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FLATIRON POWERPLANT AUTOMATIC VOLTAGE REGULATOR PERFORMANCE

October 1989

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16. ABSTRACT

Tests on the uprated unit 1 at Flatiron Powerplant were conducted during December 1988. Excitation system performance tests conducted at that time are described.

17. KEY WORDS AND DOCUMENT ANALYSIS

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by

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UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

ACKNOWLEDGMENTS

Special thanks to Mr. Hoa Vu who participated in the tests and also prepared appendix D on model representation.

Mission: As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural and cultural resources. This includes fostering wise use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also promotes the goals of the Take Pride in America campaign by encouraging stewardship and citizen responsibility for the public lands and promoting citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. Administration.

The research covered by this report was funded under the Bureau of Reclamation PRESS (Program Related Engineering and Scientific Studies) allocation No. DR-496, *Power System Stability Enhancement*.

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INTRODUCTION

Flatiron Powerplant houses two medium-size hydroelectric generators and a single pump generator. The two generating units were electrically uprated in 1985. In addition, the original Rototrol voltage regulators were replaced with new automatic voltage regulating equipment consisting of operational amplifier-type voltage regulating and limiting circuits, control relaying, and a thyristor-type power amplifier. The original rotating main exciters were retained.

Uprated turbine runners were not installed at that time; therefore, the units had never operated at their full uprated megavolt-ampere capability until the November 1988 installation of the first new runner on unit 1. Due to uncertainties concerning the rated field current of the machine at full load, the excitation system was never set for proper operation at full load. Thus, when unit 1 was ready to return to service at the uprated value, tests were required to set the excitation system limits properly for the uprated conditions.

J. C. Agee and Hoa Vu (Controls and Automation Section) participated with Bruce McCarthy (Eastern Colorado Projects Office) in the excitation system tests. Concurrent with these tests, Bill Duncan (Engineering Division, Facilities Engineering Branch), John German (Eastern Colorado Projects Office), and LeRoy Heigel and Tom Hovland (Electrical and Mechanical Engineering Division, Mechanical Branch, Hydraulic Machinery Section) conducted tests on the governor and turbine of the unit.

CONCLUSIONS

The excitation system was successfully adjusted for operation at the new uprated value. Coordination between the maximum excitation limiter and the exciter overvoltage relays is marginal and needs to be addressed further by means of a detailed technical study. This problem is being addressed on a Reclamation-wide basis. When a generator lockout occurs, phase back of the regulator should be initiated prior to opening of the field breaker. This is necessary to reduce the overvoltage experienced during load rejections. Project personnel are revising control circuits to include this function.

REGULATOR ADJUSTMENT PHILOSOPHY

Because the rating of the Flatiron machines is under 50 MV•A (megavolt amperes), power system stabilizers were not purchased. Therefore, the automatic voltage regulators could decrease the local-mode stability margin if they were adjusted for maximum speed of response. For this reason, the regulators were tuned for moderate speed and a high level of damping. Since the Flatiron unit transformers have a low impedance, the voltage regulators are set with a droop characteristic which locates the regulation point approximately 5 percent inside the machine terminals. This limits the machines' reactions to high-side voltage fluctuations while still providing needed voltage support at the 13.8-kilovolt bus for starting the unit 3 pump generator.

RATINGS AND CALIBRATIONS

The Flatiron generators are rated at 47.8 MV•A and 0.9 power factor. Rated voltage is 13.8 kilovolts and rated current is 2,000 amperes. Full megavolt-ampere output is obtained with real power at 43 megawatts and reactive power at 20.8 megavars.

The PT (potential transformer) ratio is 120:1 and the CT (current transformer) ratio is 2,000:5. The voltage regulator terminal voltage transducer (at terminal C of A5CB) produces 53.8 volts d.c. (direct current) at rated terminal voltage.

The base field current required to produce rated terminal voltage on the air gap line is 212 amperes (fig. 1). The field resistance at 25 °C is 0.3607 ohm. At a typical operating temperature, the resistance increases to 0.42 ohm. Therefore, the base field voltage is 89 volts at normal operating temperatures. The field voltage transducer in the regulator (at terminal 4 of JVT) has a calibration of -8 volts of output for 260 volts of input. This signal has a base of 2.74 volts per unit.

The rotating exciter base field current required to produce 89 volts from the exciter on its air gap line is 4.5 amperes (fig. 2). The exciter field resistance is 3.947 ohms at 75 °C. At a typical operating temperature, the corrected resistance is 3.4 ohms. Therefore, the base exciter field voltage is 15.4 volts at normal operating temperatures.

Several machine quantities and excitation levels for various conditions are shown in table 1.

Table 1. - Machine operating points

Megawatts	Megavars	Vt (kilovolts)	Ifd (amperes)	Efd (volts)	Iex (amperes)	Eex (volts)
0	0	13.8	242	93	4.26	14.2
43	1 In	13.9	357	146	7.32	24.8
43	18 Out	14.2	505	210	12.3	42.4

Vt = Terminal Voltage
Ifd = Main Field Current
Efd = Main Field Voltage
Iex = Exciter Field Current
Eex = Exciter Field Voltage

At rated conditions (43 megawatts, 20.8 megavars), field current is approximately 510 amperes at 220 volts with a winding temperature of 75 °C. These values have been selected as rated values for limiter and relay coordination.

OFF-LINE PERFORMANCE

The automatic voltage regulator was tuned by adjusting A4P to its minimum [CCW (counterclockwise)] position. The automatic regulator gain was set at 4.4, lead at 10.0, and lag at 0.0. Figure 3 shows the small signal step response of the closed-loop automatic voltage regulating system with the unit off line at rated voltage and speed. The 10- to 90-percent rise time is about 0.4 second. The overshoot is 13 percent. Response is almost symmetrical for both increases and decreases in terminal voltage. The control system performance is well damped with only one overshoot and no apparent oscillations.

A Bode plot of the frequency response of the off-line automatic regulating system is shown in figure 4. The 3-decibel bandwidth is approximately 1.2 hertz, and the resonant peak magnitude is less than 1 decibel above the steady-state gain. These values indicate a moderate-speed, well-damped control system.

The range of the automatic regulator adjuster was not tested since the unit had been in service and performing satisfactorily for several years.

The minimum setting of the 70P [d-c (direct-current) regulator adjuster] was not adjusted; however, its maximum setting was adjusted via the range pot to obtain field voltage of 230 volts (105 percent of rated). The d-c regulator response was tested by transferring from the a-c (alternating-current) regulator with an unbalance between their outputs. Figure 5 shows this response. Performance is adequate; however, it may be readjusted during the unit 2 tests in order to reduce overshoot and improve damping.

ON-LINE PERFORMANCE

The automatic voltage regulator did not need to be retuned for on-line operation. Figure 6 shows the small signal step response of the closed-loop automatic voltage regulating system with the unit on line at full load and unity power factor. The 10- to 90-percent rise time is about 1.6 seconds. There is no overshoot. The control system performance is well damped with no apparent oscillations. Figure 7 shows a Bode plot of the on-line automatic voltage regulating system. The 3-decibel bandwidth is about 0.2 hertz. Local mode resonance appears well damped. Figure 8 shows the damping of local mode when stimulated by a pulse in field voltage. The local mode frequency is near 2 hertz. The oscillations are totally damped in three to four cycles, which indicates a damping factor of about 0.2.

AUTOMATIC LIMITERS

The Flatiron regulators are equipped with V/Hz (volts per hertz) URAL (underreactive ampere limiters) and maximum excitation limiters. These limiters supervise only the a-c regulator and take control if certain conditions occur. They do not function if the regulator is in d-c (manual) regulator mode.

The V/Hz limiter was not tested because the unit had been in satisfactory commercial service. However, upon investigation in Denver, no record of tests on this device could be found in the original test report. Therefore, this device will be tested during the unit 2 tests.

The URAL prevents the generator from operating too far underexcited. Table 2 lists several points at which the URAL becomes active. These points are shown on the capability curve in figure 9.

Table 2. - URAL limiter data.

Megawatts	Megavars
10	17 In
19	17 In
30	13 In
44	8 In
48	1 In

The maximum excitation limiter has two functions: (1) it provides a fixed instantaneous exciter field current limit, allowing a high level (typically 150 percent) of excitation for a short time; and (2) it provides an inverse time characteristic after which the excitation limit is recalibrated and reduced to the rated value.

The primary limit on exciter field current is set to 16.8 amperes via the A1P dial setting of 4.8. This corresponds to about 275 volts from the rotating exciter during startup (exciter unloaded). When the exciter is at rated load, 260 volts are induced from this current. With a hot generator field (75 °C), this will produce 605 amperes of main field current (120 percent of full-load, rated power factor). With a cold field (25 °C), it will produce 725 amperes (142 percent) of main field current.

After 8 to 10 seconds (inverse-time characteristic), circuit board J2CB should operate relay J1K and reduce the exciter field current limit to 11.5 amperes. This will reduce the rotating exciter output to about 220 volts. This results in 511 amperes (100 percent) of main field current with a hot field and 610 amperes (120 percent) with a cold field. During startup when the exciter is unloaded, this value of exciter field current produces 221 volts.

During testing of the recalibrated limiter, the J1P potentiometer was found to have an open circuit at a dial setting of 7.5. The pot was therefore rewired with the opposite sense. The final setting was 4.0 on the dial.

If the maximum excitation limiter does not work properly and the rotating exciter output remains above 235 volts for 36 seconds (inverse-time characteristic), circuit board J1CB will operate relay J2K and transfer to the manual regulator at the autotracked position. For this contingency, the maximum position of the manual regulator was set to only slightly above the rated value.

RELAY COORDINATION

If the rotating exciter output remains above 255 volts for 40 seconds, relay 59E will operate through timer J2KX/TD and thereby trip the lockout relay.

If the rotating exciter output reaches 300 volts, relay 59E/H will operate and trip the lockout relay. These coordination levels are shown on figure 10.

Relay 159 is the primary terminal voltage limiter. If terminal voltage remains above 110 percent for 3 seconds, this relay will pick up through timer 159X and transfer the regulator to a fixed phase-back circuit. This circuit is set to fully phase back the regulator bridge. When terminal voltage drops below 110 percent, the relay drops out and returns bridge control to the automatic or manual regulator that was in service before the overvoltage condition. During testing of this device, it was discovered that proper operation could not be obtained if the phase-back signal was less than -3 volts; therefore, it was set to -2.5 volts. Operation of terminal voltage limiting is shown on figure 11.

If terminal voltage remains above 115 percent (or if the V/Hz ratio exceeds 115 percent) for 5 seconds, relay 159 V/Hz will pick up and trip the generator lockout relay.

If terminal voltage remains above 115 percent for 8 to 10 seconds (inverse-time characteristic), or if it ever exceeds 140 percent, relay 159 I/T will pick up and trip the generator lockout relay.

STARTUP PERFORMANCE

The Flatiron generators are not equipped with a 90-percent speed switch, so a timer is employed to close the field breaker after the low-speed switch detects rotation. When first tested, this timer was set too fast resulting in the field breaker closing at 67 percent speed. This condition was corrected.

The voltage regulators are powered by station service rather than from the machine terminals; therefore, field flashing is not employed. Because of this situation, the a-c regulator will not build voltage unless there is sufficient residual to activate the V/Hz limiter circuitry. Enough residual was detected during our tests; however, for consistent automated performance, the regulators were set up to start in d-c regulator mode and then transfer to a-c regulator mode after the field breaker is closed.

Figure 12 shows a normal automatic start of unit 1. Transfer from the d-c to the a-c regulator is apparent. Voltage buildup is accomplished in about 5 seconds with very little overshoot in terminal voltage. The 59E relay was observed to pick up, but its time delay J2KX/TD blocked further action (proper operation). Relay 59E/H did not pick up.

LOAD REJECTION PERFORMANCE

Load rejections were executed at 10-, 30-, and 44-megawatt levels. Two rejections were initiated at 44 megawatts in order to compare performance of voltage regulator phase-back operation to field breaker opening with discharge resistor insertion. Results are summarized in table 3.

Table 3. - Load rejection performance.

Load	Overspeed (percent)	Prerejection voltage (percent)	Overvoltage (percent)
10 megawatts, 0 megavars	104	101	102
30 megawatts, 0 megavars	123	100	109
44 megawatts, 17 megavars out field breaker	139	102.5	136
44 megawatts, 17 megavars out phase back	140	102.5	128

Figure 13 shows a rated load rejection executed by tripping the lockout relay (86G). This action caused the field breaker to trip immediately without regulator phase back. Figure 14 shows a rated load rejection executed by opening the unit breaker. The lockout relay was tripped later, after the voltage had recovered to its prerejection level. Project personnel will revise the control circuitry to provide regulator phase-back operation prior to field breaker opening when the lockout is tripped. This will limit the overvoltage on rated load rejections by an additional 8 percent.

PUMP START PERFORMANCE

An important function of the voltage regulators at Flatiron is to support system voltage during a start of the unit 3 pump motor. Prior to proper adjustment of the overexcitation limiters, operation of the main units was limited to half load while the pump was starting. Operation at higher loads during this time would cause either a pump synchronizing failure because of an excessive voltage drop, or the generator tripping on overexcitation, or both.

The initial setting of the overexcitation limiter resulted in a starting failure because the 59E relay was set too low. This is documented in figure 15. The field voltage was 247 volts (112 percent) when the machine tripped. Proper operation was obtained by readjusting the 59E to 255 volts (116 percent) and the overexcitation limiter time delay to a lower value. Figure 16 shows a successful pump start. Operation of the overexcitation limiter is apparent. The 59E relay was observed to check that it did not pick up.

