92-09

HUNGRY HORSE UNIT 4 EXCITATION SYSTEM COMMISSIONING TEST

April 1992

U.S. DEPARTMENT OF THE INTERIOR
Bureau of Reclamation
Denver Office
Research and Laboratory Services Division
Electric Power Branch

7-2090 (4-81)
Bureau of Reclamation

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. R-92-09	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE HUNGRY HORSE UNIT 4 EXCITATION SYSTEM COMMISSIONING TEST		5. REPORT DATE April 1992 6. PERFORMING ORGANIZATION CODE D-3772
7. AUTHOR(S) George K. Girgis and J. C. Agee		8. PERFORMING ORGANIZATION REPORT NO. R-92-09
9. PERFORMING ORGANIZATION NAME AND ADDRESS Bureau of Reclamation Denver Office Denver CO 80225		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Same		13. TYPE OF REPORT AND PERIOD COVERED 14. SPONSORING AGENCY CODE DIBR

15. SUPPLEMENTARY NOTES

Microfiche and hard copy available at the Denver Office, Denver, Colorado. Ed: TPH

16. ABSTRACT

The Bureau of Reclamation conducted commissioning tests on the uprated unit 4 at Hungry Horse Powerplant, Montana, during the week of November 12, 1990. Excitation system performance tests are described.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS-- voltage regulators/ control equipment/ excitation/ power system stability

b. IDENTIFIERS-- Hungry Horse Powerplant

c. COSATI Field/Group ***COWRR:*** ***SRIM:***

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (THIS REPORT) *UNCLASSIFIED*	21. NO. OF PAGES 33
	20. SECURITY CLASS (THIS REPORT) *UNCLASSIFIED*	22. PRICE

92-09

HUNGRY HORSE UNIT 4 EXCITATION SYSTEM COMMISSIONING TEST

by

George K. Girgis
J. C. Agee

Electric Power Branch
Research and Laboratory Services Divsiion
Denver Office
Denver, Colorado

April 1992

UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

ACKNOWLEDGEMENT

The authors would like to thank the plant and project staff for their assistance during these commissioning tests.

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.

CONTENTS

TABLES

FIGURES

CONTENTS—Continued

APPENDIXES

APPENDIX FIGURES

INTRODUCTION

Hungry Horse Powerplant, Montana, houses four medium-size hydroelectric generators. Unit 4 was electrically uprated in 1990 as part of the powerplant modernization. New automatic voltage regulating equipment consisting of operational amplifier-type voltage regulating and limiting circuits, control relaying, and a thyristor-type power amplifier replaced the original voltage regulator. The original rotating main exciter was retained.

George Girgis, J. C. Agee, and Lori Rux, Denver Office; field office personnel; and a manufacturer's representative commissioned the new General Electric excitation system. This report summarizes the commissioning test results. Special conditions used during commissioning are listed in Appendix A. Test connections employed to collect data during the commissioning are documented in Appendix B. The excitation system and PSS (power system stabilizer) final parameters are listed in Appendix C. A computer model representation of the off-line excitation control system is presented in Appendix D.

CONCLUSIONS

The excitation system was successfully commissioned and the unit was placed into commercial service. Field flashing was added to provide consistent operation. The excitation system response was well damped, and the response time was reasonable for a rotating exciter system. All limiters were tested and set to appropriate levels. Problems with the upper guide bearing limited the duration of the tests and prevented a full PSS test. A full PSS test will be accomplished during commissioning of the next unit.

REGULATOR ADJUSTMENT CRITERIA

The response time of a unit with a rotating exciter is slow compared to the response time of a fully static system. Therefore, the regulator was aligned to provide an intermediate response speed while maintaining a well-damped system. This alignment resulted in moderate overshoot with the unit off-line. With the unit on-line, the response time was slow, but local mode oscillation was well damped. Unit 4 is equipped with a PSS because the unit is rated above 50 megavolt-amperes. The PSS was aligned to provide damping of the low-frequency system oscillation modes (interarea modes), because the local mode was well damped.

Unit 4 shares a step-up transformer with unit 3. Therefore, impedance compensation is required for better reactive load sharing. The impedance compensator (droop adjustment) supplied has a range of 0 to 25 percent. The impedance compensator is usually set at 5 to 10 percent, providing voltage regulation ranging from 5 to 10 percent inside the machine terminals. A higher percentage of compensation provides a faster response time and wider bandwidth, but also causes larger steady-state error and higher overshoot. Five-percent compensation was selected for the Hungry Horse units.

RATINGS AND CALIBRATIONS

Unit 4 is rated at 112.632 megavolt-amperes and 0.95 power factor. Rated voltage is 13.8 kilovolts and rated current is 4712 amperes. The unit obtains full megavolt-ampere output with real power at 107 megawatts and reactive power at 35.2 megavars.

The terminal voltage potential transformer (PT) ratio for unit 4 is 120:1 and the line current transformer (CT) ratio is 5000:5. Therefore, rated PT secondary voltage is 115 volts and the rated CT secondary current is 4.712 amperes.

The base field current required to produce rated terminal voltage on the generator air gap line is 700 amperes (see fig. 1). The field resistance at 25 °C is 0.1577 ohm. Therefore, the base generator field voltage is 110 volts. The field voltage transducer in the regulator (at terminal 4 of terminal board JVT) has a calibration of –5 volts output at 225 volts input. This signal has a base of –2.6 volts per unit.

The base field current required to produce 110 volts out of the rotating exciter air gap line is approximately 14 amperes (see fig. 2). The exciter field resistance at 25 °C is 1.05 ohms. Therefore, the base exciter field voltage is approximately 14.7 volts.

At rated load (107 megawatts, 35.2 megavars), the generator field current is approximately 1220 amperes, and the generator field voltage is 192 volts. Therefore, the exciter field current is approximately 28 amperes at 29.4 volts. Because of operating limitations during these initial tests, these values are calculated and/or obtained from design data. These values are based on a generator field winding temperature of 25 °C.

Allowing for a generator field winding temperature of 70 °C, the resulting generator field voltage would be approximately 226 volts. This value will be used as rated to determine the limiter and relay coordinations.

