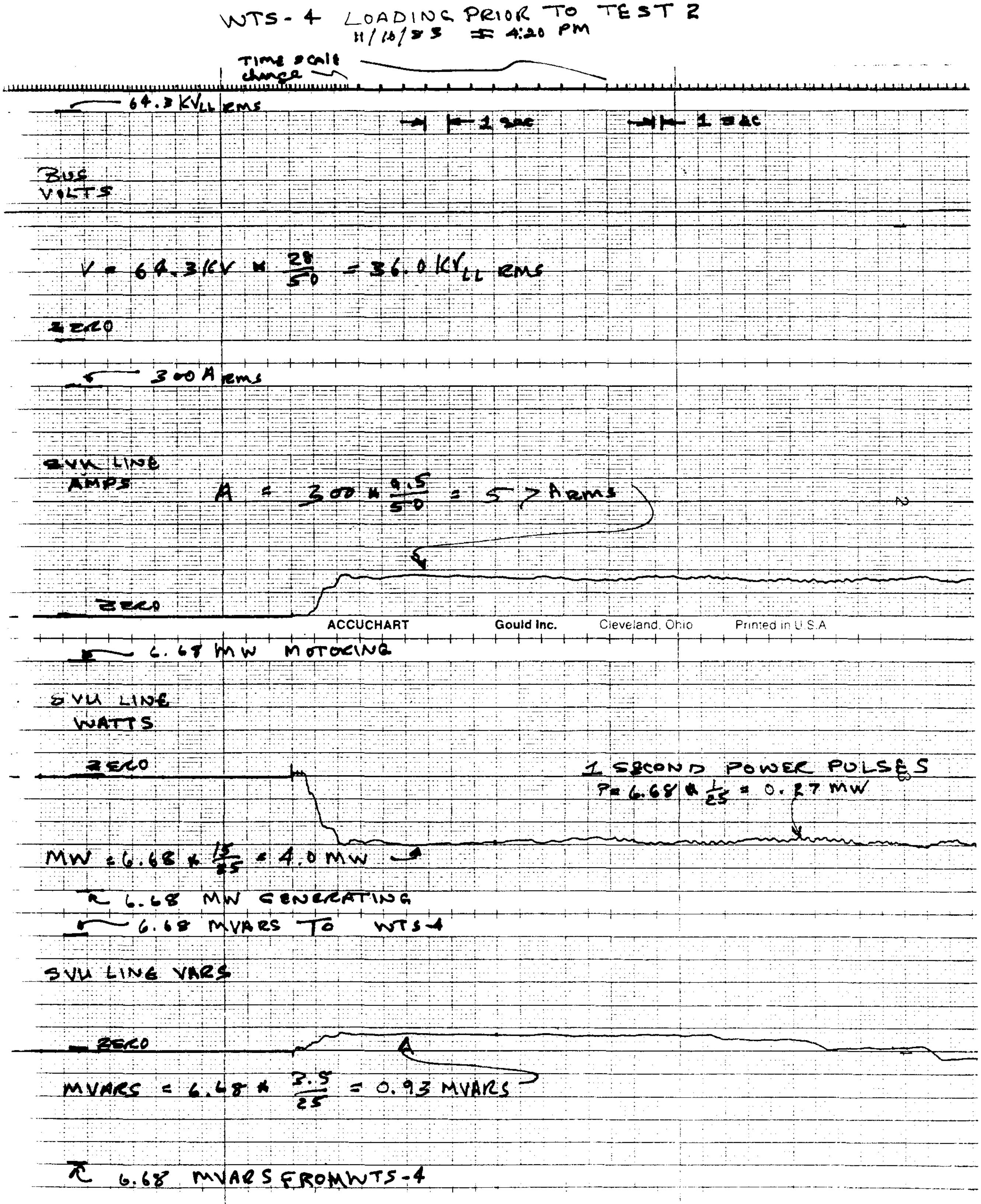


Figure 6. – Loading record prior to test 2

APPENDIX A

CONTRACTOR LETTER

APPENDIX A

UNITED TECHNOLOGIES
HAMILTON STANDARD

Windsor Locks, Connecticut 06096
203/623-1621

1-3-8
September 14, 1983
TMH-83-036

Mr. R. J. Gyllenborg
Department of Interior
Bureau of Reclamation
P. O. Box 25247
Denver, CO 80225

Subject: Transmittal of HSER 9003 - Test Plan - Utility Interaction Testing of the WTS-4 at Medicine Bow, Wyoming

Dear Gil:

Enclosed is the test plan for the utility interation testing planned for the WTS-4 in October, 1983.

I have received and incorporated suggestions from Eric Hinrichsen and Bert Milano. As we discussed in Denver in July, Bill Young will coordinate activities at the WTS-4 site and Bert Milano will coordinate activities at the Medicine Bow substation.