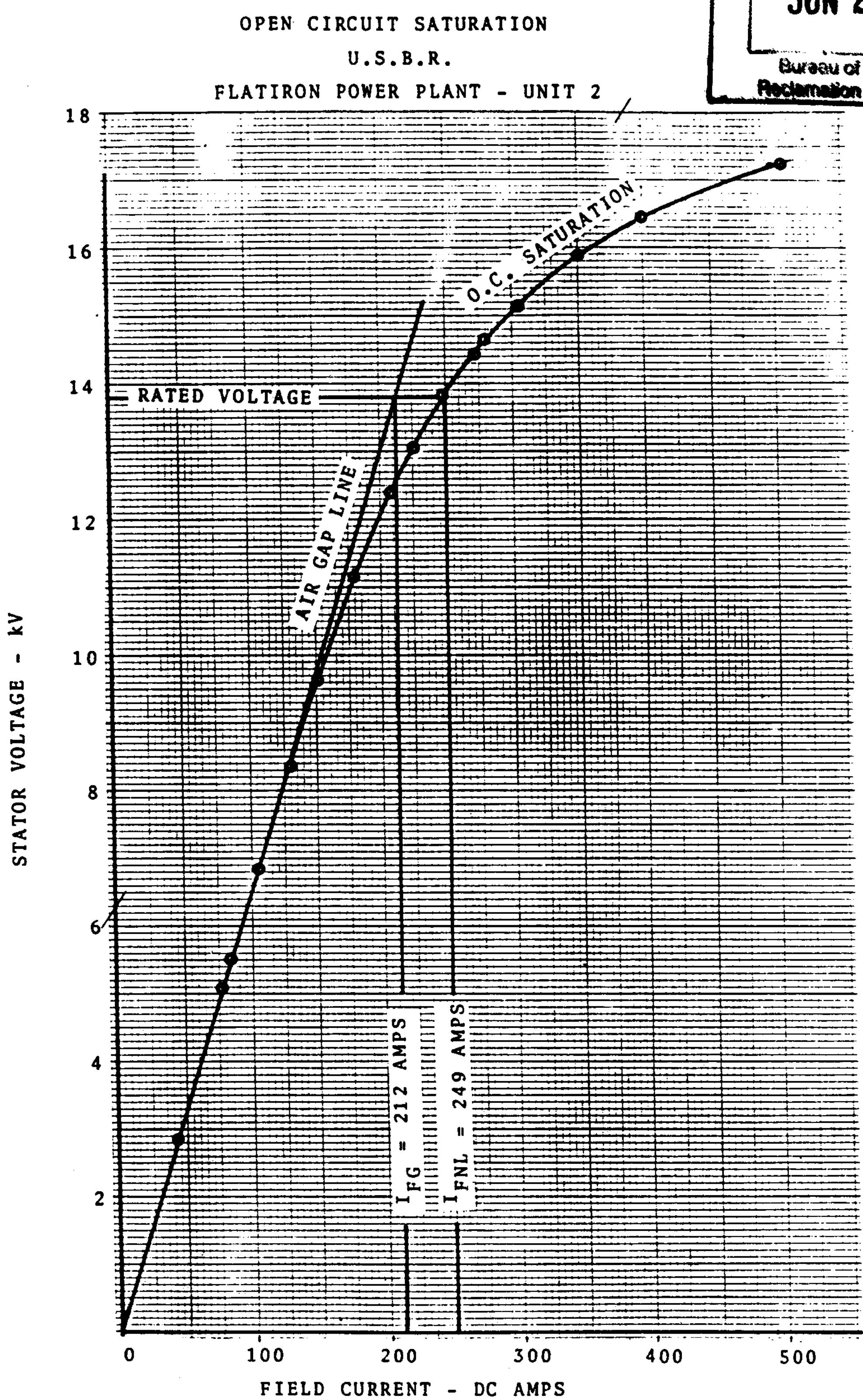


Figure 1. - Generator saturation curve.

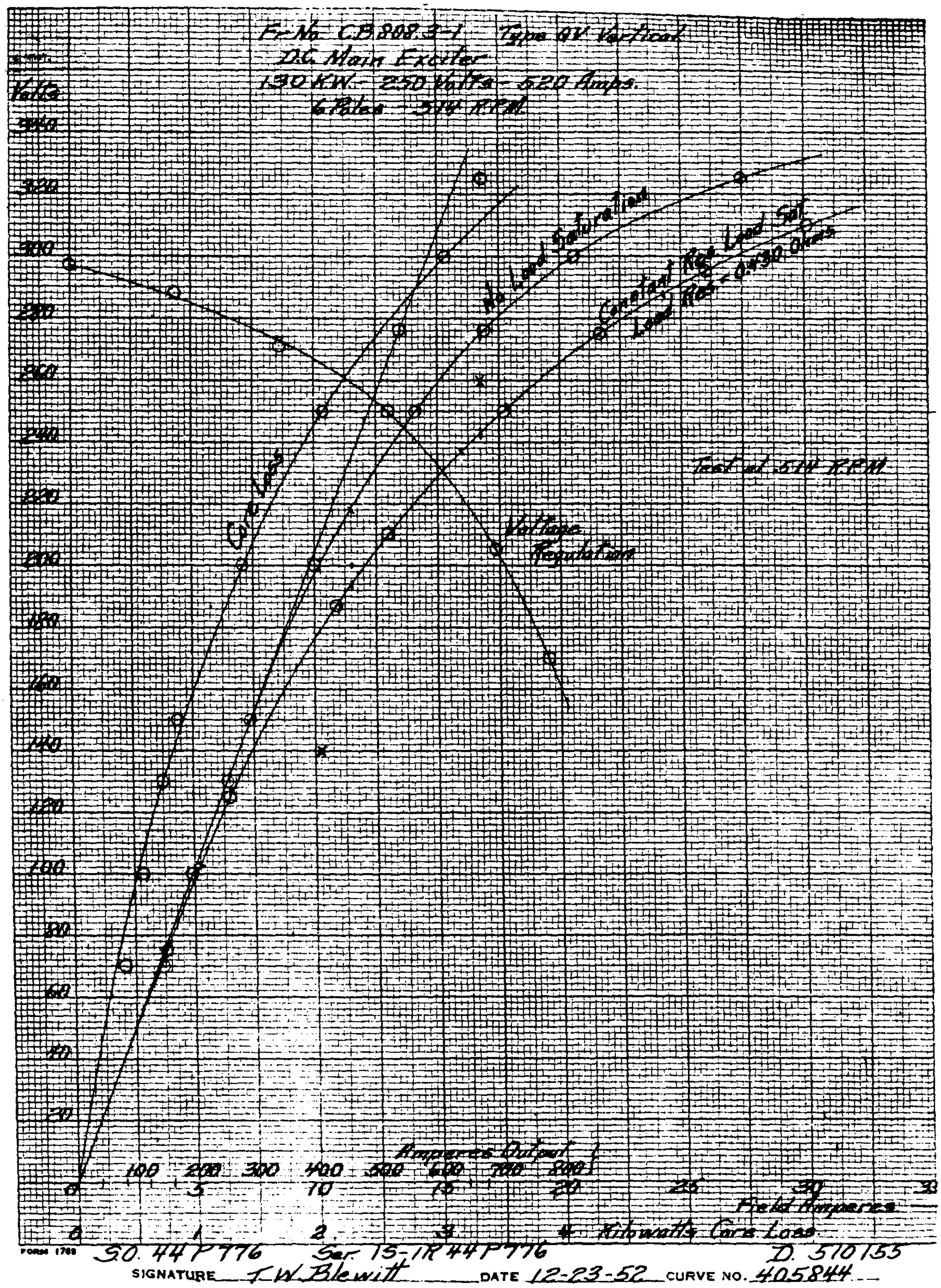


Figure 2. - Exciter saturation curve.

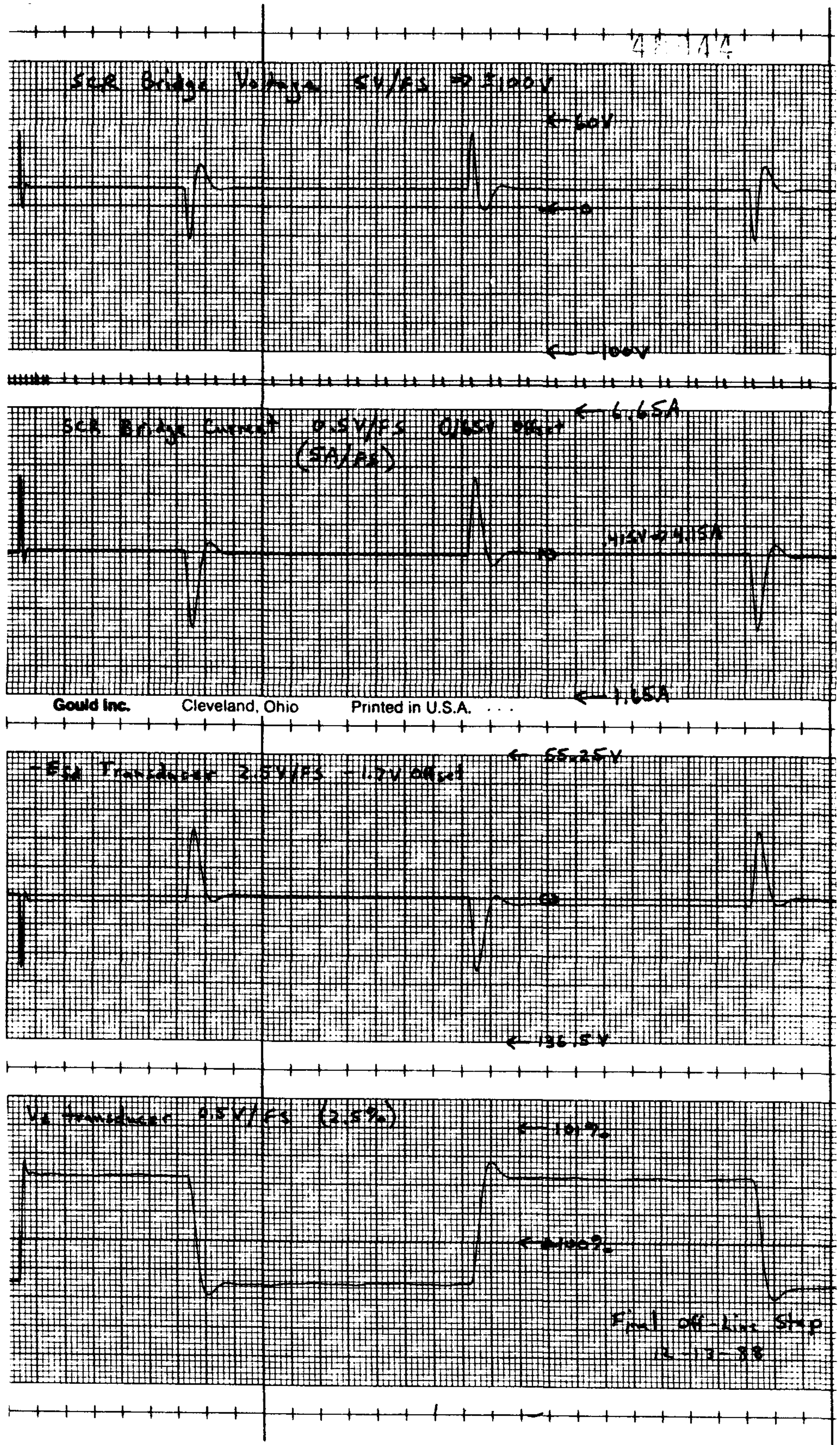


Figure 3. - Small signal step response of off-line a-c regulator.

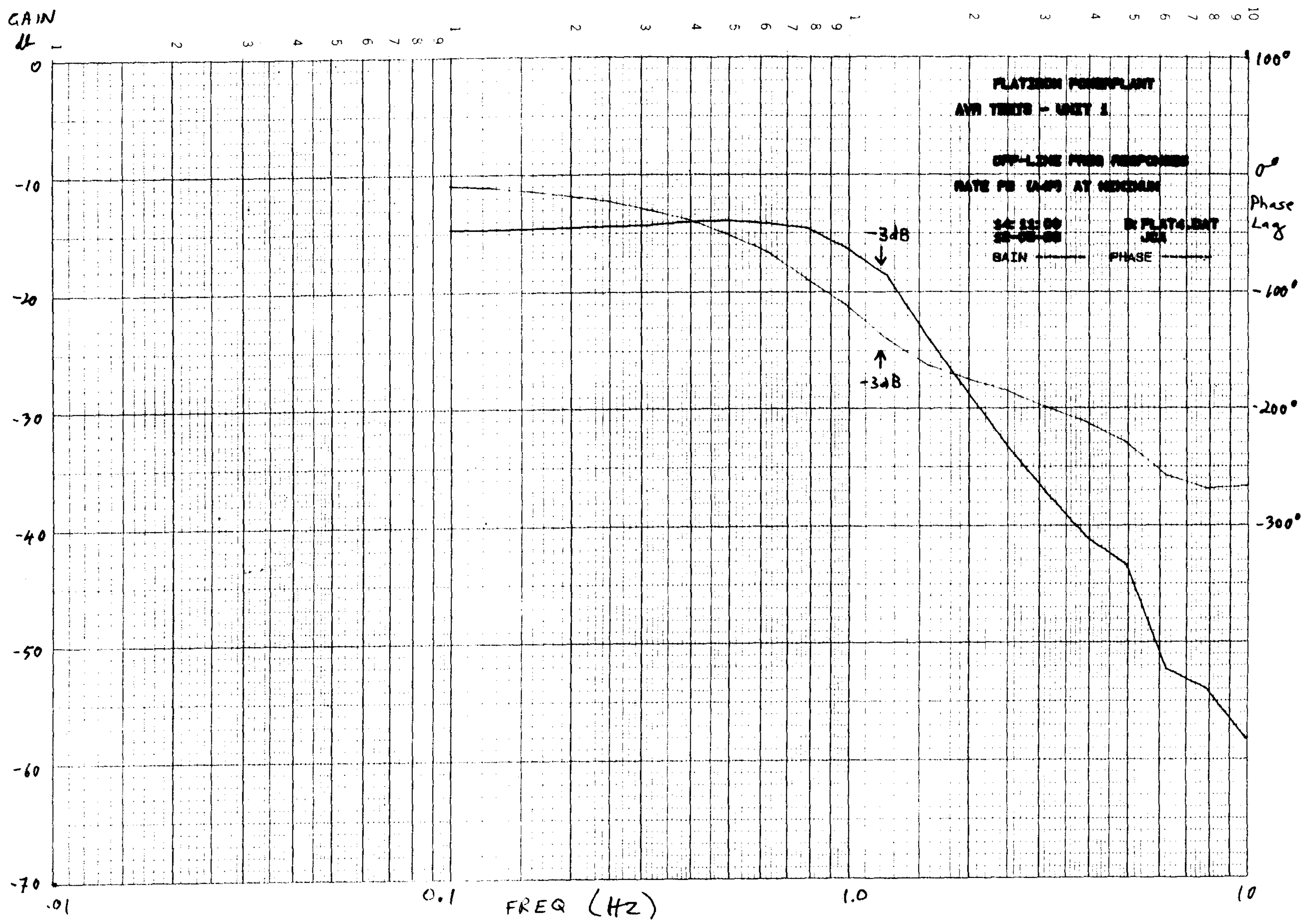


Figure 4. - Frequency response of off-line a-c regulator.