UNIT OFF-LINE PERFORMANCE

The automatic voltage regulator was tuned by adjusting the rate feedback potentiometer (A4P) to a dial setting of 9.0. An investigation undertaken to determine the reason for this abnormally high A4P setting revealed reversed wiring of the A4P potentiometer. A manufacturer's representative corrected the wiring, which resulted in a final A4P potentiometer setting of 1.6 on the dial.

The automatic voltage regulator was set with the gain potentiometer at 6.0, lead potentiometer at 10.0, and lag potentiometer at 0.0 on the dials. These lead/lag settings removed the effect of the transient gain reduction compensation from the regulator (controller). Therefore, compensation was provided by connecting and tuning the rate feedback stabilization circuit.

Systems using rotating exciters normally use rate feedback stabilization. Fully static systems employ transient gain reduction compensation.

Small-signal step responses of the closed-loop automatic voltage regulating system with the unit off- line at rated voltage and speed are shown in figure 3. The 10- to 90-percent terminal voltage rise time is approximately 0.4 second and overshoot is about 18 percent. The control system performance is well damped with one overshoot and no apparent oscillation.

A Bode plot of the automatic voltage regulating system with the unit off-line is shown in figure 4. The 3-decibel bandwidth is approximately 0.88 hertz and the peak magnitude is less than 2 decibels above the steady-state gain. These values indicate a moderate-speed, well-damped control system.

The automatic regulator bias potentiometer was adjusted to provide 85 percent of the rated terminal voltage with the voltage adjuster (90P) at minimum position. The range potentiometer was set to provide 110 percent of rated terminal voltage with the automatic regulator voltage adjuster (90P) at maximum position. This setting allows the voltage regulator to vary the off-line unit voltage between 85 and 110 percent of rated voltage. This unit normally operates at a terminal voltage below the rated value. Therefore, the cam switches for pre-positioning of the 90P and the cam switches for the nominal voltage set point indicating lights were set accordingly.

The manual regulator for this unit is a closed-loop controller that controls generator field voltage. The gain, lead, and lag settings are set to produce the off-line small-signal step response shown in figure 5. These parameters are adjusted with 3/4-turn trim pots that do not have dial indication. The 10- to 90-percent rise time of E_{fd} (main field voltage) is approximately 0.4 second, with no overshoot.

The manual regulator bias potentiometer was adjusted to produce 75 percent of rated terminal voltage (machine off-line at rated speed) with the voltage adjuster (70P) at minimum position. The generator field voltage (E_{fd}) was 85 volts at this setting. The range potentiometer was set to produce 100 percent of rated generator field voltage (machine on-line, rated load) with the manual regulator voltage adjuster (70P) at maximum position. This setting should correspond to a field voltage of 226 volts. The field voltage of 226 volts was not verified because of operating limitations imposed by upper guide bearing problems; however, the method used should produce this value (226 volts).

UNIT ON-LINE PERFORMANCE

On-line performance tests are usually conducted at full load, unity power factor. However, operating limitations caused by upper guide bearing problems limited the test load to 59 megawatts. This reduced megawatt level affected the step response and frequency response only slightly, but caused difficulty in determining the existence of local mode oscillation damping problems.

The automatic voltage regulator did not require additional adjustment for on-line operation. The small-signal step response of the closed-loop automatic voltage regulating system with the unit on-line at 59 megawatts and unity power factor is shown in figure 6. The 10- to 90-percent rise time is approximately 1.1 second, and overshoot is less than 5 percent. The control system performance is well damped, with no apparent oscillation.

A Bode plot of the automatic voltage regulating system with the unit on-line at 59 megawatts is shown in figure 7. The 3-decibel bandwidth is approximately 0.34 hertz. The peak magnitude is less than 0.5 decibel above the steady-state gain. These values indicate a moderate-speed, well-damped control system. Local mode oscillation is not apparent because of the lower operating condition (59 MW) and light plant loads encountered this time of year. However, data from previous alignments at this powerplant show the local mode oscillation to be well damped. Local mode frequency was approximately 0.9 hertz during the previous tests.

The impedance compensator was set to 5 percent on the reactance potentiometer. This setting provides voltage regulation approximately 5 percent inside the machine terminals. The impedance compensator was tested with units 3 and 4 on-line. Both units were loaded to 12 megawatts, unity power factor. The excitation was adjusted on unit 3 to provide 20 megavars out, and the unit 4 response was recorded. This process was then repeated with unit 4. Test results are summarized in table 1.

Table 1. – Impedance compensator test data.

Unit	Pretesting	Unit 3 adjusted to provide Mvars out	Unit 4 adjusted to provide Mvars out
3	12 MW 0 Mvars	12 MW 20 Mvars out	12 MW 14 Mvars in
4	12 MW 0 Mvars	12 MW 11 Mvars in	12 MW 20 Mvars out

POWER SYSTEM STABILIZER PERFORMANCE

The power system stabilizer was adjusted to provide more gain for system oscillation damping because the automatic voltage regulating system was adjusted for a slow response time. The slow response time of the regulator is caused by the rotating exciter. In this case, the PSS would not provide significant damping to the local mode oscillation because the voltage regulating system is too slow to influence this mode. To provide more gain for system oscillation damping, the machine terminal frequency was selected for the input to the PSS (the PSS input can be either terminal frequency or internal machine frequency). The terminal frequency input was accomplished by opening the CT shorting switch at the PSS input panel and placing a jumper across the L1X reactor transformer secondary.

The PSS lead time constants were set to 0.4 second (corner frequency of 0.4 hertz). Therefore, dials TCT2F and TCT4 on the signal conditioning card were set to 1.8 on the dial. The PSS lag time constants were set to 0.04 second (corner frequency of 4.0 hertz). Therefore, dials TCT3 and TCT5 on the signal conditioning card were set to 3.0 on the dial.

The gain dial on the PSS was set to 0.12, which corresponds to a gain of 1.6 volts per volt (V/V). This setting provides a stabilizer gain of approximately 1.9 per unit. The gain was set conservatively because of operating limitations which prevented the performance of a full PSS test series. Final alignment of the PSS will be performed during the commissioning of unit 3.