We should be in a position by October 10, 1983 to confirm activity on this test plan for the following week. Unless I hear otherwise, this input will go directly to you.

Again, I want to thank you and the people involved for their splendid cooperation thus far.

Sincerely,

Thad Hasbrouck

Thad M. Hasbrouck
Program Manager

TMH/hj

Enclosure

cc: Eric Hinrichsen - PTI
Frank Goodman - EPRI

UNITED TECHNOLOGIES
HAMILTON STANDARD

HSER 9003

TEST PLAN

UTILITY INTERACTION TESTING OF THE WTS-4

AT

MEDICINE BOW, WYOMING

SEPTEMBER 15, 1983

UNITED TECHNOLOGIES
HAMILTON STANDARD

HSER 9003

UTILITY INTERACTION TESTING OF THE WTS-4 AT MEDICINE BOW, WYOMING

1.0 INTRODUCTION

The testing performed under this plan of test is part of Task V - Utility System Impact of the EPRI program number RP-1994-6. This plan of test covers descriptions of instrumentation, test conditions and test sequences for the utility interaction testing of the WTS-4.

2.0 TEST ITEMS

The items to be tested are the WIS-4 wind turbine at Medicine Bow, Wyoming, and the 34.5 KV line connecting the WTS-4 to the Medicine Bow substation. A one-line diagram showing the Medicine Bow substation and the WTS-4 (SVU) 34.5 KV line is shown in Figure 1.

3.0 PURPOSE OF TEST

The purpose of this test program is to obtain operational data on the wind turbine and the utility line during various transient conditions. These include breaker open-close tests and testing of the WTS-4 over the full range of its VAR capability, measuring line and wind turbine operating parameters. Also, measurements will be made on the line and WTS-4 during three-phase testing to determine adverse interactions, if any.

4.0 TEST SETUP

4.1 Breaker Open-Close Test

The test setup for the breaker open-close test is the normal operating mode of the WTS-4 with the engineering data system (EDS) operating and the power system in its normal configuration.

4.2 VAR Test

The test setup for the VAR testing is the normal operating mode of the WTS-4 with the EDS operating and the power system in its normal configuration. Analysis has shown that the 34.5 KV voltage at Medicine Bow will vary by 4.7 percent over the full

4.2 (Continued)

range (4 MVAR) of the WTS-4. Before starting the VAR testing, the system voltage shall be set to midpoint of allowable range so as not to cause any adverse effects. The voltage setting will be established by Western Area Power Administration.

4.3 Three-Phase Fault Test

The test setup for the three-phase fault testing is the normal operating mode of the WTS-4 with the EDS operating and with the power system altered as follows:

For the three-phase fault test, the 115 KV line from Cheyenne to Seminoe shall remain intact. The load at Shirley Basin shall be fed from Difficulty. The loads off of PCB 342 at Medicine Bow shall be fed radially out of Sinclair. The loads off of PCBs 442 and 542 at Medicine Bow will be affected by the fault testing. Switch 341 shall be open and the fault will be placed between switch 341 and breaker 342. Breaker 342 should clear the fault in high speed. Appropriate controls should be installed to trip the 115 KV circuit switcher 164 in the event Breaker 342 fails to trip. Should breaker 342 fail to trip, there will be a short service interruption of any loads fed off of PCBs 442 and 542.

4.4 Instrumentation

4.4.1 Breaker-Open Close Test

4.4.1.1 WTS-4 Parameters - The WTS-4 parameters to be measured during the breaker open-close test includes MW, MVAR, generator voltage, line voltage, RPM and blade angle.

4.4.1.2 34.5 KV Line Parameters - The 34.5 KV line parameter to be measured during the breaker open-close test is line voltage.

4.4.2 VAR Test

4.4.2.1 WTS-4 Parameters - The WTS-4 parameters to be measured during the VAR test include MVAR, MW, turbine-to-line phase angle, generator voltage, line voltage, generator exciter field current, low speed shaft torque and blade angle.

4.4.2.2 34.5 KV Line Parameters - The 34.5 KV line parameter to be measured during the VAR test is line voltage.

4.4.3 Three-Phase Fault Test

4.4.3.1 WTS-4 Parameters - The WTS-4 parameters to be measured during the three-phase fault include MW, MVAR, turbine-to-line phase angle, generator voltage, line voltage, generator exciter field current, low speed shaft torque and blade angle.

4.4.3.2 34.5 KV Line Parameters - The 34.5 KV line parameters to be recorded by oscillograph during the three-phase fault test include voltage and current for all three (3) phases and the trip and close signals of breaker[3] 442 and 542 and circuit switch 164. Three-phase VARs, three-phase watts, phase 'a' current and phase 'a' voltage will be recorded by strip chart.