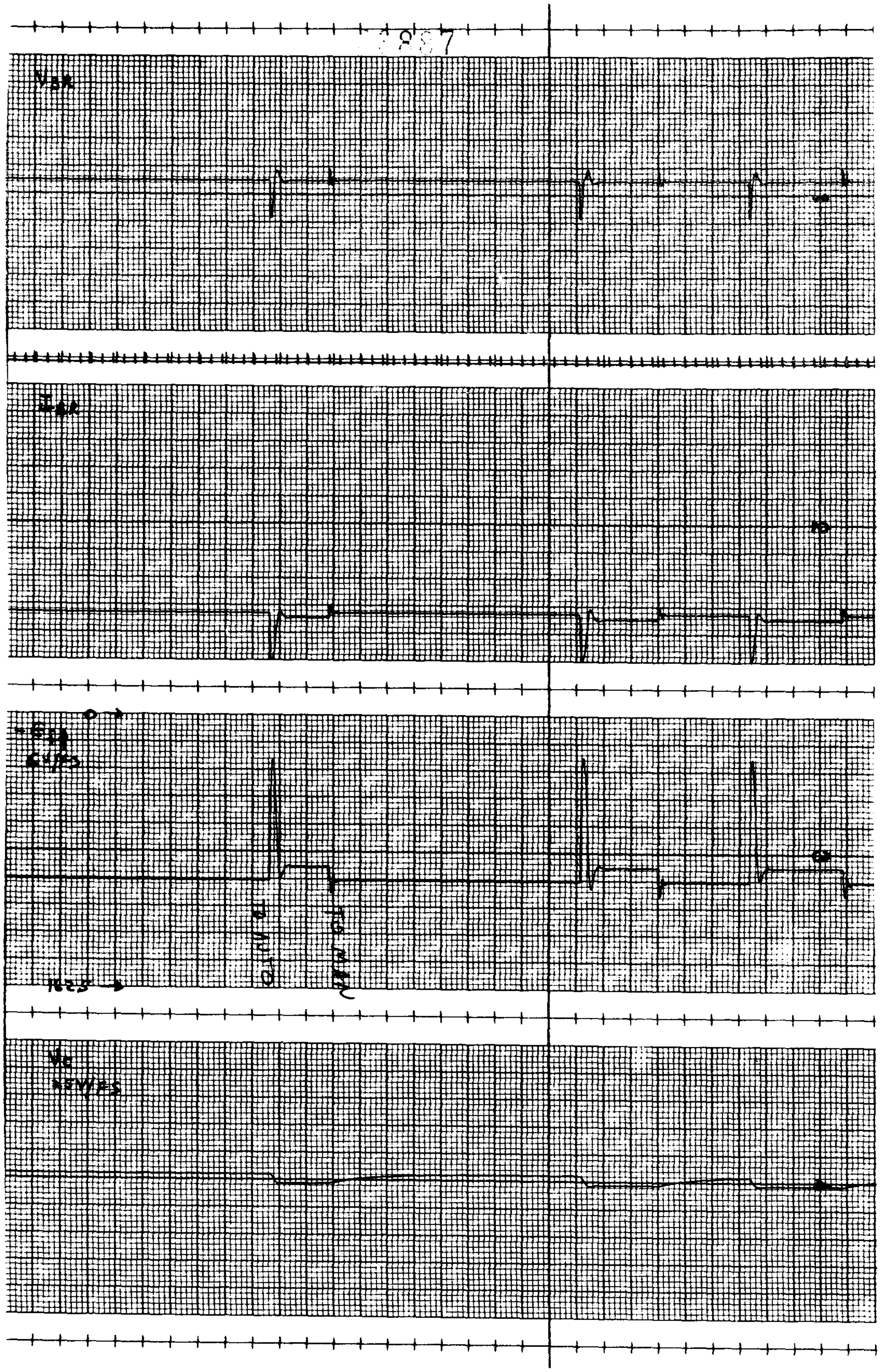


Figure 5. - Off-line step response of d-c regulator.

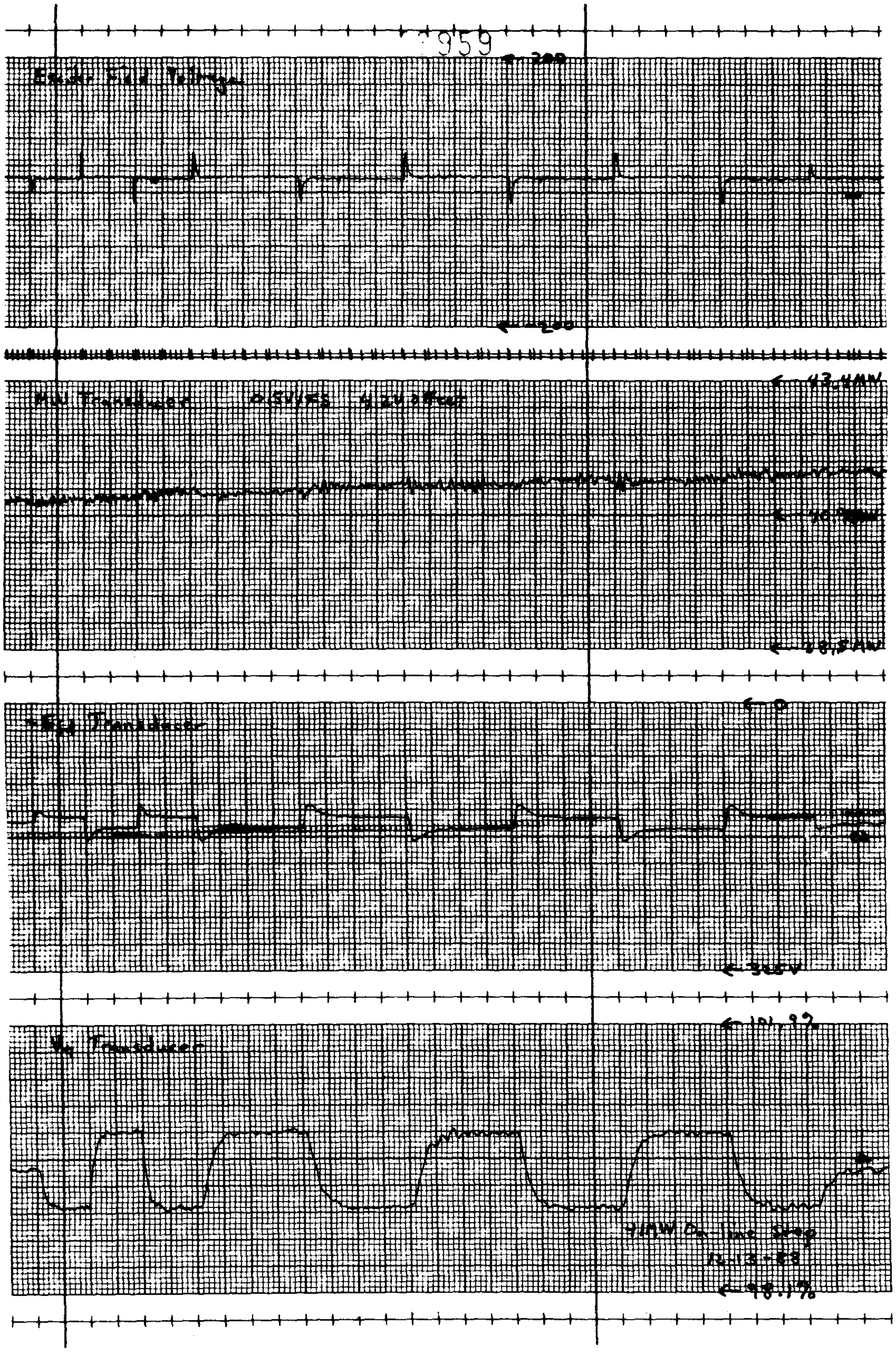


Figure 6. - Small signal step response of on-line a-c regulator.

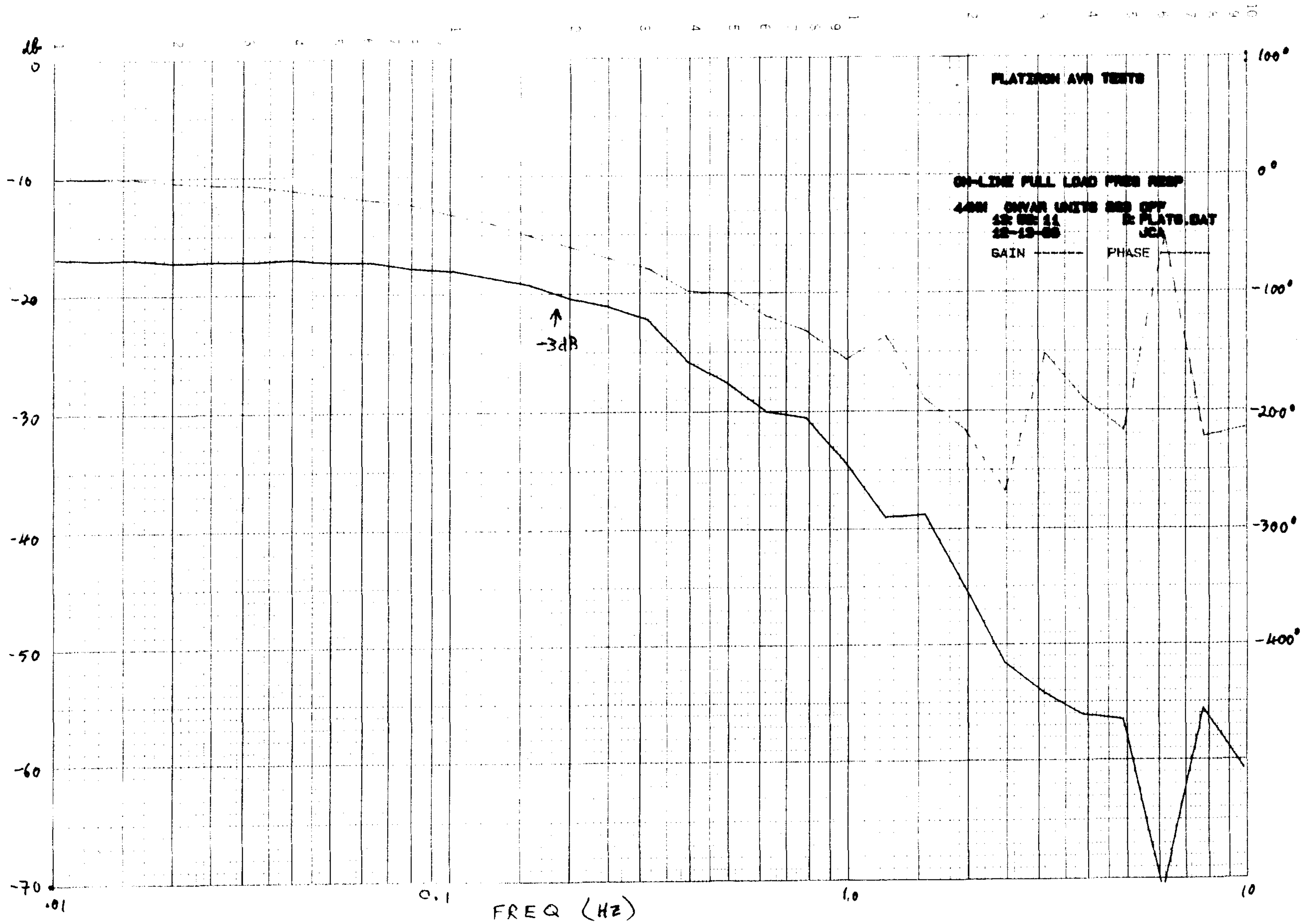


Figure 7. - Frequency response of on-line a-c regulator.