The PSS Washout & Output limits were adjusted to 5.5 on the dial, which causes limiting at approximately 5.0 volts. The Washout and Output time constant was set to 9.1 on the dial, which provides a time constant of approximately 32 seconds. The ceiling sensing delay was adjusted to 3.0 on the dial, providing approximately an 11-second time delay. The ceiling sensing positive and negative thresholds were set to 6.0 on the dial, which disables the PSS if the output exceeds approximately 5.5 volts.

The under/over voltage detection board is a limiter used to remove the PSS from service whenever the terminal voltage deviates from a prescribed range (disables the PSS output). The range was set between 90 and 108 percent of rated terminal voltage. Operation of the under/over voltage detector was verified by lowering the terminal voltage, off-line, to 90 percent of rated and using the frequency analyzer to inject a 1-volt sine wave into the regulator through the PSS. The terminal voltage was monitored, and limiting on the negative side of the sine was observed. This process was then repeated for the positive limit. The results of this test are illustrated in figure 8.

AUTOMATIC LIMITER PERFORMANCE

The Hungry Horse regulators are equipped with a V/Hz (volts per hertz) limiter, a URAL (Under Reactive Ampere limiter), and a maximum excitation limiter. These limiters work in conjunction with the automatic voltage regulator and take control under certain conditions. They do not function in the manual regulator mode.

The V/Hz limiter limits the ratio of terminal voltage to speed. The frequency of the terminal voltage signal is used to monitor the machine speed. The speed is converted to a voltage. The limiter uses this voltage along with a terminal voltage signal to determine the V/Hz ratio. The V/Hz limiter, in conjunction with the automatic regulator, maintains the ratio of terminal voltage to speed.

The V/Hz limiter was set to a ratio of 2.12, which corresponds to 110 percent of rated terminal voltage at 60 Hz. The V/Hz calibration was adjusted to produce 6.0 volts at 60.0 hertz, with a variation of 1 volt per 10 hertz. Limiter performance was verified by increasing the terminal voltage to 110 percent of rated and then lowering speed. The V/Hz limiter maintained a ratio of 2.12 volts per hertz (± 0.01) at all values of speed as shown in table 2.

Table 2. – V/Hz limiter data.

PT (volt)	126.5	120.7	114.3	103.0
Speed (Hz)	59.9	57.0	53.9	48.7
Ratio	2.11	2.12	2.12	2.12
Ratio in P.U.	1.102	1.105	1.106	1.104

The URAL limits the level of megavars flowing into the generator. The URAL monitors the three-phase terminal voltage (line to neutral) and the phase B line current to determine the level of underexcitation (megavars into the machine). The URAL limits the megavars flowing into the machine depending on the megawatts and terminal voltage. The URAL will permit a higher level of megavars to flow into the generator if terminal voltage is raised or load is lowered. Three points at which the URAL becomes active are documented in table 3 (the test was conducted at a terminal voltage of 13.2 kilovolts). Coordination of the URAL curve with the generator capability curve is shown in figure 9.

Table 3. – URAL data.

MW	75	91	100
Mvars in	47	32	23

The maximum excitation limiter has two functions. First, it provides a fixed instantaneous exciter field current limit by way of potentiometer A1P. Potentiometer A1P allows a high excitation level (typically 150 percent) for a short time. Second, it provides an inverse time characteristic, after which the excitation limit is recalibrated and reduced to the rated value. This unit cannot be excited to 150 percent of rated because of PPT (power potential transformer) current limitations. The secondary PPT current limit is 48 amperes alternating current, which corresponds to an output of 65 amperes direct current from the SCR bridge (48 multiplied by 1.35, bridge factor), producing approximately 290 volts out of the rotating exciter, which corresponds to a maximum excitation limit of 128 percent.

The primary limit on exciter field current is set to 65 amperes by way of an A1P potentiometer dial setting of 4.4. This current corresponds to approximately 304 volts out of the rotating exciter (unloaded exciter startup), and produces 290 volts with the exciter at rated load. This setting limits short term generator rated field voltage to 128 percent.

The maximum excitation limiter recalibrating potentiometer (J1P) works in conjunction with the maximum excitation limiter potentiometer (A1P). The J1P potentiometer is set to 6.0 on the dial. This setting limits exciter field current to approximately 45 amperes, which produces rated generator field voltage (226 volts).

Circuit board J2CB is an inverse time characteristic device which monitors generator field voltage. If the generator field voltage remains at 120 percent for approximately 25 seconds, this circuit board will operate relay J1K. Operation of relay J1K will place J1P into the maximum excitation circuitry and reduce the excitation level to rated value. Circuit board J2CB is adjusted to operate at 230 volts with a time wiper of 1.0 volt (inverse time characteristic).

If the maximum excitation recalibration limiter does not function properly, and the rotating exciter output remains above 271 volts for 29 seconds (inverse time characteristic), circuit board J1CB will operate relay J2K, initiating a transfer to the manual regulator at the auto tracked position. For this reason, the maximum position of the manual regulator is set to the rated value of generator field voltage. Circuit board J1CB is set to operate at a field voltage of 235 volts (9 volts above rated), with a time wiper of 1.2 volts to properly coordinate with circuit board J2CB.

RELAYING COORDINATION

The V/Hz relay will operate the generator lockout (86G) whenever the ratio of terminal voltage to speed exceeds the set point for a period longer than the time delay. The V/Hz relay is set to a ratio of 2.2 with a 13-second time delay. A ratio of 2.2 corresponds to 115 percent of rated terminal voltage at 60 Hz.

The over excitation protection (OEP) device is an inverse time characteristic device similar to the J1CB and J2CB circuit boards. This device monitors generator field current. If the current remains above the OEP set point for the required time, the OP2 relay initiates a transfer to the manual regulator. If the problem persists for 5 seconds after the initiation of the transfer, the OP2 relay will operate relay OP2X which initiates the 86G (generator lockout relay). The OEP circuit board is set to a current level which corresponds to a voltage that is approximately 14 volts above rated generator field voltage (this corresponds to a generator field voltage of 240 volts with the field winding at 70 °C, and a generator field current of 1298 amperes, 106 percent of rated). The time wiper on the OEP board is set at 2.0 volts. These coordination levels, along with the J1CB, J2CB, A1P, and generator field winding short time thermal capability curve, are shown in figure 10. The relay and limiter settings are summarized in table 4.