4.4.3.3 Fault and Timing Instrumentation - The fault will be a three-phase bolted ground fault. Western will provide USBR with a fault current study. The breaker closing into the fault and tripping time to clear the fault will be accomplished using a USBR sequence controller. An electric motor-operated mechanical timer will be used as backup protection.

5.0 SEQUENCE OF TEST

The breaker open-close test, the VAR test and the three-phase fault test may be run in any sequence. The paragraphs following apply only to the sequence of events with each test.

5.1 Breaker Open-Close Test

Open breaker 542 at the Medicine Bow substation and re-close in approximately ten (10) seconds. The WTS-4 should come off-line to a normal shutdown and restart when the circuit breaker is closed.

5.2 VAR Test

The WTS-4 should be operating at or close to rated power. The line voltage should be set by Western to a nominal value such that the VAR test will not cause excessive voltage variation. The WTS-4 generator excitation shall be varied in 500 KVAR steps. At each step the WTS-4 shall be operated for fifteen (15) minutes to provide ample time for monitoring performance.

5.2 (Continued)

The WTS-4 generator excitation shall be varied such that the WTS-4 supplies VARs to the line in steps of 500 KVAR from unity power factor (0 KVAR) to 3000 KVAR and absorbs VARs from the line from unity power factor (0 KVAR) to 1000 KVAR. There will be ten (10) test settings:

- 0 KVAR
- 500 KVAR
- 1000 KVAR
- 1500 KVAR
- 2000 KVAR
- 2500 KVAR
- 3000 KVAR
- 0 KVAR
- -500 KVAR
- -1000 KVAR

5.3 Three-Phase Fault Test

The WTS-4 should be operating at or near rated power. Breaker 342 will be closed into the three-phase bolted ground fault and tripped to clear the fault with a clearing time of two (2) cycles. The behavior of the WTS-4 and the 34.5 KV line will be monitored. As conditions warrant, the test will be repeated increasing clearing time in two (2) cycle increments up to a maximum clearing time of ten (10) cycles. Decisions to increase clearing times longer than two (2) cycles will come from the WTS-4 operation personnel.

6.0 COMMUNICATIONS

6.1 Notification of Testing

Western dispatchers require one (1) week notification prior to beginning tests.

6.2 Communication During Testing

During the breaker open-close test and three-phase fault test, a three-way telephone conference arrangement shall be established for simultaneous communication among the WTS-4 facility, the Medicine Bow substation and the Area Dispatch Center.

Since the VAR testing does not require staging, a communication to the WTS-4 facility that the line voltage has been set will be sufficient.

7.0 TEST LOGS

A written log shall be maintained at the WTS-4 facility for all tests listed in this plan. Entries shall include, but not necessarily limited to:

A. Test identification
B. Run identification
C. Time of day of test start and finish
D. Channels monitored on the strip chart recorder
E. Significant events.

A written log shall be maintained at the Medicine Bow substation during the three-phase fault test. Entries shall include, but not necessarily limited to:

A. Test identification
B. Run identification (i.e., clearing time)
C. Time of day of test start and stop
D. Channels monitored on the strip chart recorder
E. Channels monitored on the oscillograph
F. Significant events.

8.0 REPORTS

Each group involved with the testing shall prepare a report of activities and findings (supported by data) for their portion of the test. These reports will be compiled into one (1) report for inclusion in the final report to EPRI.