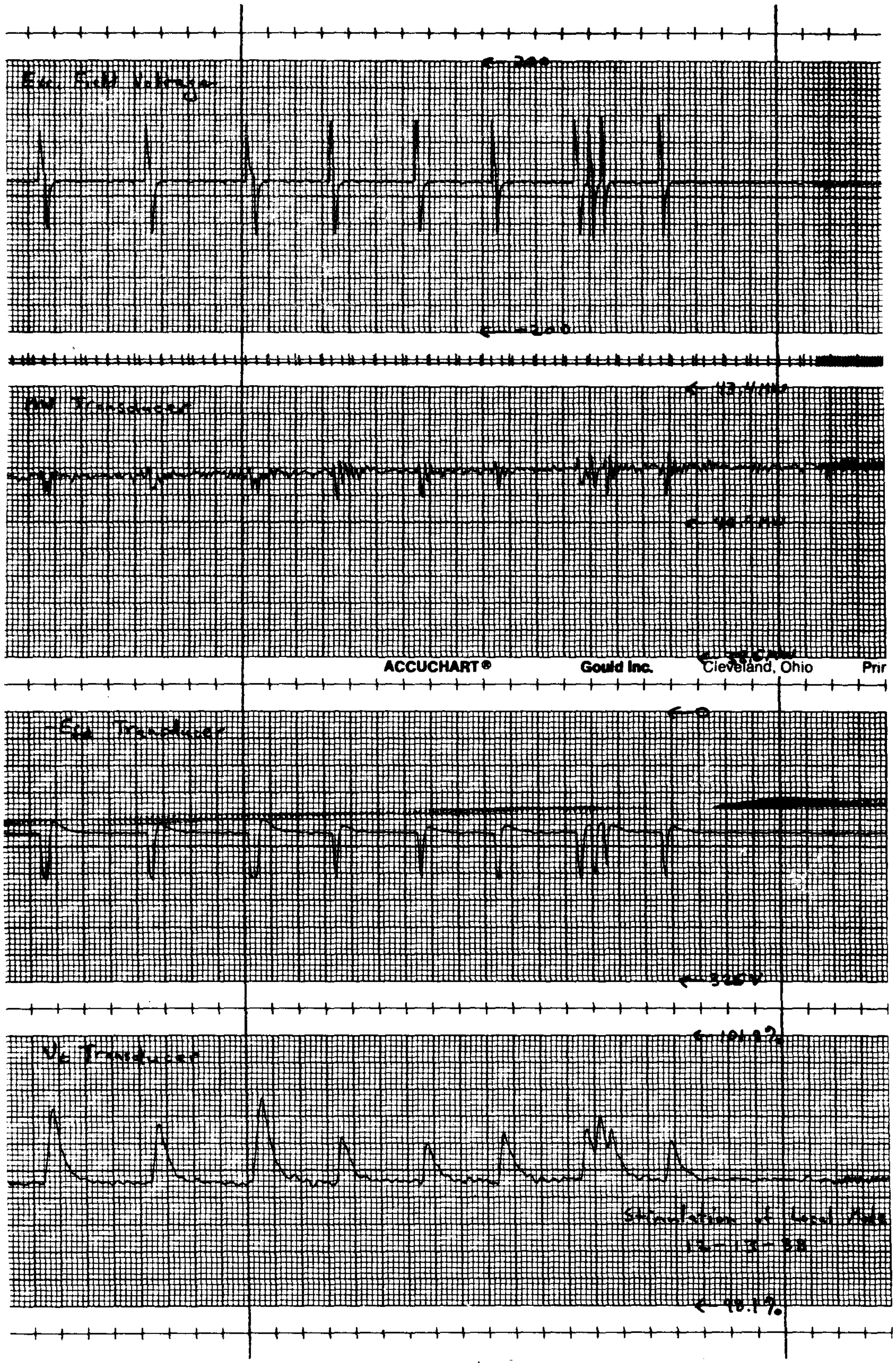


Figure 8. - Local mode damping response.

Flatiron Units 1 & 2

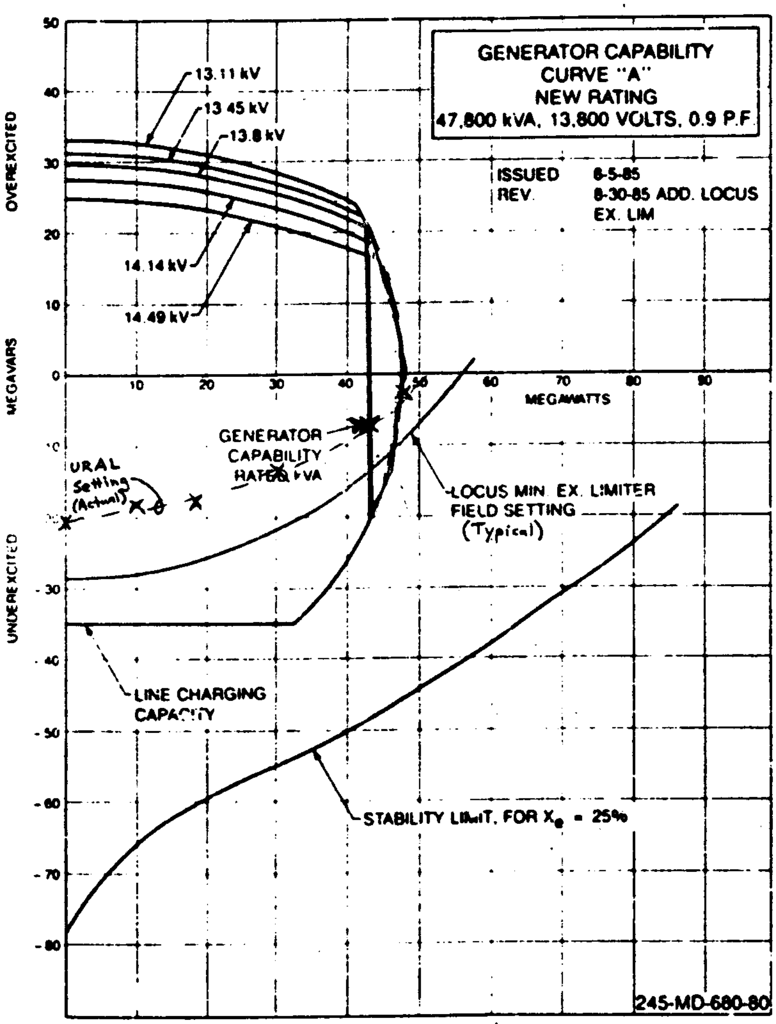


Figure 9. - Capability curve.

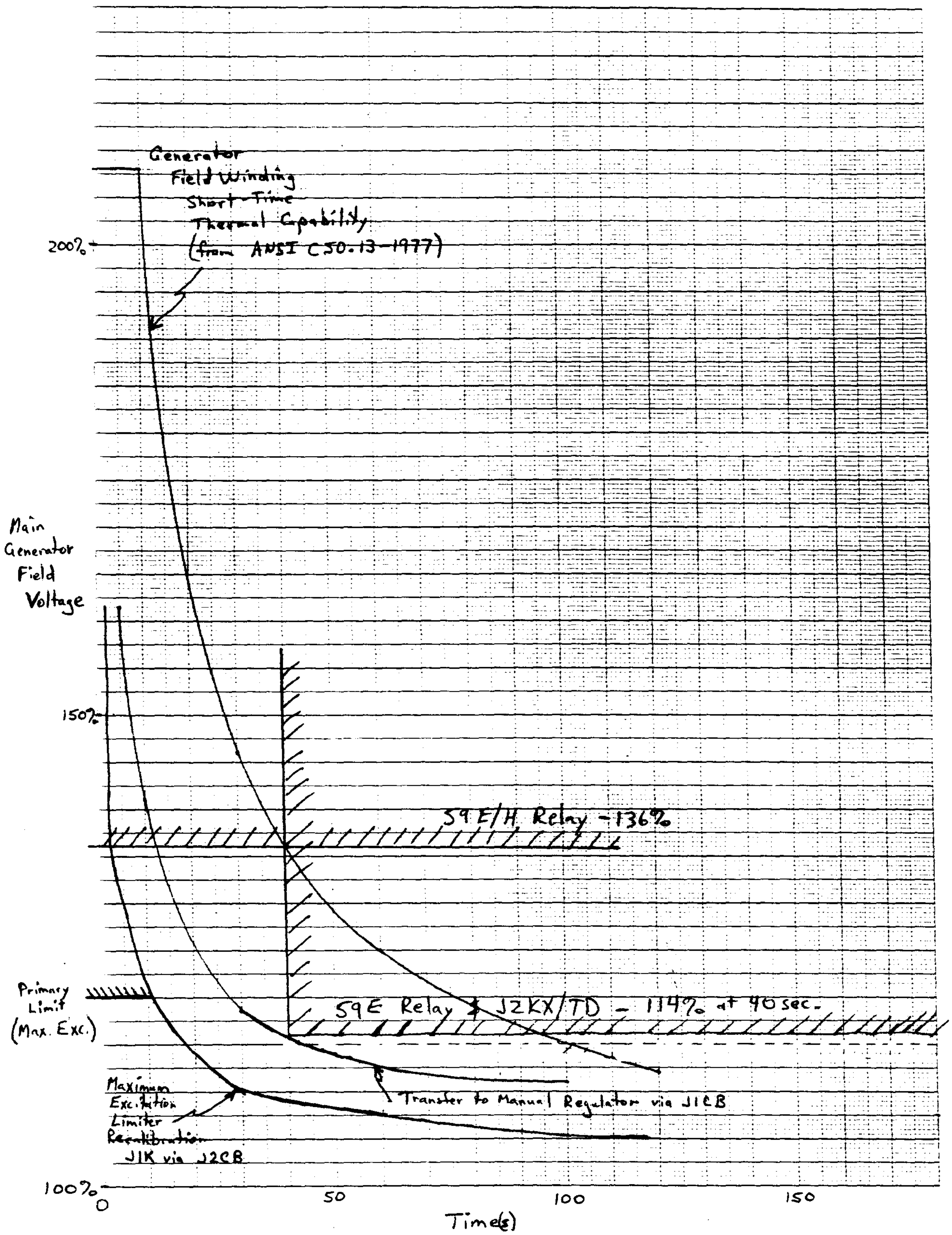


Figure 10. - Overexcitation limiting coordination.

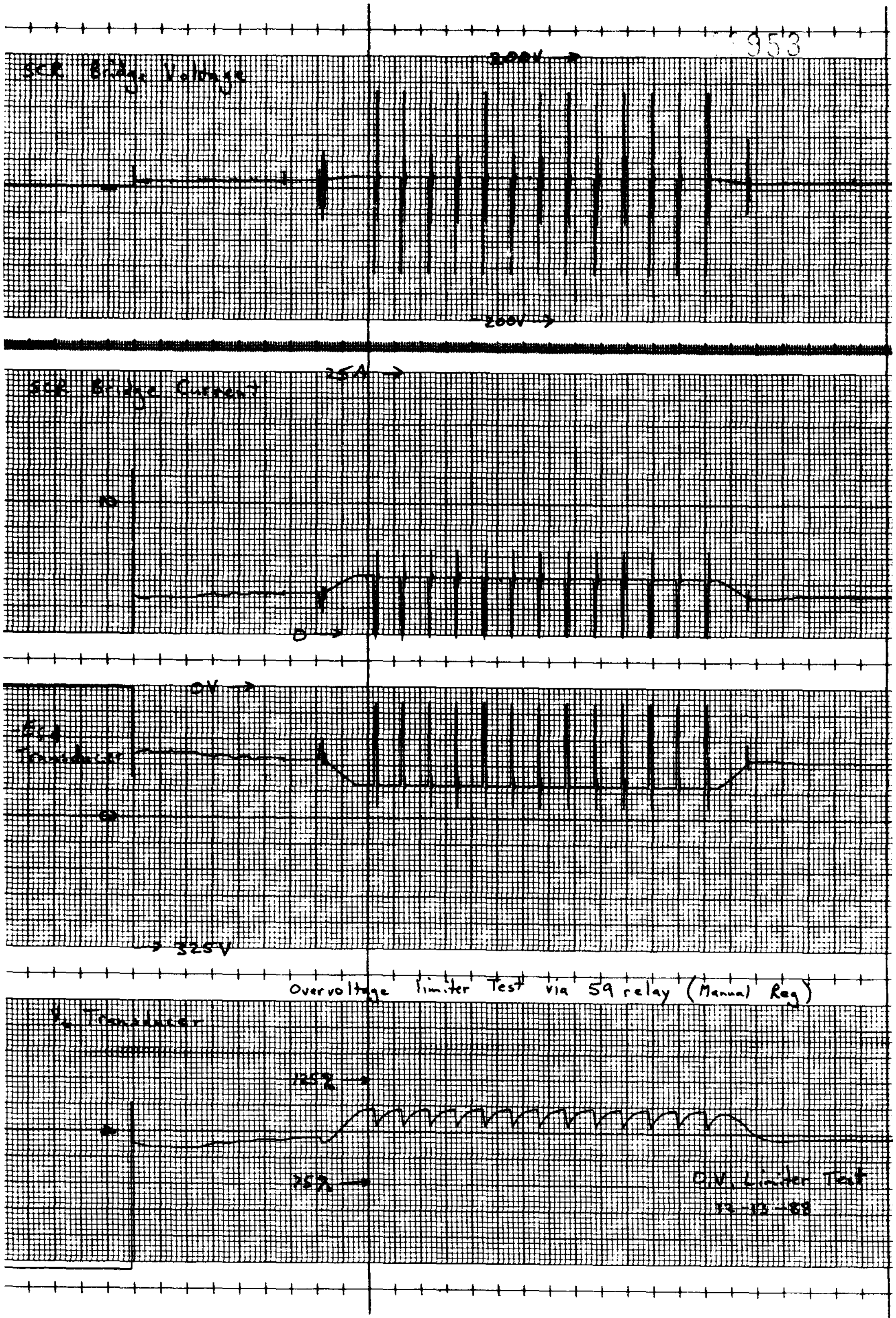


Figure 11. - Terminal voltage limiter operation.