Table 4. – Relay and limiter settings.

Device	Settings	Time delay
A1P	Dial setting of 4.4 I_{ex}= 65amps	None
J1P	Dial setting of 6.0 I_{ex}= 45 amps	None
J2CB	E_{fd}= 230 V Time wiper = 1.0 V	Inverse time
J1CB	Ef_{d} = 235 V Time wiper = 1.2 V	Inverse time
OEP/OP2	E_{fd} = 240 V I_{fd} = 1298 A Time wiper = 2.0 volt	Inverse time
OEP/OP2X	Same as OP2 with 5-s delay	Inverse time
V/Hz limiter	Ratio of 2.12	None
V/Hz relay	Ratio of 2.2	13.0 s

START-UP PERFORMANCE

The residual terminal voltage at the PT secondary was approximately 7.0 volts. The residual was not large enough to operate the V/Hz limiter properly, which prevented the automatic regulator from building voltage consistently. Field flashing was employed to alleviate the problem (field flashing is not normally employed when the excitation system is powered from station service, as it is in this case). Voltage buildup in the automatic regulator mode was accomplished consistently after field flashing was enabled. Typical startup in the automatic regulator mode is shown in figure 11. The generator field voltage was limited to 304 volts (A1P dial of 4.4). Terminal voltage overshoot was only 2.5 percent.

LOAD REJECTION PERFORMANCE

Load rejections were executed at 23, 64, and 101 megawatts, 35 megavars by tripping the unit breaker. This method allows the unit to recover to a speed-no-load condition, thus verifying the phase back capability of the regulator. Speed and voltage recovered to normal operating values after the load rejections. The 101-megawatt, 35-megavar load rejection is shown in figure 12. Load rejection data are summarized in table 5.

Load rejections by way of the lockout relay were not performed. However, the operation of the fixed phase back circuits was verified by operating the 9 and 59Y relays manually. Satisfactory phase back and voltage decay were observed during these tests.

Table 5. – Load rejection data.

Loads	Overspeed (%)	Prerejection voltage (%)	Overvoltage (% above pre-rejection voltage)
23 MW; 0.0 Mvar	105	97.3	101
64 MW; 0.0 Mvar	111	97.3	102.7
101 MW; 35 Mvar	130	97.3	114

APPENDIX A

Special Conditions

SPECIAL CONDITIONS

The following special conditions were useful during the tests. The tests began with all these special conditions in force:

- Preset positioning of the 70 and 90 adjusters was disabled at contacts 7, 8, 11, and 12 of 41R1 relay (located in the field breaker enclosure).

- Transfer to automatic regulator was blocked by lifting wire ERT at T108.

- Bridge voltage was fed back to field voltage transducer instead of the field voltage (for initial voltage buildup).

- The J1K socket was pulled, thus activating J1P current limiter action and limiting the field voltage to the minimum value (approximately rated condition).

- The following cards were pulled: V/Hz, Current Compensation, URAL, AC Regulator, and all cards on the power system stabilizer rack.

APPENDIX B

Test Connections

TEST CONNECTIONS

The test set voltage and frequency transducers were connected to the PT voltage on the knife switch in the regulator cabinet.

The exciter field voltage was measured by way of an isolation amplifier connected at terminals K77-K80 in the relay cabinet. The isolation amplifier was used with unity gain and 2.5 percent divider, giving 5 volts output for 200 volts input (40 volts per volt transducer).

The main field voltage was measured by way of an isolation amplifier connected at terminals T6-T7 in the regulator cabinet. The isolation amplifier was also used with unity gain and 2.5 percent divider, again giving 5 volts output for 200 volts input (40 volts per volt transducer).

The input signal to the automatic regulator card was connected through the IN1 jack of the washout & output card in the power system stabilizer rack.

The input signal for the manual regulator step response was connected at terminals HM19-HM20.

APPENDIX C

Final Parameter Record

FINAL PARAMETER RECORD

Regulator parameters		Settings
Auto reg:	Gain	6.0
	Lead	10.0
	Lag	0.0
A1P		4.4
A2P		0.0
A4P		1.6
J1P		6.0
60 MR		15.0 s
60ML		15.0 s
Impedance comp		5 %

PSS parameters	Settings
Signal Cond:	
TCT2V	0.0
TCT2F	1.8
TCT3	3.0
TCT4	1.8
TCT5	3.0
Washout & output:	
Neg limit	5.5
Pos limit	5.5
Gain K	0.12
TCT1	9.1
Ceiling sensing:	
Delay	3.0
Pos limit	6.0
Neg limit	6.0

APPENDIX D

Computer Model Representation

COMPUTER MODEL REPRESENTATION

The off-line model of Hungry Horse unit 4 excitation control system was studied. The block diagram of the modeled system on a per unit basis is shown in figure D-1. All values used for modeling purposes are at a generator field temperature of 35 °C, which will provide a better match to actual field data obtained at this field temperature.

The generator was modeled with a gain of 0.43 per unit and a pole at 3.5 seconds. The exciter was modeled with a gain of 1.0 per unit and a pole at 2.0 seconds. The generator and exciter data were obtained from the saturation curves and manufacturer design data.

The bridge gain is calculated by multiplying the bridge supply voltage power potential transformer line-to-line voltage by the full-wave bridge factor of 1.35, and dividing by the maximum output of the automatic regulator. The bridge gain is 23.1 volts per volt. The regulator gain is calculated to be 6.37 (from the circuit schematic). The gain of the bridge and regulator can be combined and converted to a per unit value. Multiplying this combined value by the E_{fd} (generator field voltage) base and dividing by the regulator input V_t (terminal voltage) base yields the per unit gain. The V_t base at the input to the regulator is approximately 54 volts per unit, and the E_{fd} base is 117 volts per unit. Therefore, the per unit gain of the regulator and bridge is approximately 320.