9.0 SCHEDULE

9.1 Testing Schedule

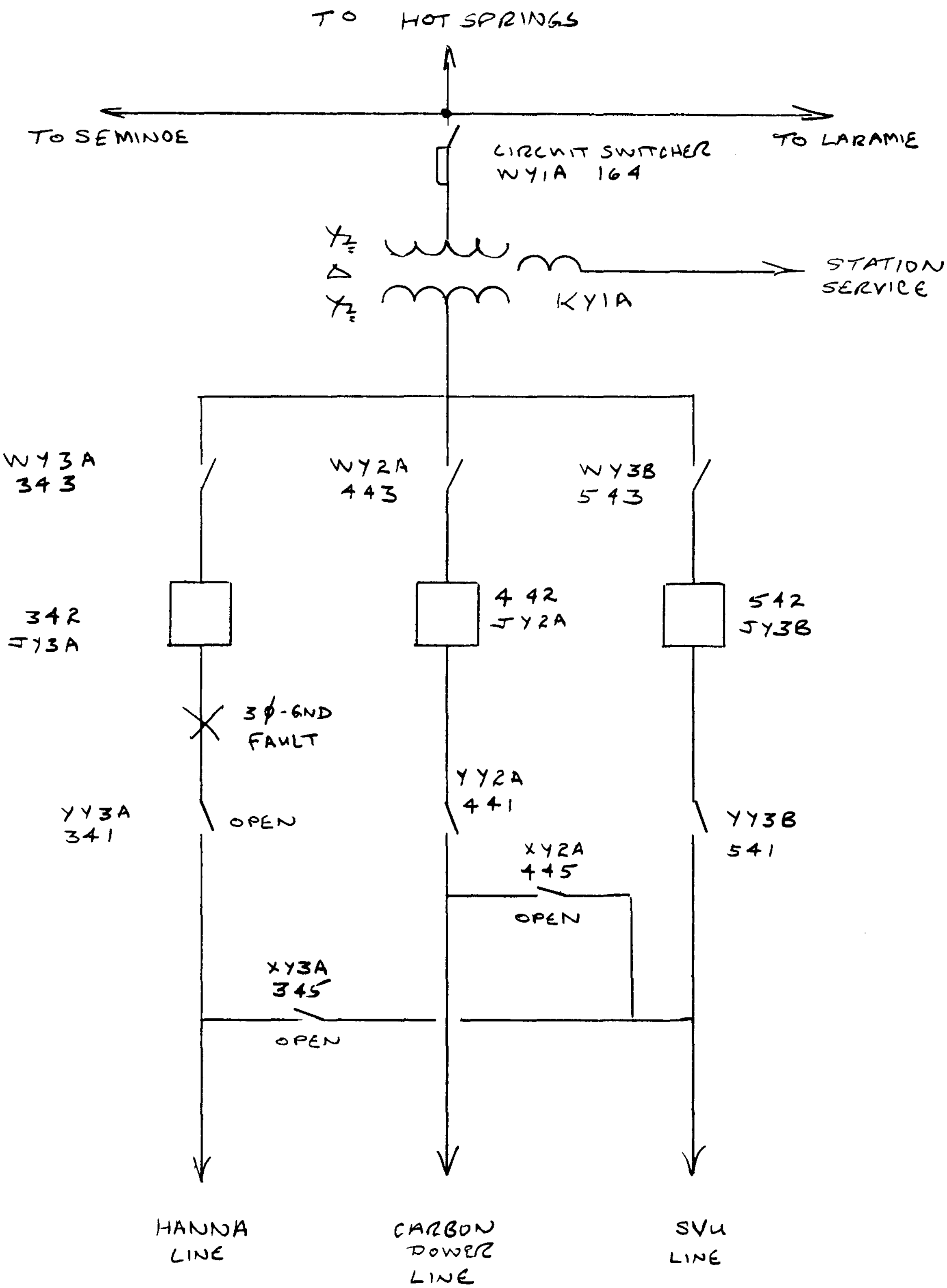
Scheduling of these tests is tentatively set for the week of October 17, 1983. The VAR testing is scheduled for October 18, wind conditions permitting. The breaker open-close test and the three-phase fault test are scheduled to be conducted October 19, wind conditions permitting. October 20, is scheduled as a back-up date to account for delays or additional testing.

It is anticipated that the equipment to perform the breaker open-close test and three-phase fault test will be in place and checked out prior to initiating testing on October 19, 1983.

9.2 Report Schedule

Responsible parties should have their reports drafted and submitted to the HS project manager within thirty (30) days from the data of testing.

APPENDIX A – Continued



APPENDIX B

STABILITY CALCULATIONS

APPENDIX B

Machine Data

4 MW	5 MV·A	4160 V	694A	1800 RPM
0.8 pf	X_Q = 0.828 pu	X_d = 0.215 pu	R_A = 0.028 Ω	X_d' = 0.208

$$\text{Base } Z = \frac{V_{\text{rated phase}}}{I_{\text{rated}}} = \frac{4160/\sqrt{3}}{694} = \frac{2402}{694} = 3.46\ \Omega$$