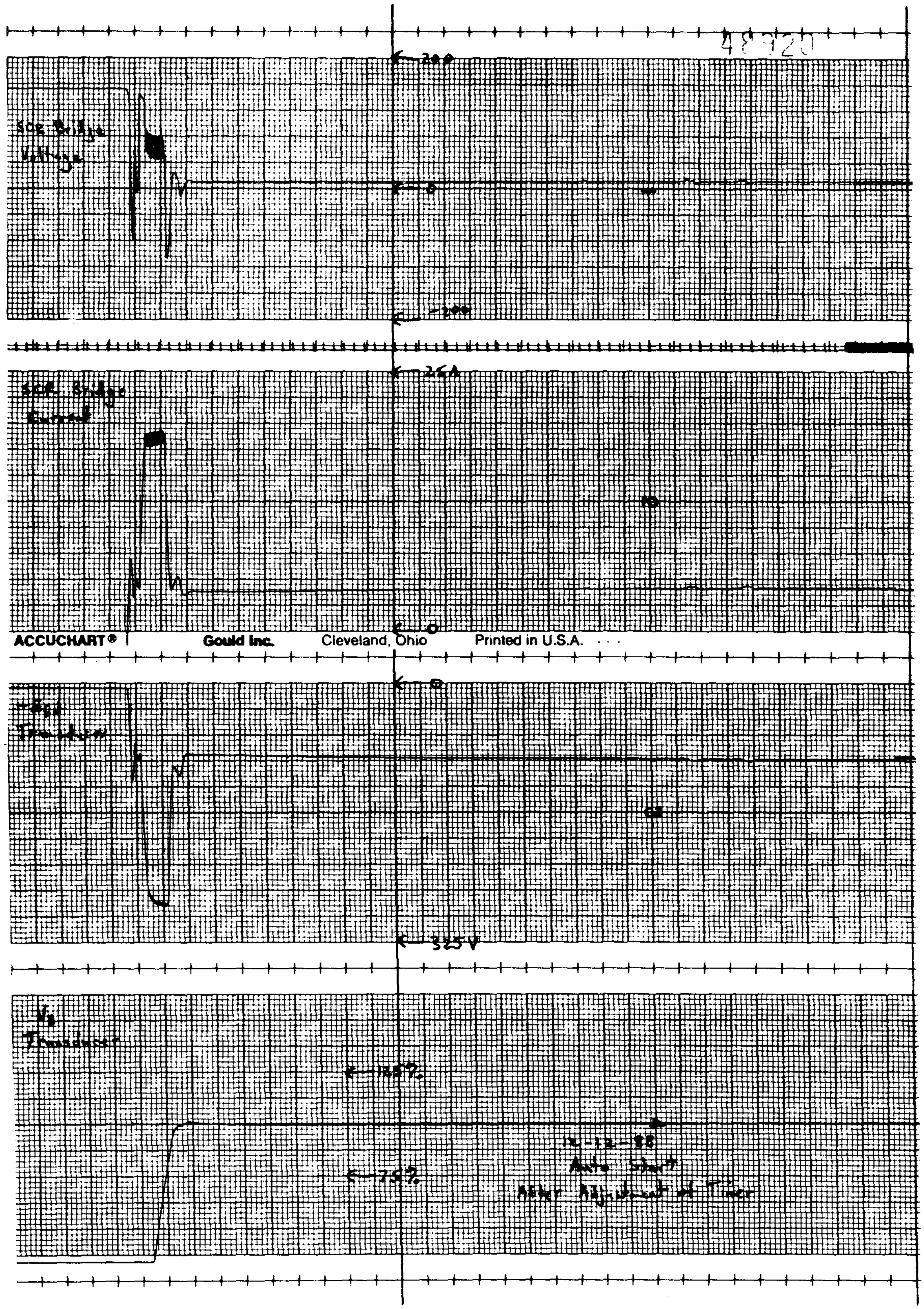


Figure 12. - Normal startup performance.

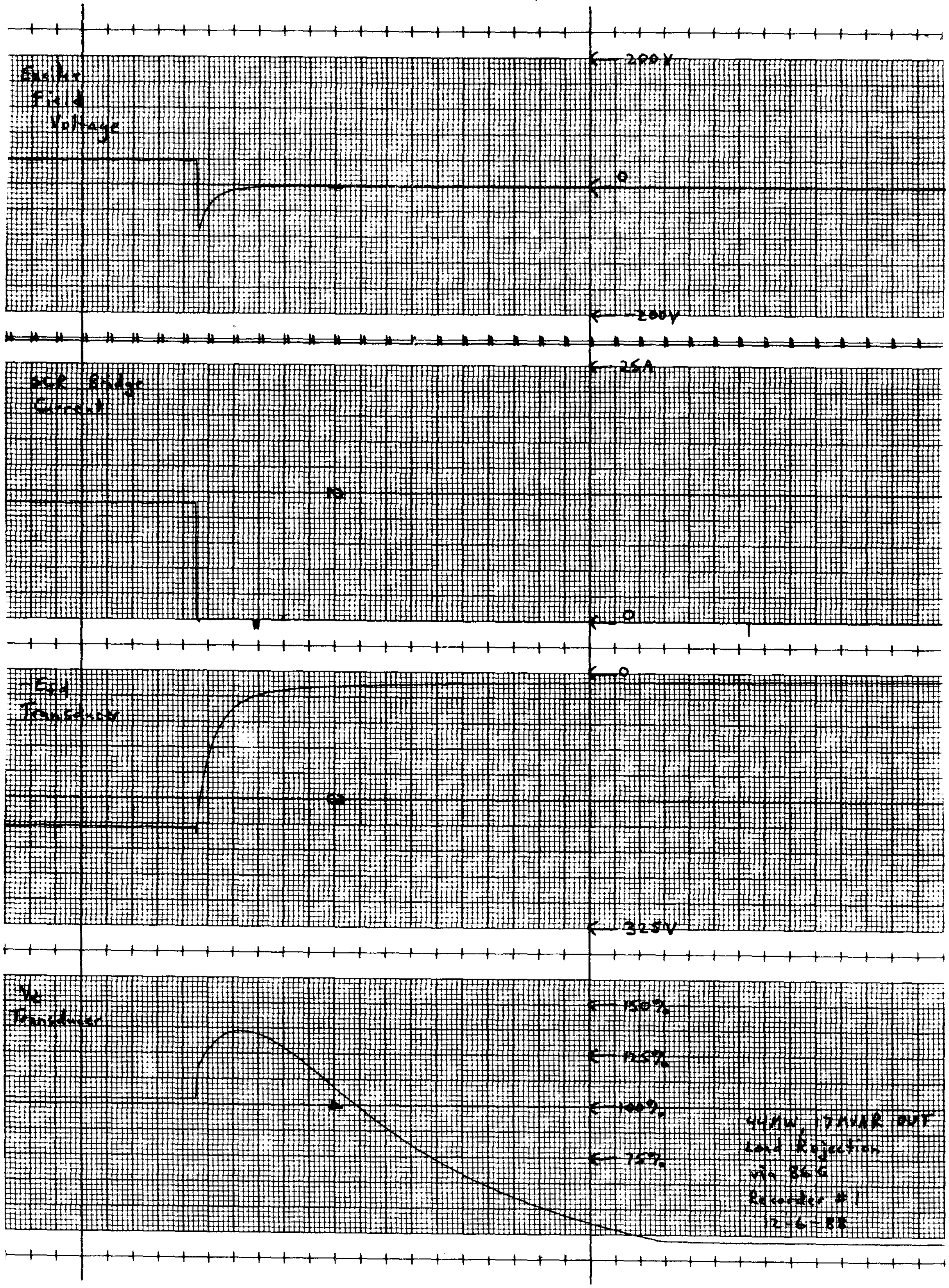


Figure 13a. - Rated load rejection via lockout relay, recorder No. 1.

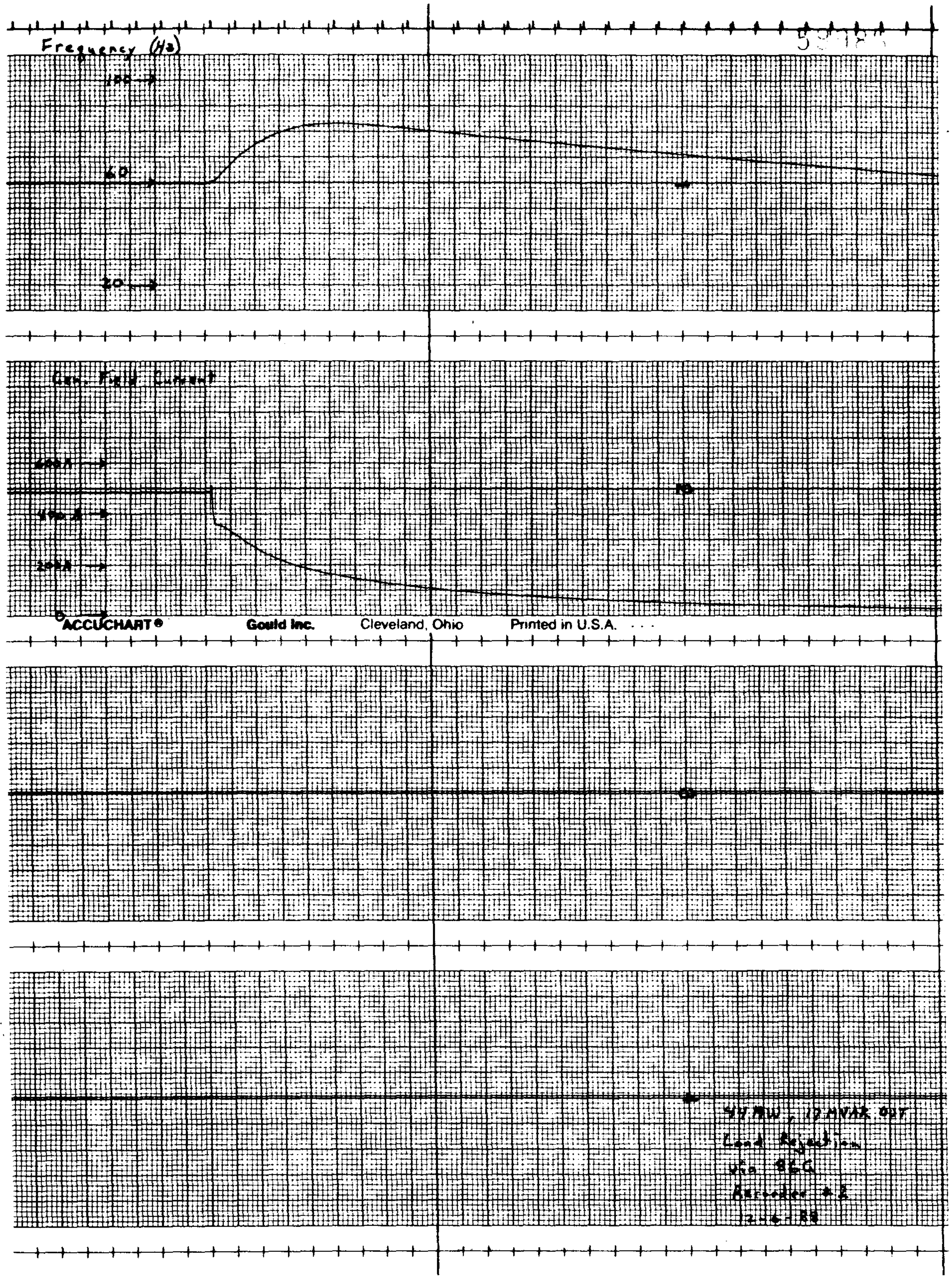


Figure 13b. - Rated load rejection via lockout relay, recorder No. 2.

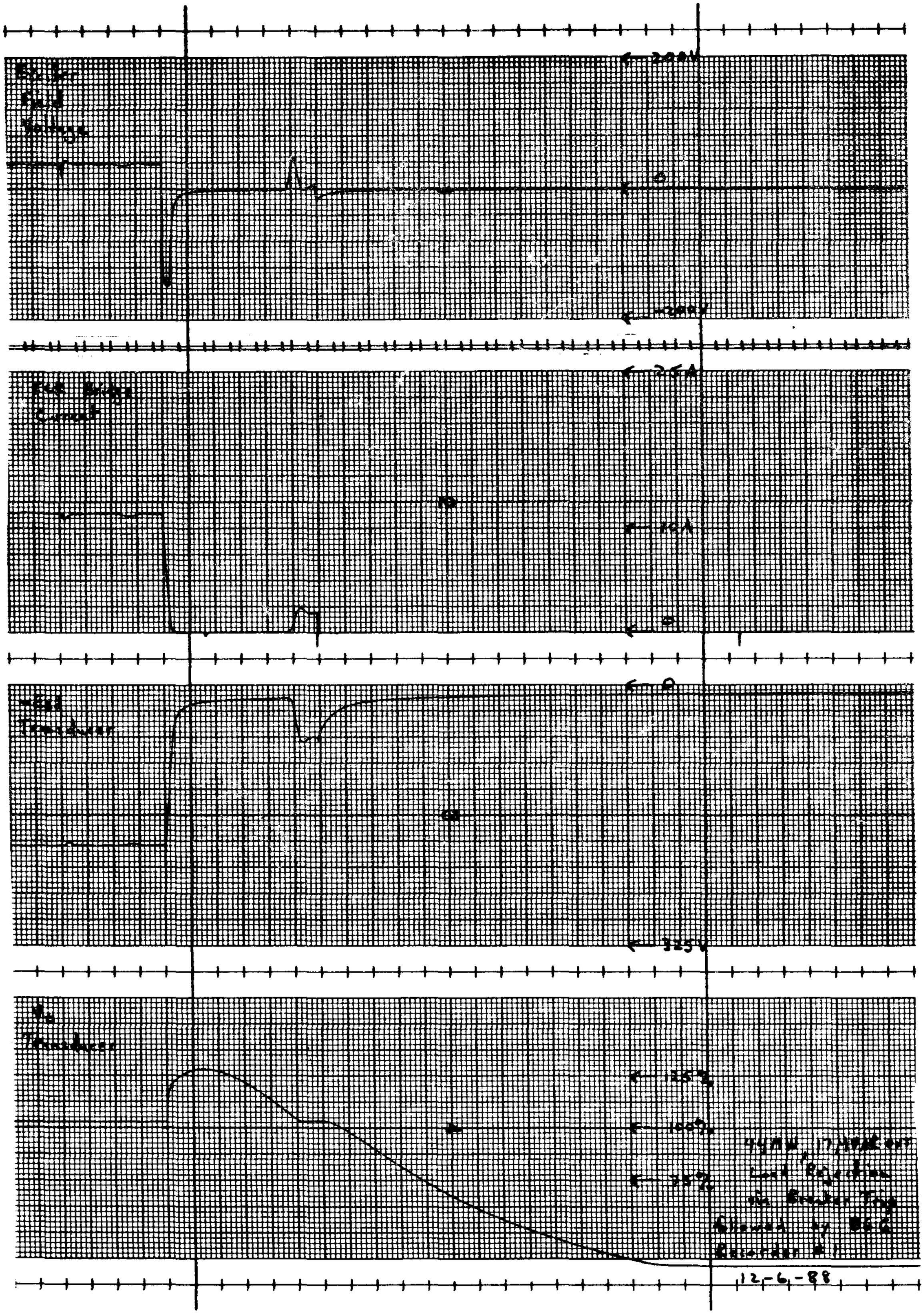


Figure 14a. - Rated load rejection via unit breaker operation, recorder No. 1.