The rate feedback circuit is measured to be a differentiator with a gain of 2.95 volts per volt and a pole at 1.8 seconds. The input of the rate feedback circuit comes from the E_{fd} transducer (ratio of 225/5). Therefore, the base at the input of the rate feedback circuit is 2.6 volts per unit. The output of rate feedback is not truly connected at the reference summer as represented in standard models. A gain of 3.18 volts per volt (one-half of the regulator gain) occurs between the reference summer output and the rate feedback connection point. If the rate feedback connection is modeled at the reference summer then a gain factor of 1.0/3.18 occurs in the rate feedback gain. The rate feedback gain of 2.95 volts per volt becomes 0.93 volts per volt when transposed to the reference summer. Multiplying by the transducer base and then dividing by the terminal voltage base converts the 0.93 volts per volt gain to 0.05 per unit.

The step and frequency responses of the modeled system are shown in figures D-2 and D-3, respectively. The step response has approximately 16 percent overshoot and a 10- to 90-percent rise time of 0.38 second. From field data, the system step response has approximately 18 percent overshoot and a rise time of 0.4 second. The frequency response of the modeled system has a 3-decibel bandwidth of approximately 0.87 hertz. The actual system has a 3-decibel bandwidth of about 0.88 hertz. These values indicate a good match between the model and the actual system. Responses found in the model will vary slightly from those found in the actual system because the model is a linearization of the actual system. Also, the model does not include every detailed parameter of the actual system.

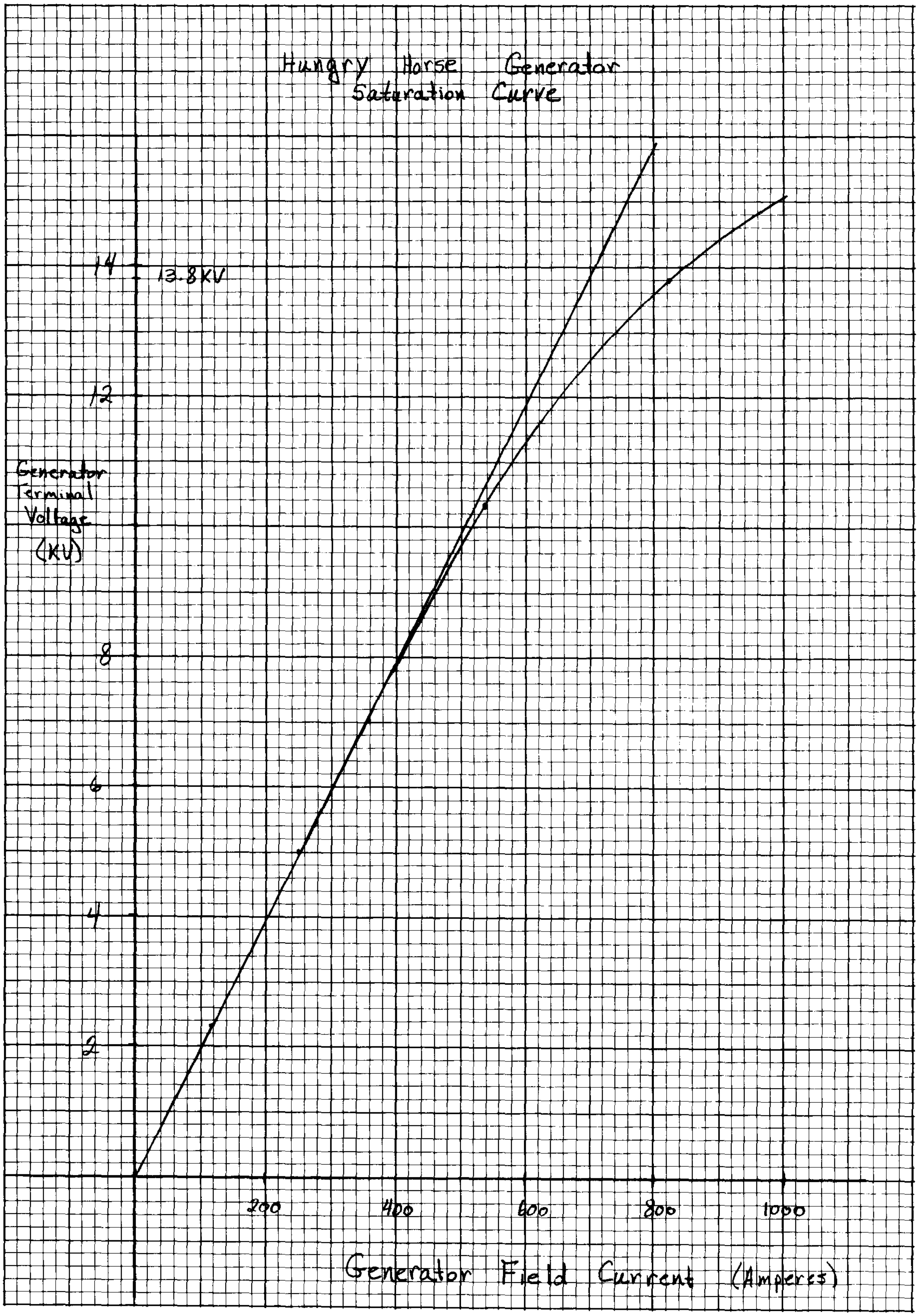

Figure 1. – Generator saturation curve.