Check Base

694A * 4160 V * √3 = 5 MV·A

Machine is at 4 MW, unity power factor, 1.08 per unit

Find current

$$I = \frac{4\text{ MW}}{2402 * 3 * 1.08} = 514\text{ A}$$

$$I_{pu} = \frac{514}{694} = 0.741\text{ pu}$$

APPENDIX B – Continued

7-1654 (7-73)
Water and Power

COMPUTATION SHEET

BY	DATE	PROJECT	SHEET ____ OF ____
CHKD BY	DATE	FEATURE	
DETAILS			

$X_d = 2.15$

$V_t = 1.08$

$I = 0.741$

$X_Q = 0.828$

$X_Q I = 0.828 * 0.741 = 0.6135$

$X_d I = 2.15 * 0.741 = 1.593$

$X_d' = 0.208$

$i_d = 0.741 * \sin 30^\circ = 0.37$

$i_Q = 0.741 * \cos 38 = 0.64$

$I_d(X_d - X_q) = 0.37(2.15 - 0.828) = 0.49$

$i X_d' = (0.741)(0.208) = 0.154$

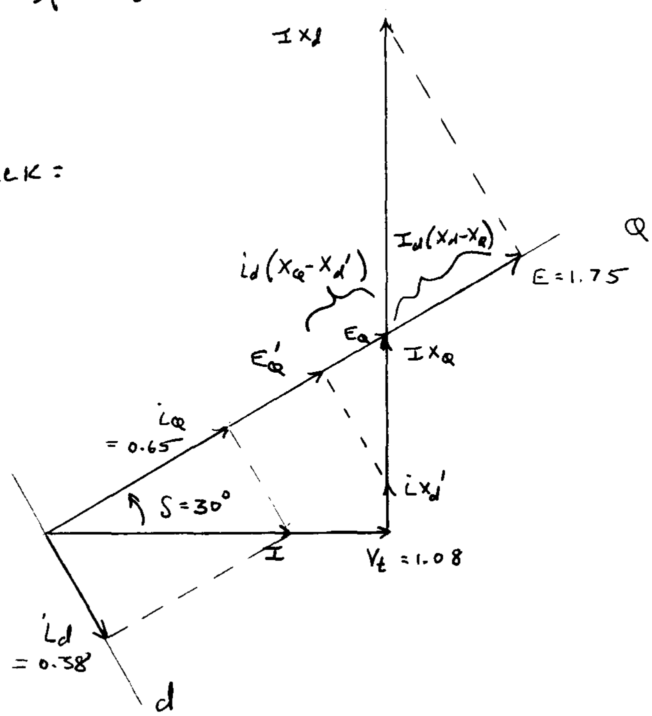
$i_d(X_Q - X_d') = 0.37(0.828 - 0.208) = 0.23$

$E_Q' = 1.03$

$E_Q' = E - (X_d - X_d') i_d$

$E_Q' = 1.75 - (2.15 - 0.208)(0.37) = 1.03$

GRAPHICAL CHECK:



$$P = \frac{E'_Q V_t}{X_d'} \sin\delta + \left(\frac{1}{X_Q} - \frac{1}{X_d'}\right) \frac{V_t^2}{2} \sin 2\delta$$

$$P = \frac{(1.03)\ (1.08)}{.208} \sin\delta + \left(\frac{1}{.828} - \frac{1}{.208}\right) \frac{(1.08)^2}{2} \sin 2\delta$$

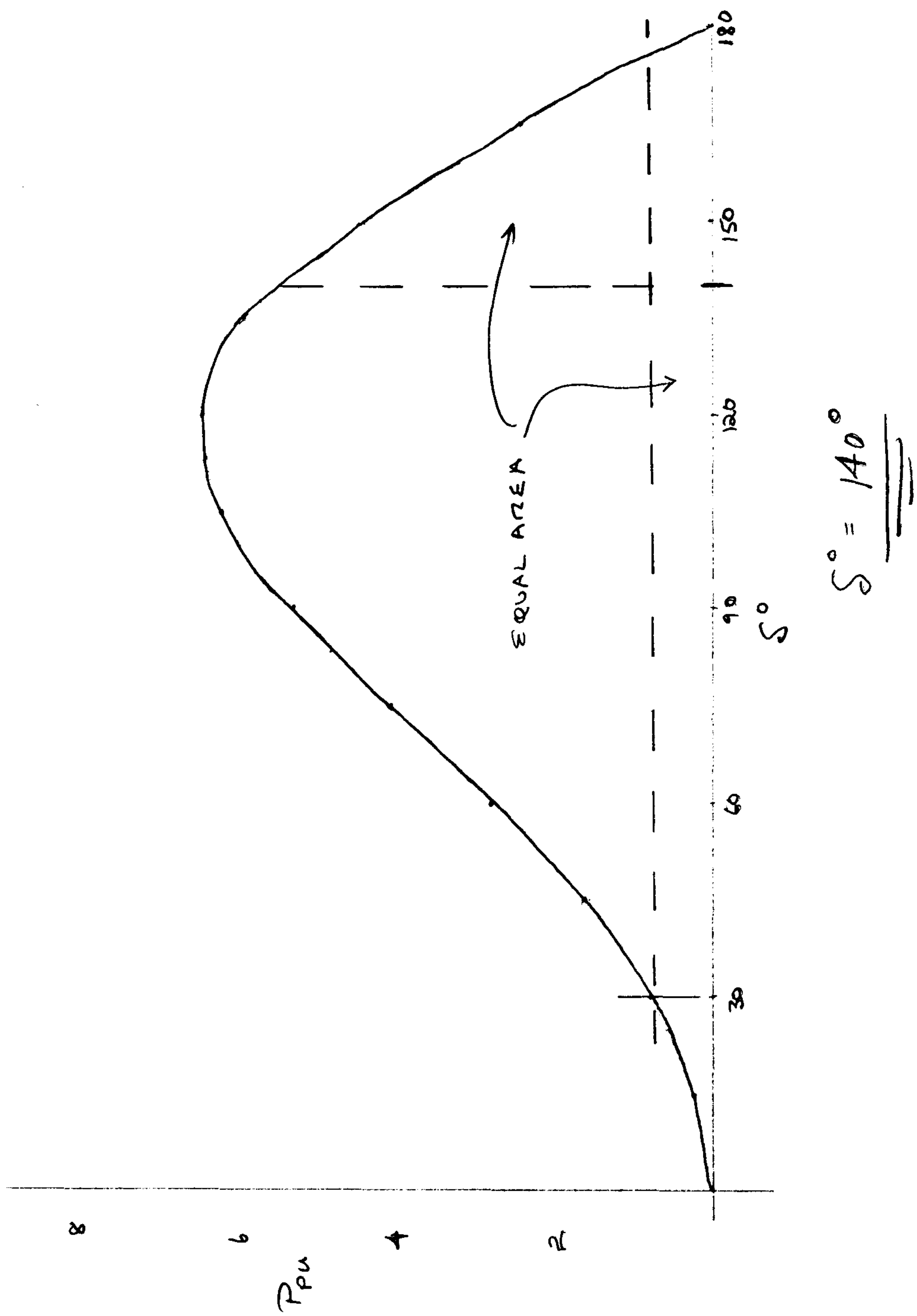
$$P = 5.35 \sin\delta - 2.099 \sin 2\delta$$