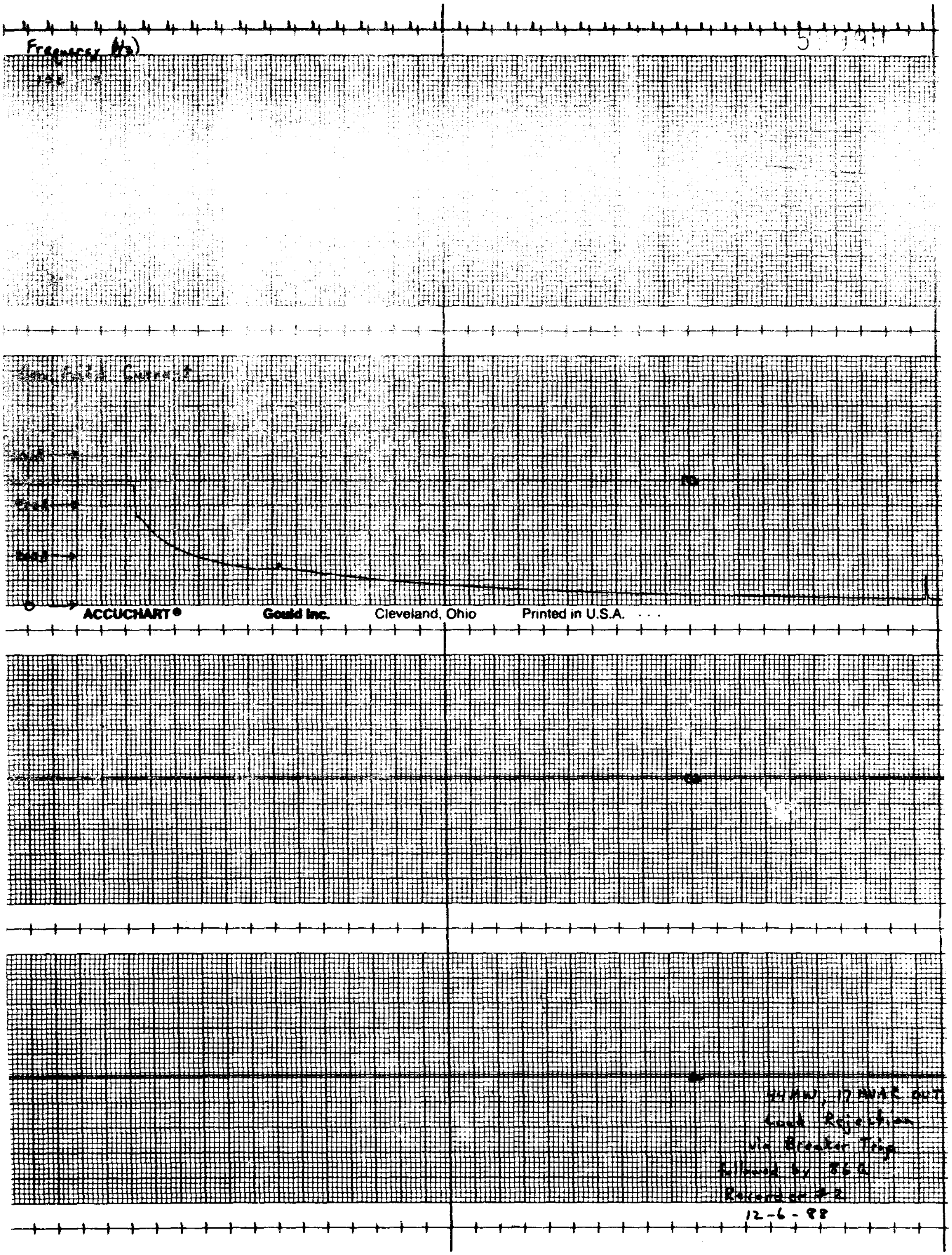


Figure 14b. - Rated load rejection via unit breaker operation, recorder No. 2.

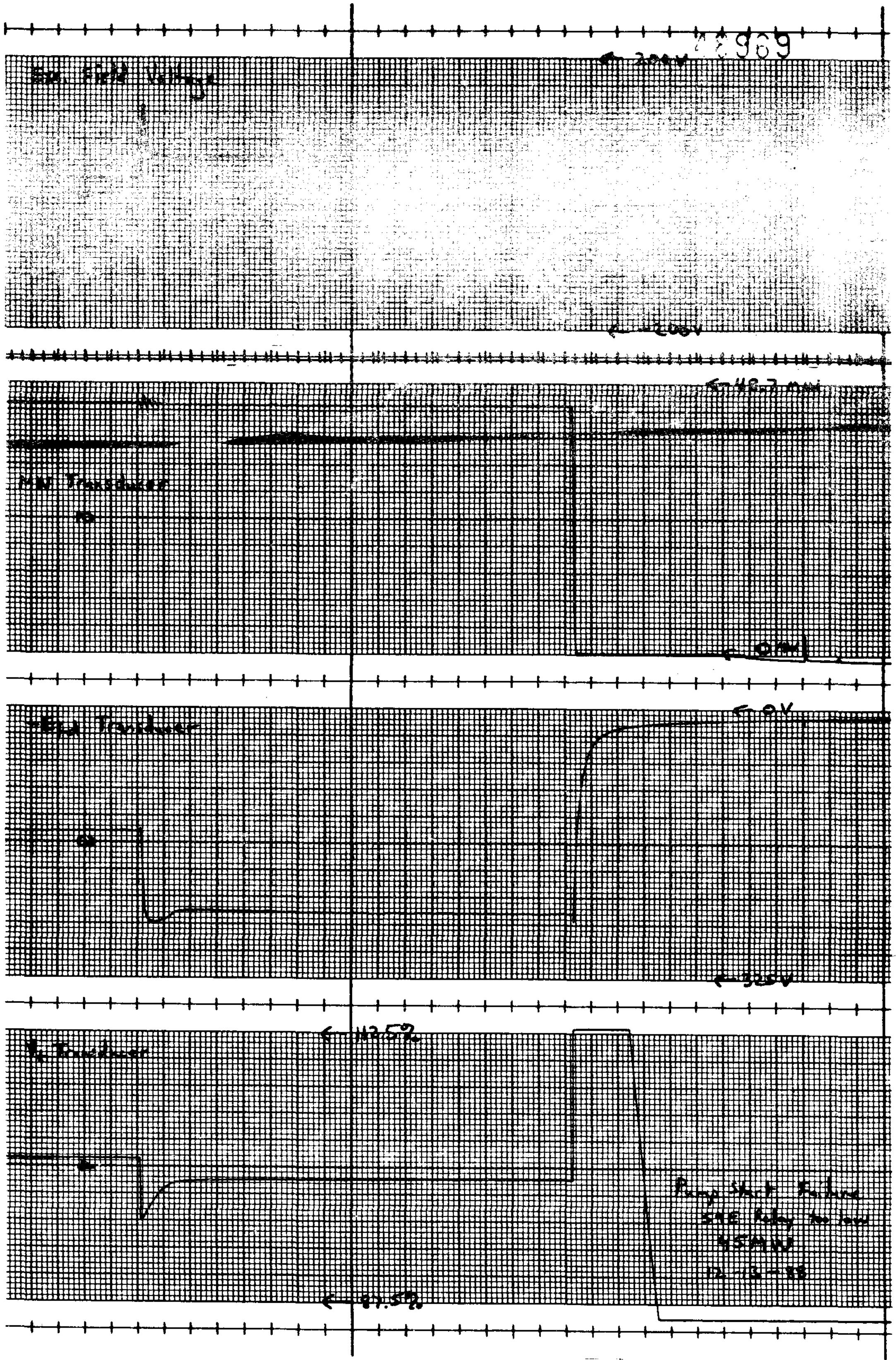


Figure 15. - Pump start failure.

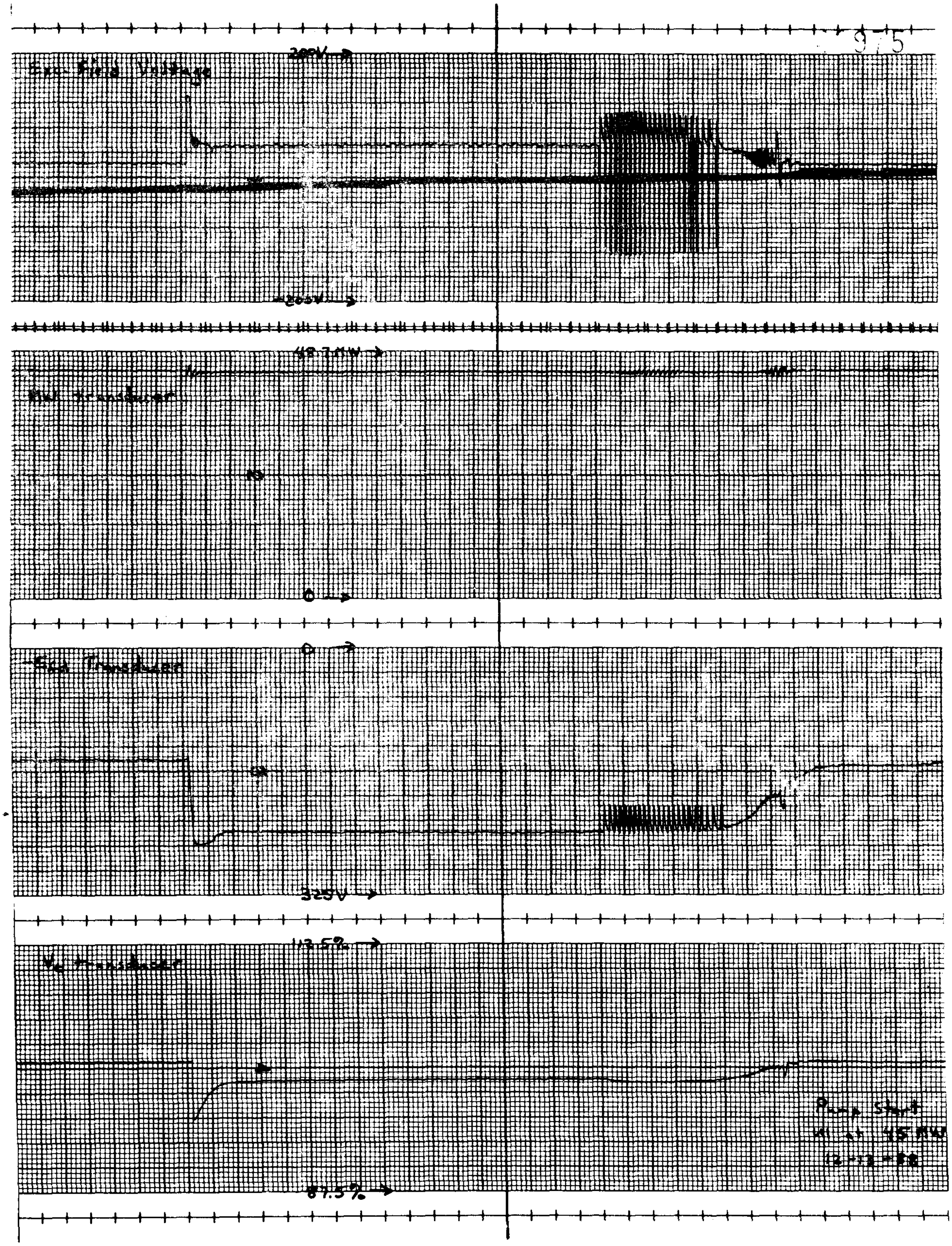


Figure 16. - Successful pump start.

APPENDIX A

Special Conditions

The phase-back circuit did not function properly unless the voltage was greater than -3 volts. The circuit was set to -2.5 volts to provide a safety margin.

The overexcitation limiter recalibration potentiometer (J1P) had an open circuit at a dial position of about 7.5. Its connections had to be reversed to obtain proper operation.

During the pump start, the inverse timer board for J1K acted erratically. This should be checked during the unit 2 tests.

The cams for the d-c regulator need to be reset since the range was adjusted. Project personnel were planning to do this.

APPENDIX B

Test Connections

The test set frequency and voltage transducers were connected to the PT disconnect knife switch in the relay cubicle.

Exciter field current was measured at the shunt in the field breaker cubicle. Exciter field voltage was measured both at terminals in this cubicle and directly across the exciter field at the field breaker terminals for certain tests.

Main field voltage was measured at the GE (General Electric) transducer in the regulator cubicle.

The input signal to the regulator was applied at the spare input (power system stabilizer signal input) on the regulator motherboard connector.

APPENDIX C

Parameter Record

By: JCA

Date: 12-88

General Data:

Project: Flatiron

Apparatus: Unit 1 AVR

PARAMETER	AS FOUND	EXPERIMENTAL VALUES	AS LEFT	NOTES
A4P (Rate Stability Adjust)	4.9	4.0, 3 0, 2.0, 1.0	0.0 (ccw)	Full ccw
A1P (Current Limit Adjust)	5.7		4.8	275V limit
A2P (Liner Signal Adjust)	0.0		0.0	
Impedance Compensator	R - 0.0 X - 5.0		R - 0.0 X - 5.0	
Auto Regulator Lead	10.0		10.0	
" " Lag	0.0		0.0	
" " Gain	4.4		4.4	
J1P (AFFL Calibration)	10.0		4.0	Pot has open ckt. at 7.5 cw & ccw end were reversed

APPENDIX D

Flatiron Computer Model Representation
(by Hoa Vu)

The off-line model of Flatiron unit 1 was studied. The block diagram of the model is presented in figure D-1. The generator is modeled with a gain of 0.51 p.u. (per unit) and a pole at 3.6 seconds. The exciter has a gain of 5.1 V/V (volt/volt), and a pole at 1.33 seconds. The base of Efd is 92 V/p.u. If the exciter gain is changed from 5.1 V/V to 1 p.u., then the base for Vbr is 18 V/p.u. The bridge gain is 37 V/V; the regulator is 5 V/V; and the base of Vt is 54.15 V/p.u. The gains of bridge and regulator are combined and then converted to a per unit value of 550.