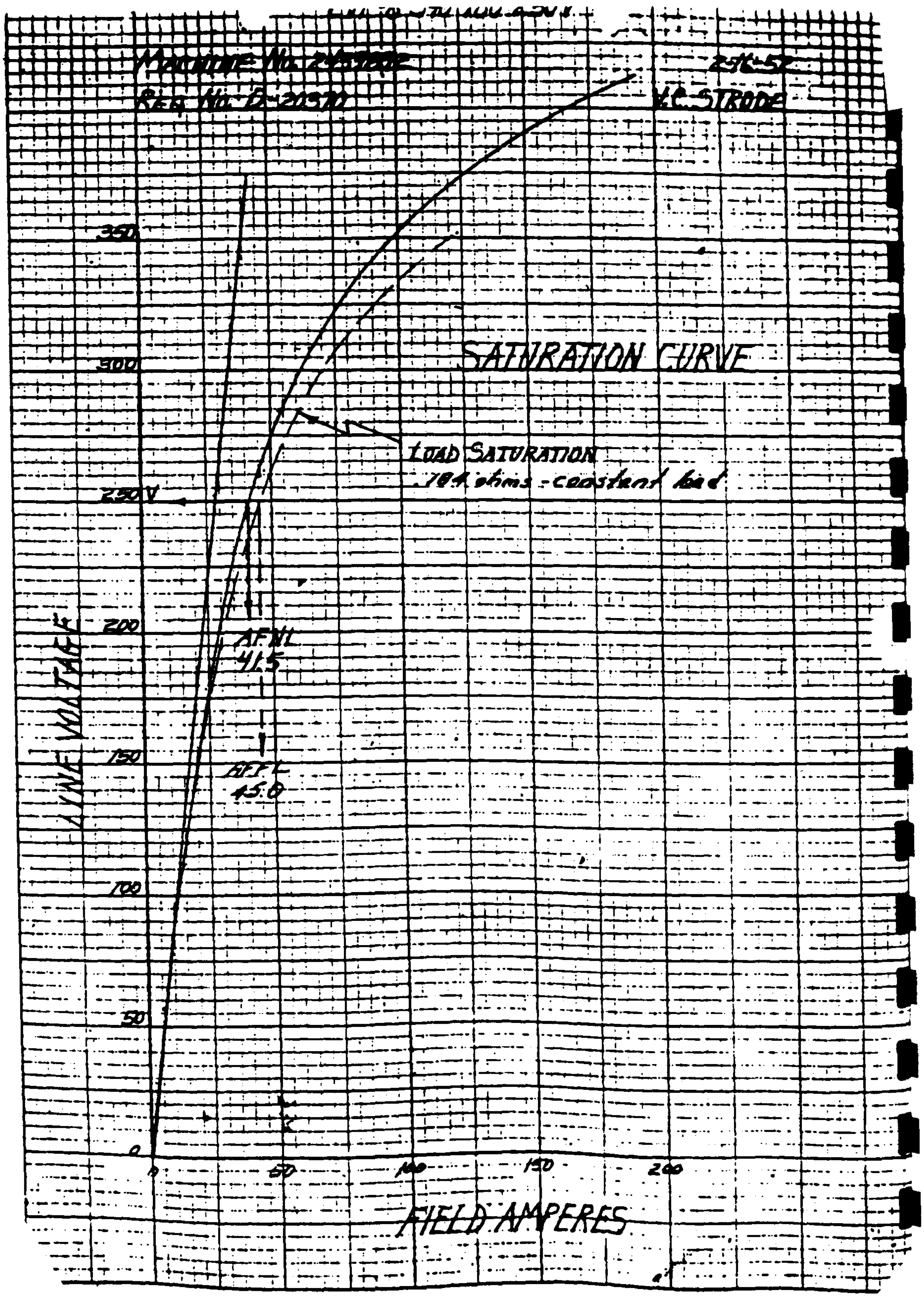

Figure 2. – Exciter saturation curve.

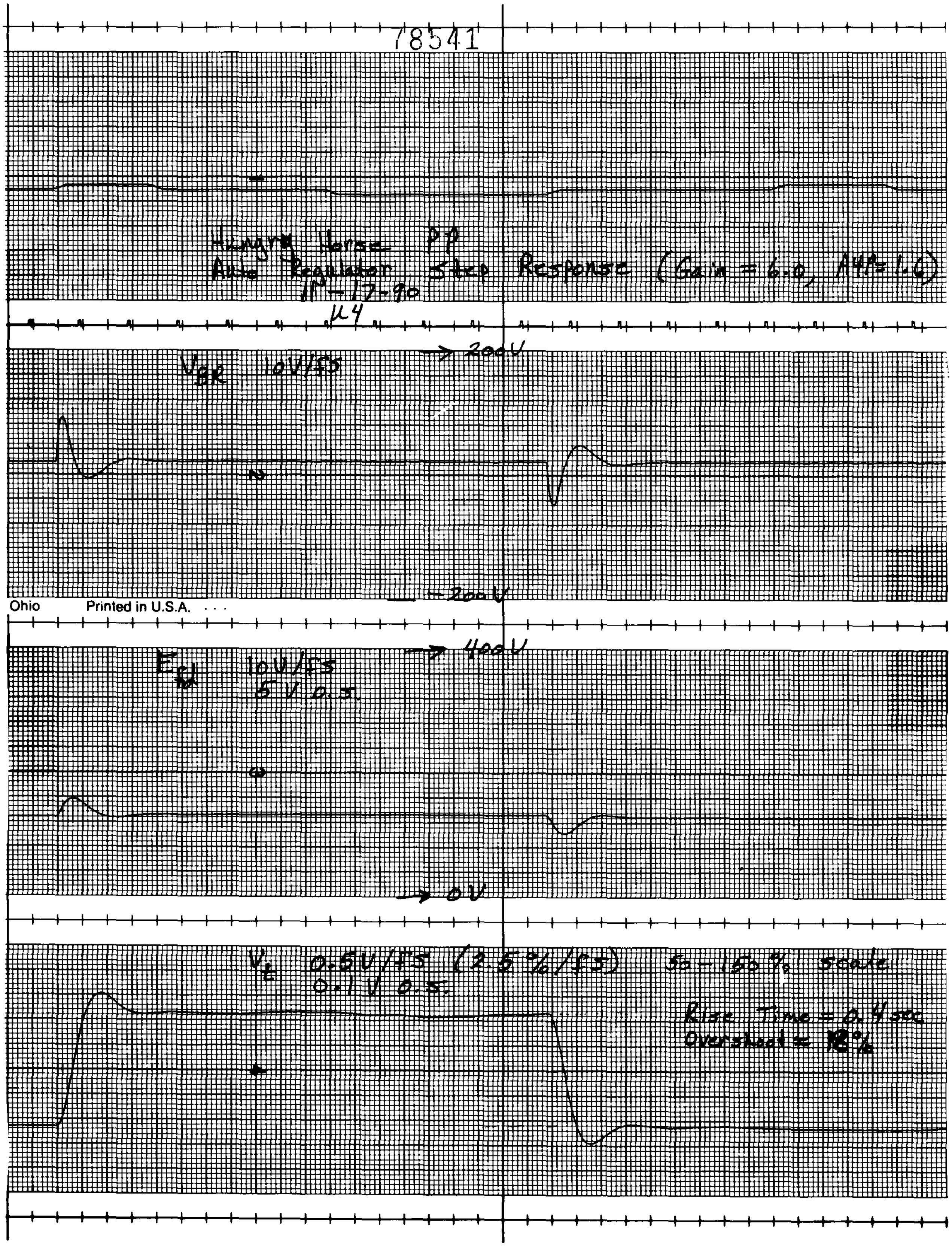

Figure 3. – Small signal step response of the off-line automatic voltage regulating sytem.