δ	P_1	P_2	P
15°	1.38	-1.05	0.33
30°	2.67	-1.82	0.85
45°	3.78	-2.10	1.68
60°	4.63	-1.82	2.81
75°	5.16	-1.05	4.11
90°	5.35	0	5.35
105°	5.16	+1.05	6.21
120°	4.63	1.82	6.45
135°	3.78	2.10	5.88
150°	2.67	1.82	4.49
165°	1.38	1.05	2.43
112.5°	4.94	1.48	6.42

7-1654 (7-73)
Bureau of Reclamation

COMPUTATION SHEET

BY	DATE	PROJECT	SHEET B4 OF
CHKD BY	DATE	FEATURE	
DETAILS			



Now convert δ_c to per unit cycle value

$\delta_c = 140°$

per unit $\delta_c = \frac{140°}{360} = 0.388$

Now from oscillograph records

Test #1:

0.1 pu cycle point occurs at 7th cycle of fault. Therefore, the system is stable

Test #2:

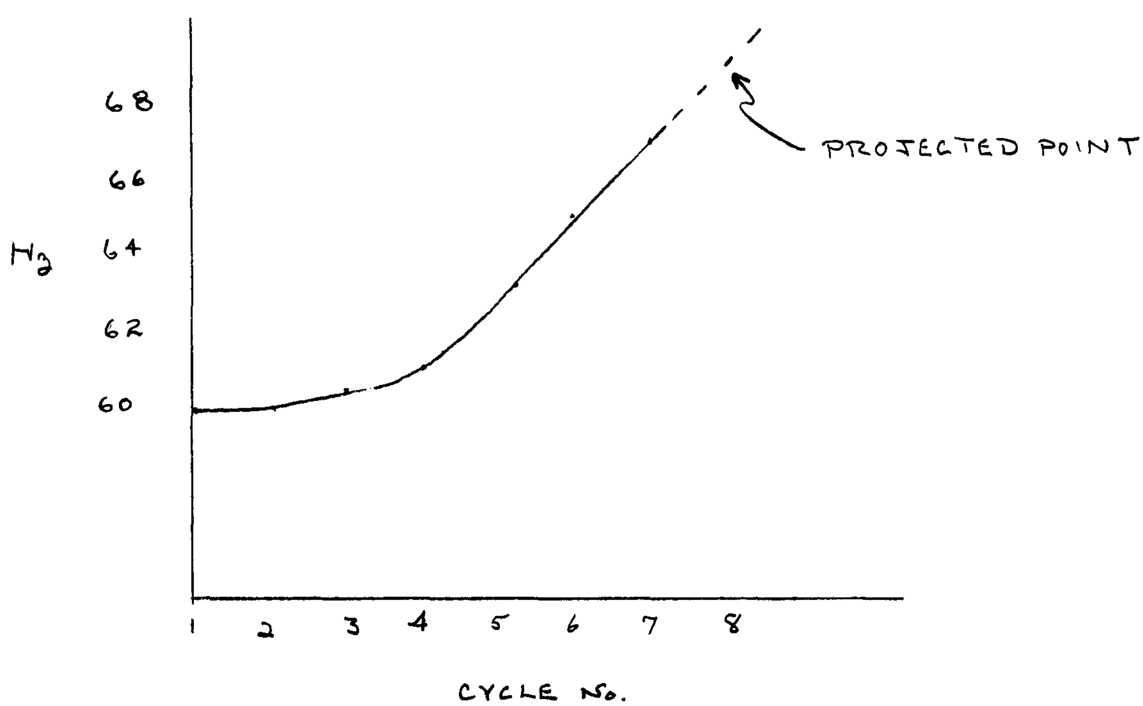
0.22 pu cycle point occurs at approximately the 7th cycle of fault. Therefore, the system is stable.