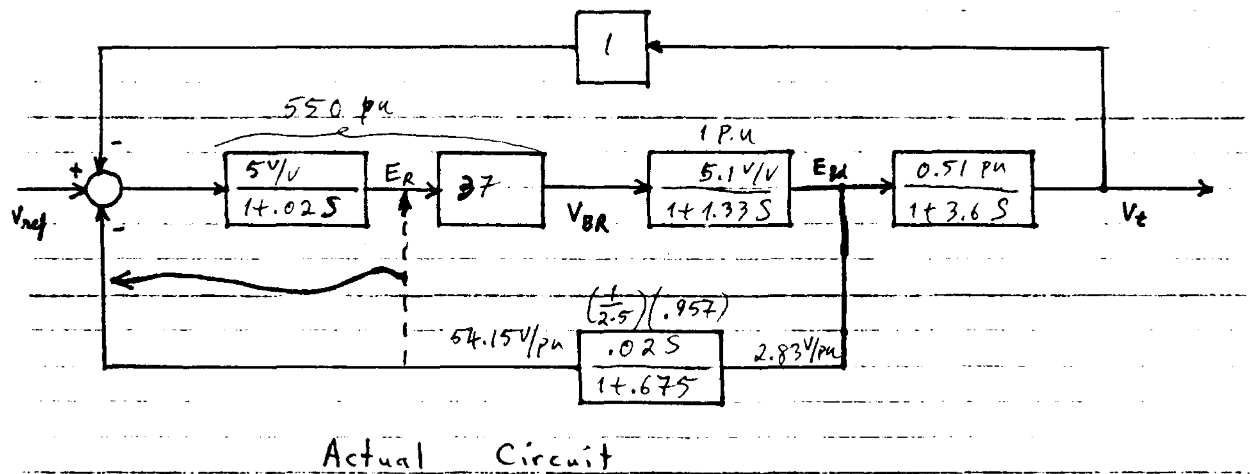
The rate feedback is modeled with a zero at d.c., gain of 0.02 p.u., and a pole of 0.675 second. The input of rate feedback circuit is from Efd transducer (ratio of 260/8). Therefore, the base at the input of rate feedback circuit is 2.83 V/p.u. The output of rate feedback is not truly connected at the reference input summer. There is a gain of 2.5 V/V from the output of the reference summer to the point where the output of rate feedback is connected. If the connection of the rate feedback is modeled at the reference summer, then there is a factor of 1/2.5 in the gain of rate feedback.

This model gives responses that match field data very well (see figs. D-2 through D-7), but there are two problems:

1. The rate feedback gain of 0.02 p.u. is converted to 0.3827 V/V. Then, take a factor of 1/2.5 out to have the gain of the circuit itself of 0.957 V/V. The rate feedback circuit has the gain of the feedback resistor [20 k (k ohm)] times the input capacitor. Therefore, the capacitor should be 47.8 microfarads. The real circuit configuration shows it should be 100 microfarads because of two 50-microfarads connected parallel. Therefore, maybe one capacitor is failed or open.

2. The rate feedback time constant of 0.675 second is calculated as the combination of two 100-k resistors paralleled with 100-k pot (min), added with 4.75 k and then multiplied with the input capacitor (50 microfarads). If the factor of the capacitor is taken out of 0.675 second, then the total resistance should be 13.5 k. If 4.75 k is subtracted from the total resistance, then there is 8.75 k left for the pot (min) paralleled with two 100 k. If the pot is at minimum, then its resistance paralleled with two 100 k should be zero. Therefore, the minimum of the pot may have 10 k ohms.

These problems can be reconciled by measuring the transfer function of the rate feedback circuit directly. This will be accomplished during the tests of unit 2.



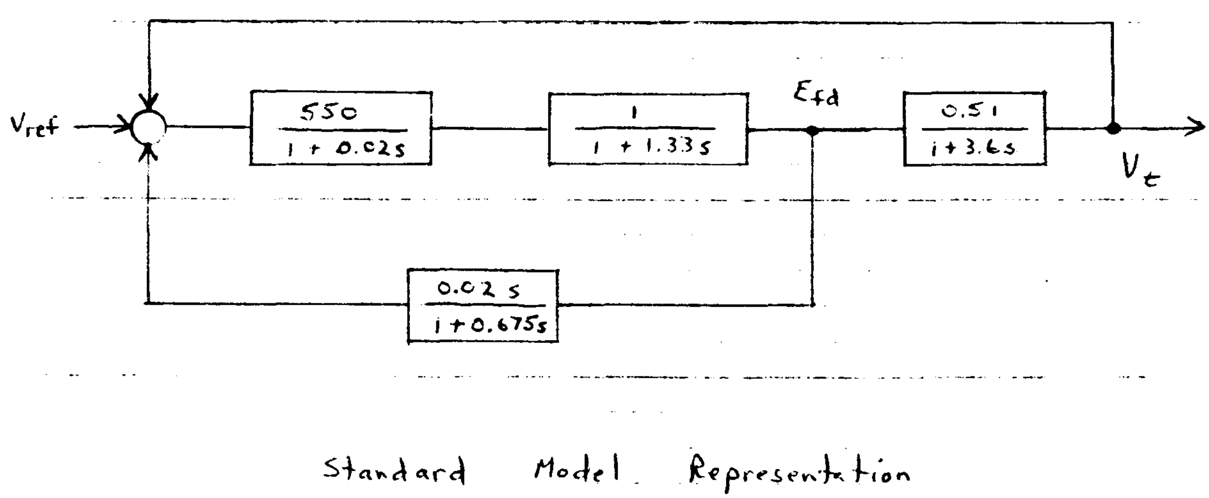


Figure D-1. - Excitation system model block diagrams.

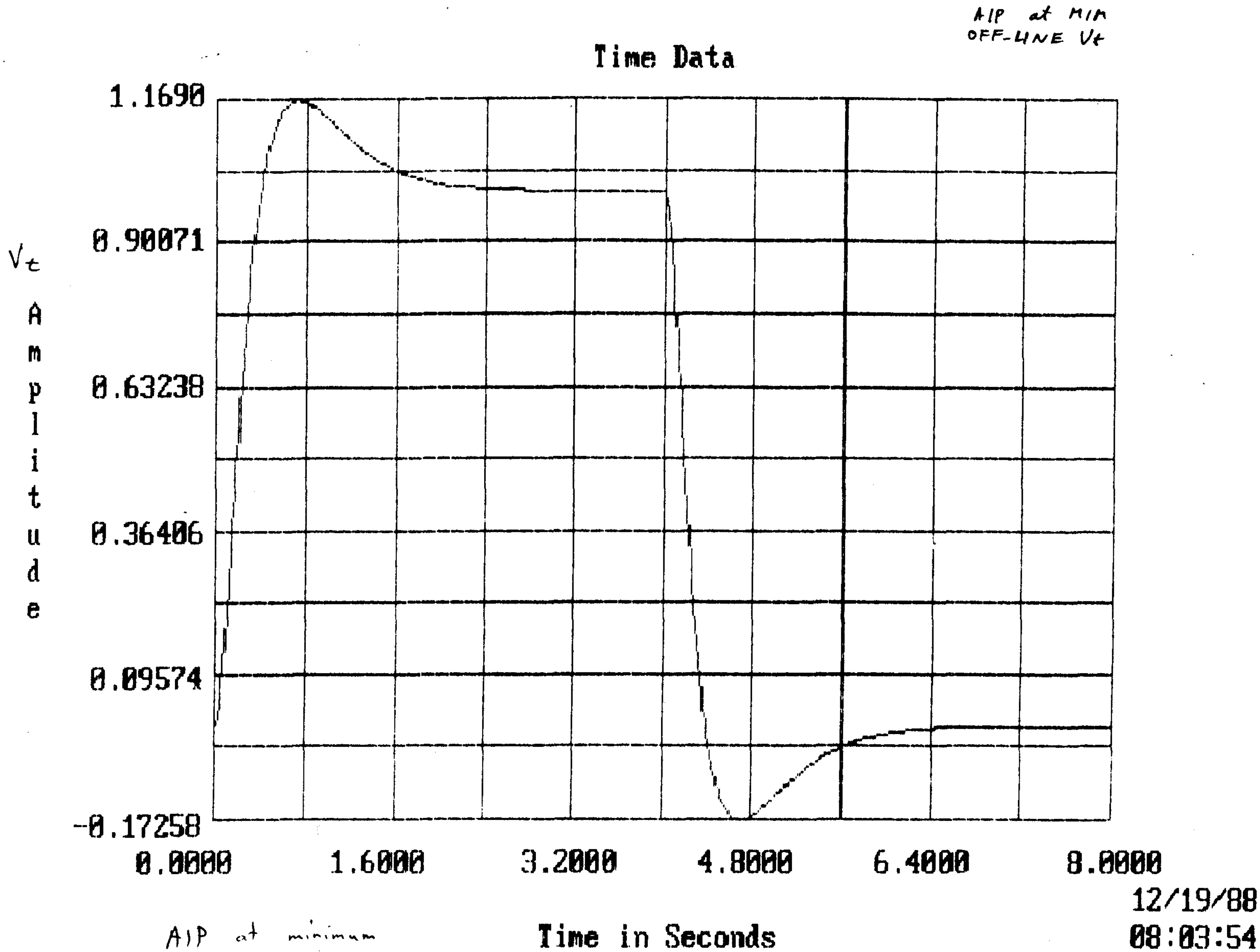


Figure D-2. - Model time domain response of terminal voltage.

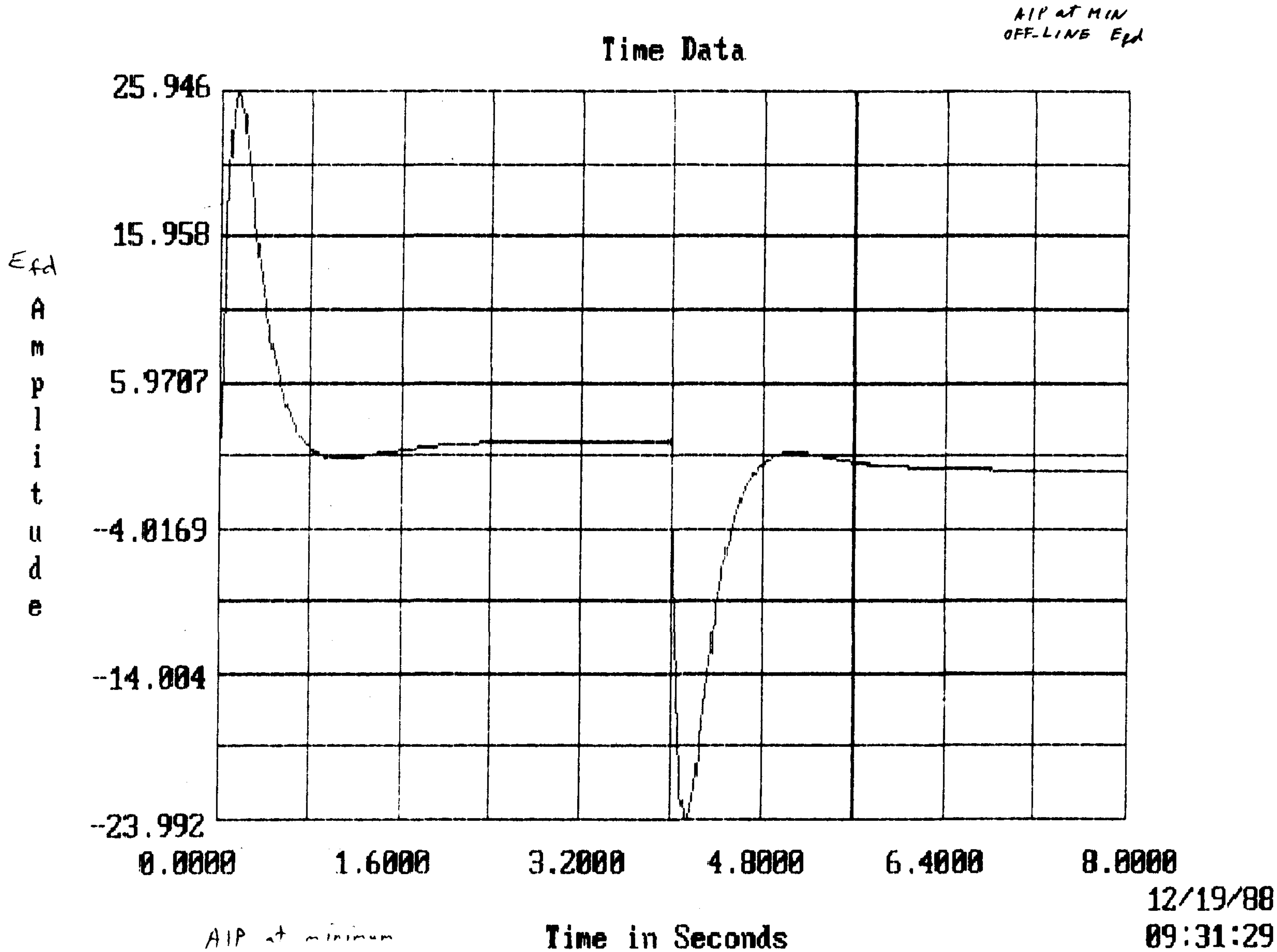


Figure D-3. - Model time domain response of field voltage.