46 5490

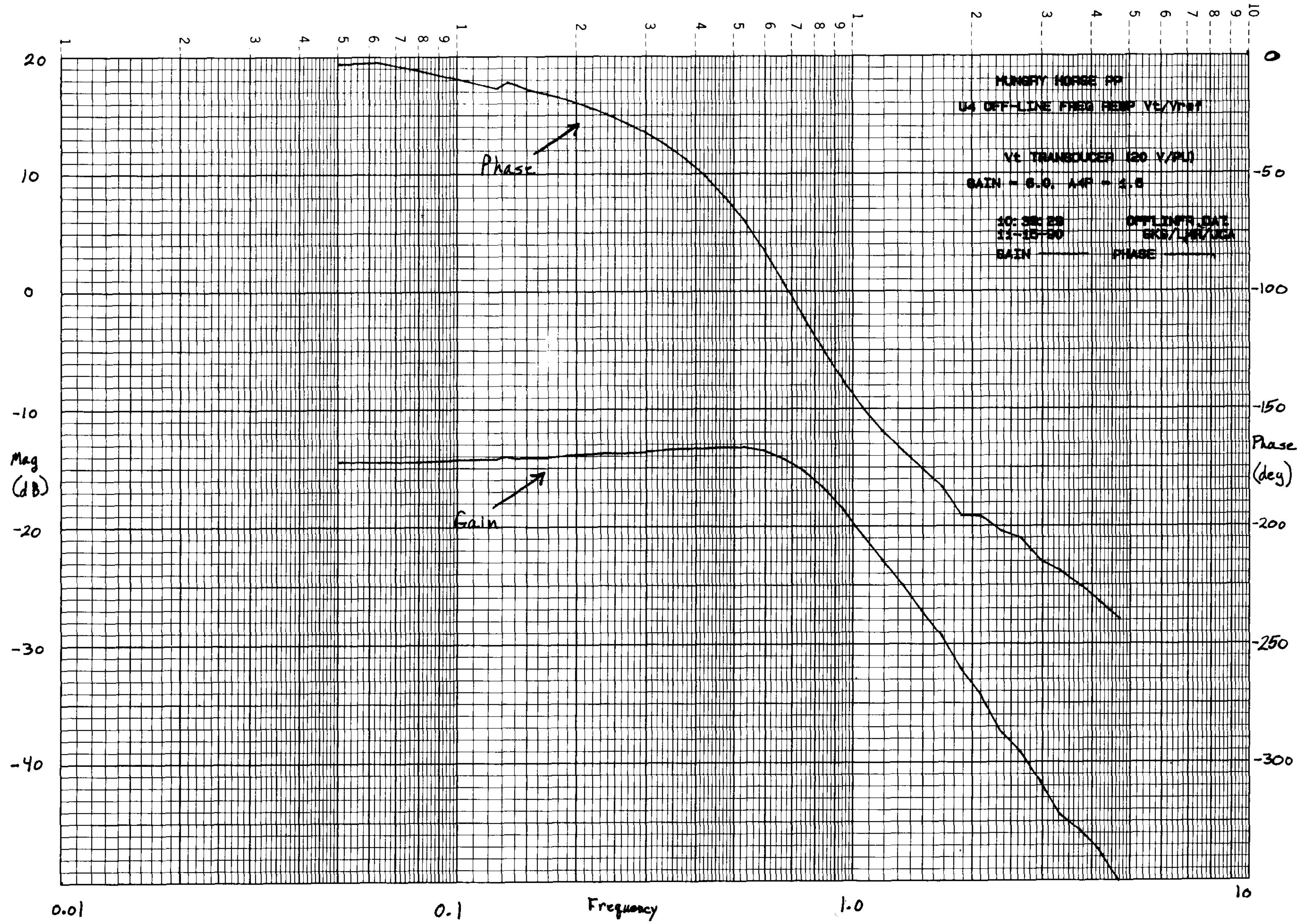

Figure 4. – Bode plot of the off-line automatic voltage regulating system.