Note: From the projected point on the next page, the machine would not be stable beyond cycle #8

APPENDIX B – Continued

Test #2 Frequency Data

Cycle #	Freq.	Period (pu)	Σ Δ ∢ pu	Σ Δ ∢
1	60	1		0
2	60	1		0
3	60.5	.99	.01	4°
4	61	.98	.03	11°
5	63	.95	.08	29°
6	65	.92	.16	58°
7	67	.90	.26	94°
8[1]	69	.87	.39	140°



[1]Projected point

Now, assume the soft shaft decouples the generator from the wind turbine and H_{gen} = 0.823 second. One can estimate the critical clearing time from the swing equation as follows:

$$2 \frac{H_{gen}}{\omega_r} \frac{\delta^2 \delta}{\delta t^2} = P_a \approx P_{stored\ in\ soft\ shaft\ spring} \approx P_{out} \approx \text{constant}$$

$$\frac{\delta^2 \delta}{\delta t^2} = \frac{0.8\ (30 * 2\pi)}{2\ (0.823)} * 57.3 \text{ degrees/rad}$$

$$\frac{\delta^2 \delta}{\delta t^2} = 5250$$

Solve for $\delta(t)$ critical

$$\delta(t) = \delta_0 + \frac{5250}{2} t^2$$

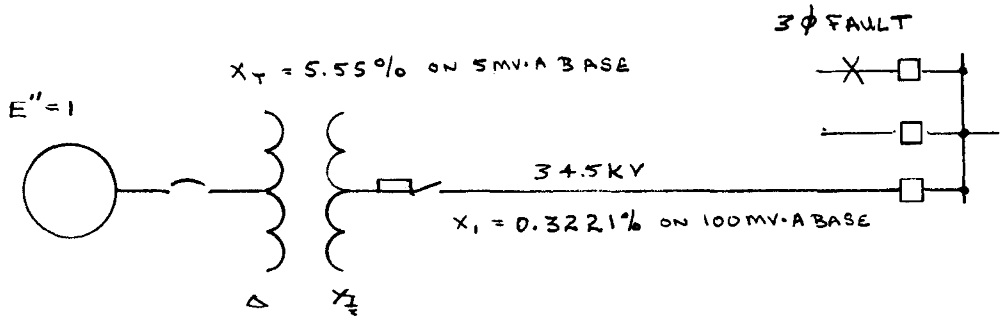
$$140^\circ = 30^\circ + 2625\ t^2$$

$$t = 0.2 \text{ second}$$

$$\boxed{\text{or} \approx 12 \text{ cycles}}$$

Note, this is somewhat higher than that obtained from the critical clearing angle and oscillograph data. This is due to the neglect of transmission line and transformer impedances in the critical clearing angle calculations and in ignoring the wind turbine effects in the solution of the swing equation. Both of these simplifications will result in an optimistic value of the critical clearing time as shown above.

APPENDIX B – Continued



X''_d = 11.4%

X'_d = 20.8%   5 MV·A Base

X_d = 215.4%

Z_{base} = 11.9025 Ω   (100 MV·A Base)

X_1 = 3.8338 Ω

Z_{base} = 238.05 Ω   (5 MV·A Base)

T'_{do} = 7.5 s

T'_d = 0.72 s

T''_d = 0.05 s

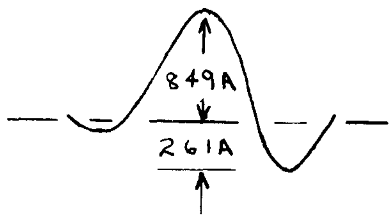
$$I_1 = \frac{1}{0.114 + .0555 + 0.0161} = \frac{1}{0.1856} = 5.3879\%$$

$$I_{base} = \frac{5000}{4.16 \sqrt{3}} = 693.93 \text{ A}$$

I_1 = 3739 A $I_{Relay} = \dfrac{3739}{240} = 15.58$ A

IOC unit → 1.50 (15.58) = <u>23 A</u>

PTI recommended an IOC setting of 22 A. We concur.