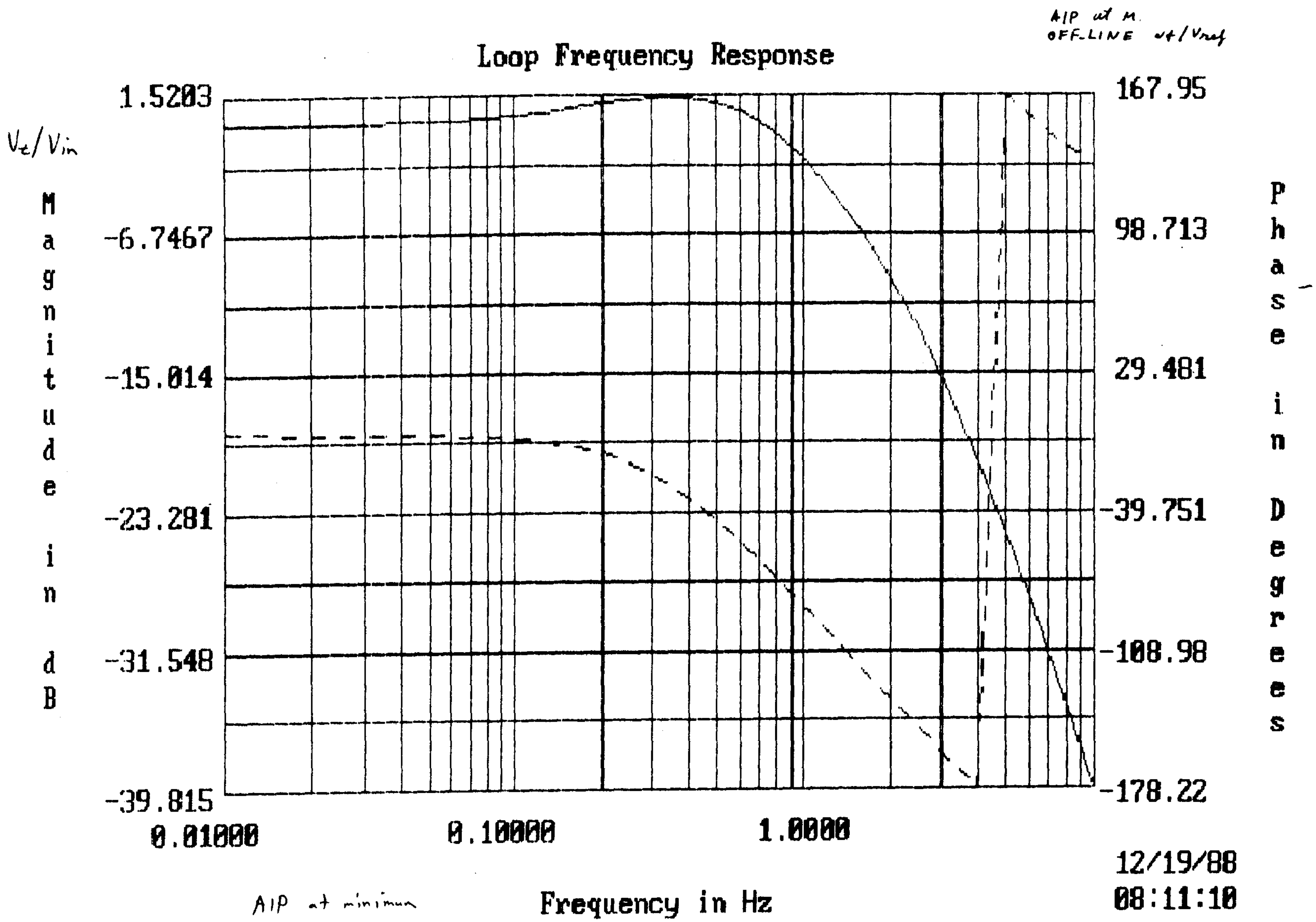


Figure D-4. - Model frequency response.

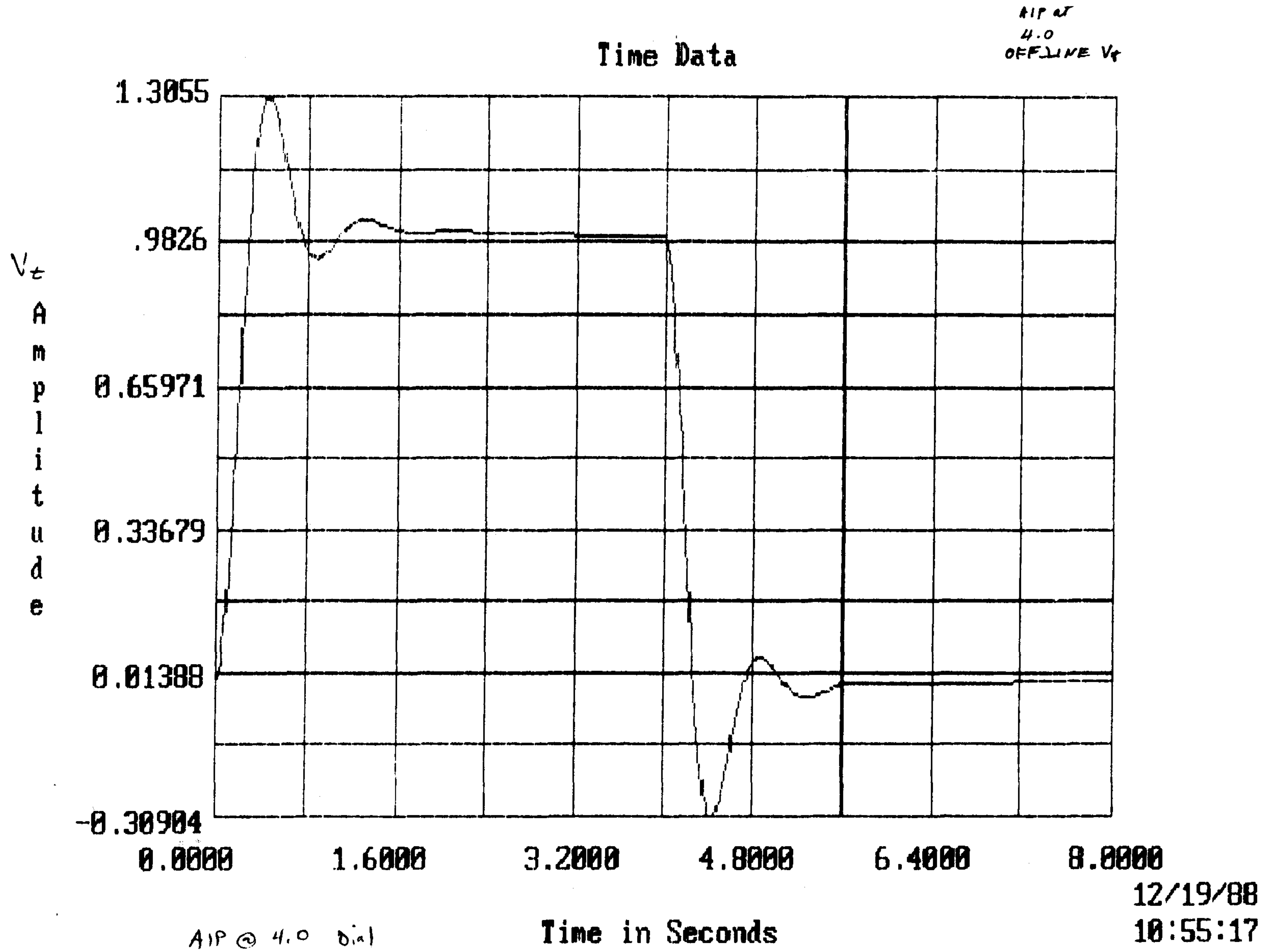


Figure D-5. - Model time domain response of terminal voltage with A1P at 4.0.

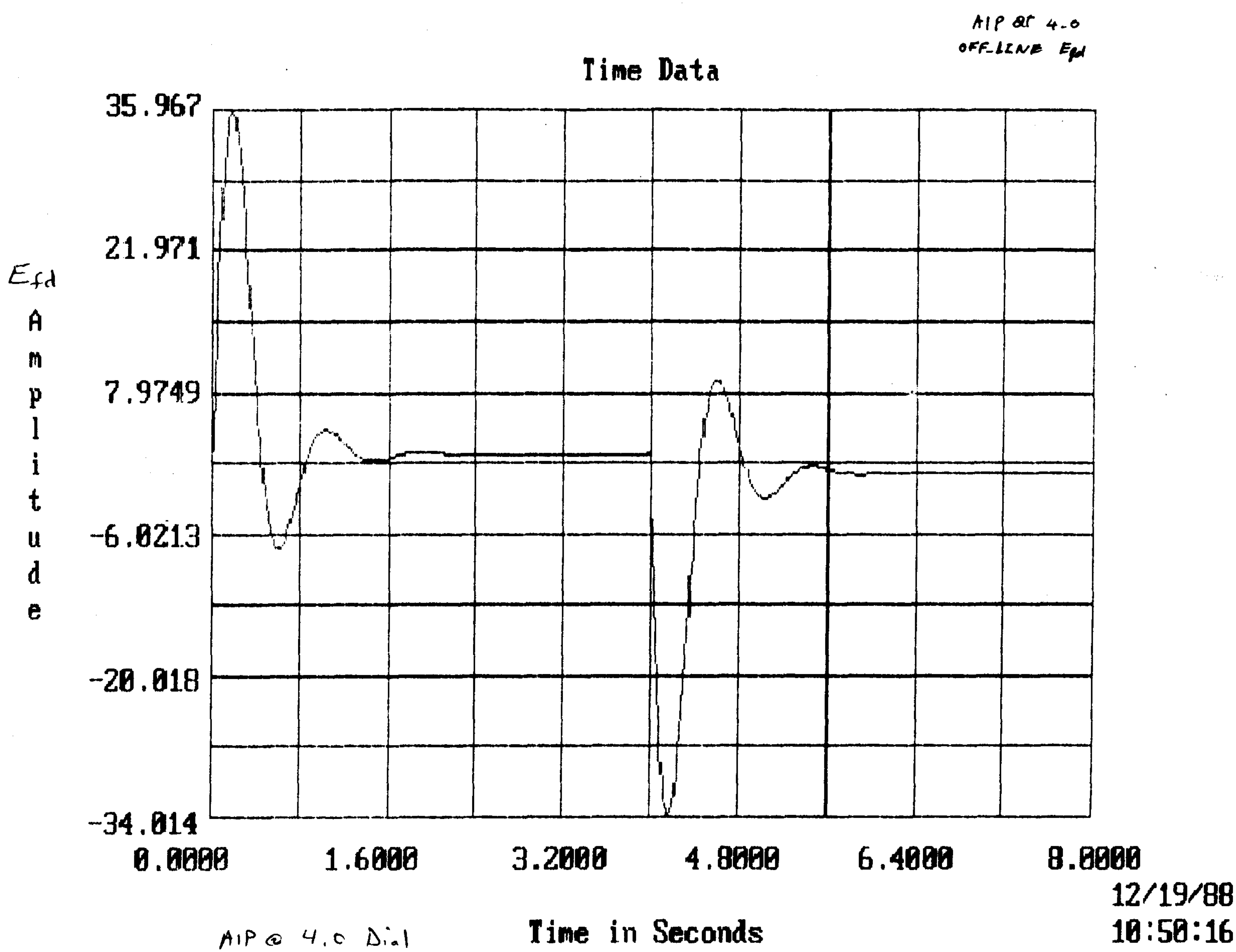


Figure D-6. - Model time domain response of field voltage with A1P at 4.0.

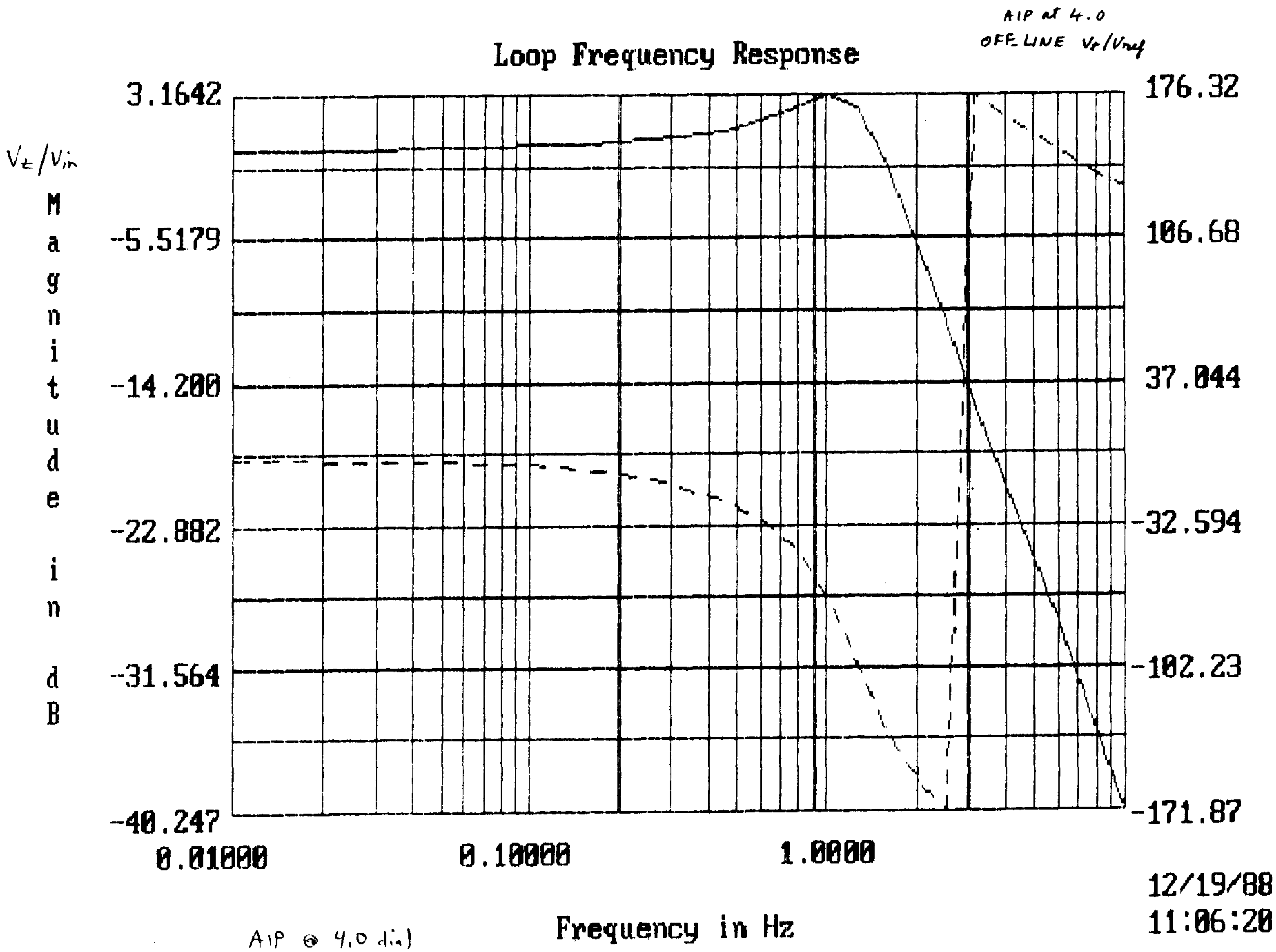


Figure D-7. - Model frequency response with A1P at 4.0.

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-7923A, PO Box 25007, Denver Federal Center, Denver CO 80225-0007.