$I_{fault\ svu\ line}$

peak to peak → 261 + 849 = 1110 A

rms value of sym wave = $0.5\ (1110)/\sqrt{2}$
= 392 A

d-c offset = $849 - \dfrac{1110}{2} = 294$ A

rms value of asym wave = $[294^2 + 392^2]^{1/2}$

= 490 A

I @ 4.16 kV = $490\ \left(\dfrac{34.5}{4.16}\right) = 4064$ A

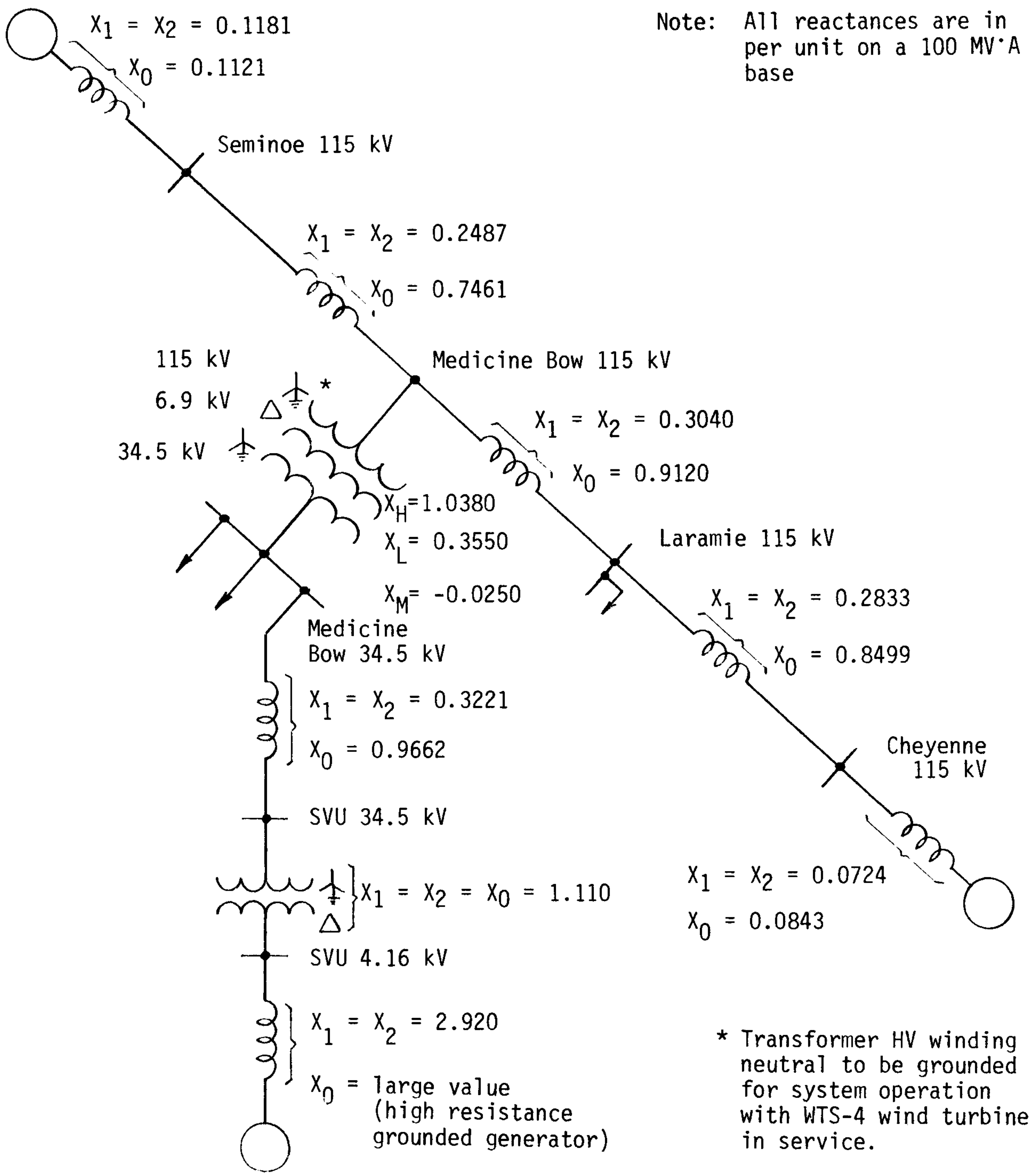
$I_{relay} = 4064/240 = \underline{17\ A}$

COMPUTATION SHEET

* U.S. Government Printing Office: 1977-779-651

BY	DATE	PROJECT	SHEET ___ OF ___
SJT	6-6-80	Missouri River Basin Project	
CHKD BY	DATE	FEATURE Medicine Bow Hamilton Standard WTS-4 Wind Turbine SVU (System Verification Unit)	
WRR	6-6-80		
DETAILS	Reactance Diagram -- Interconnected Power System		

Note: All reactances are in per unit on a 100 MV·A base



* Transformer HV winding neutral to be grounded for system operation with WTS-4 wind turbine in service.

GPO 845-555

Mission of the Bureau of Reclamation

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.

A free pamphlet is available from the Bureau entitled "Publications for Sale." It describes some of the technical publications currently available, their cost, and how to order them. The pamphlet can be obtained upon request from the Bureau of Reclamation, Attn D-922, P O Box 25007, Denver Federal Center, Denver CO 80225-0007.