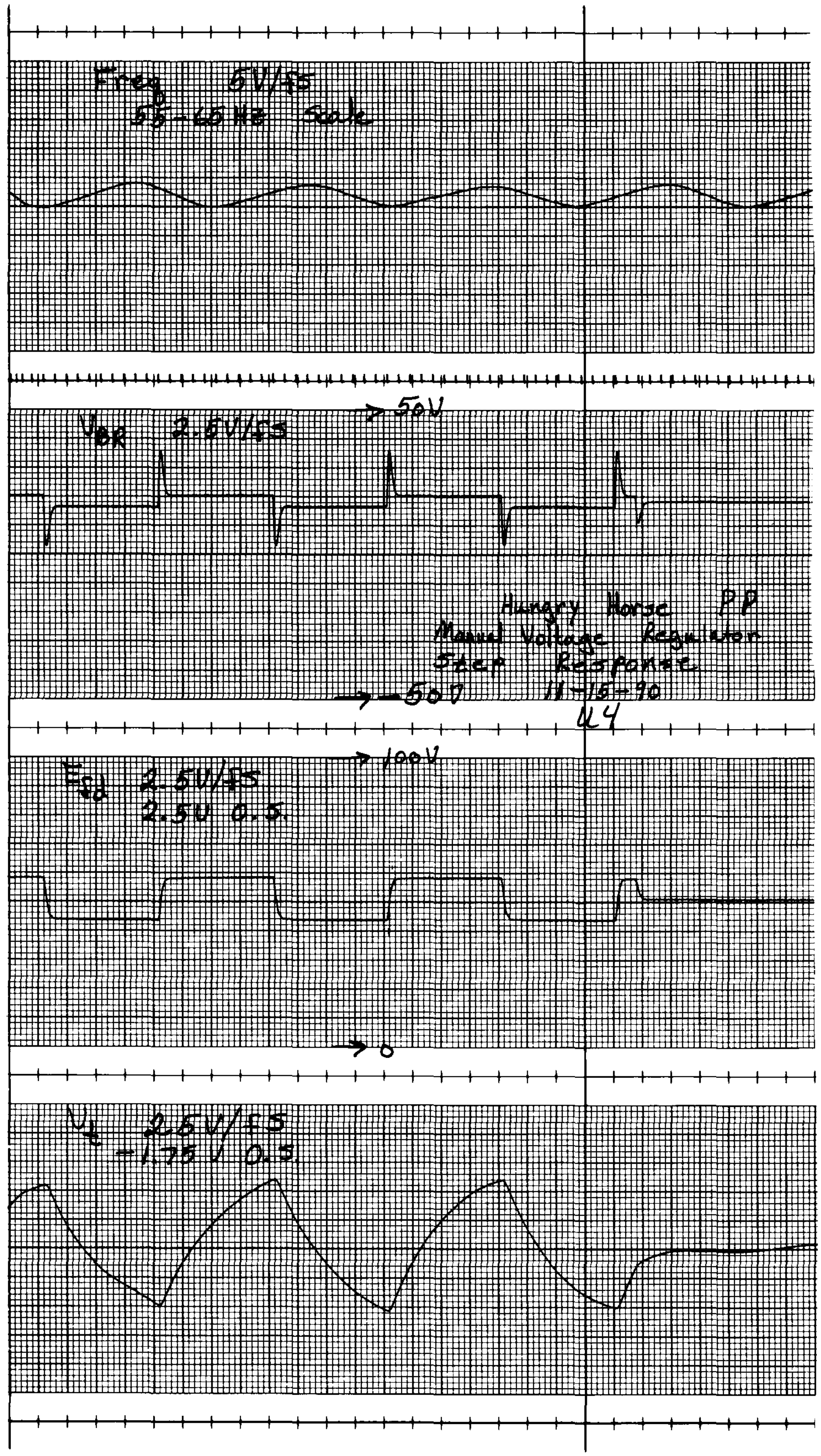

Figure 5. – Small signal step response of off-line manual regulating system.

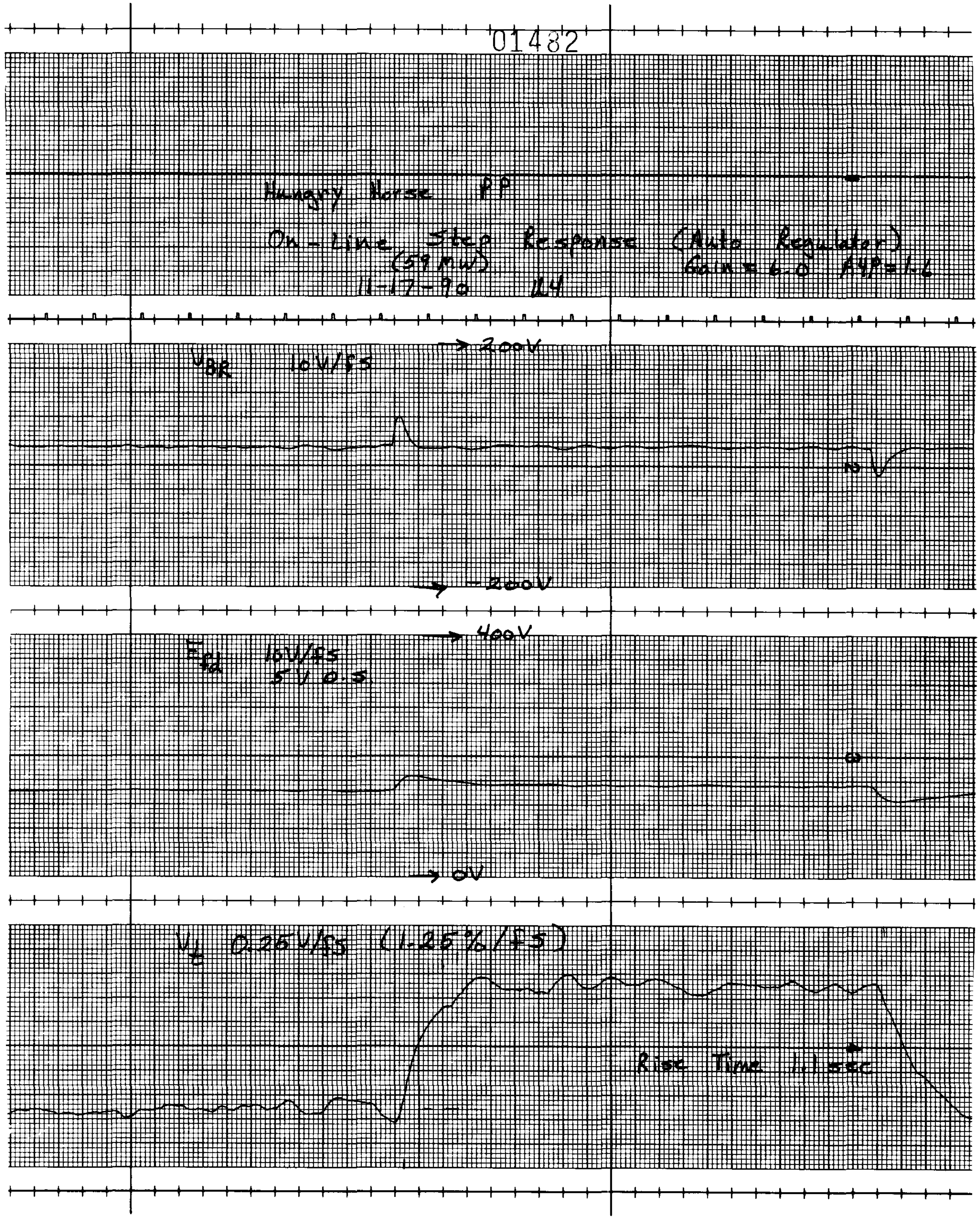

Figure 6. – Small signal step response of on-line automatic voltage regulating system.

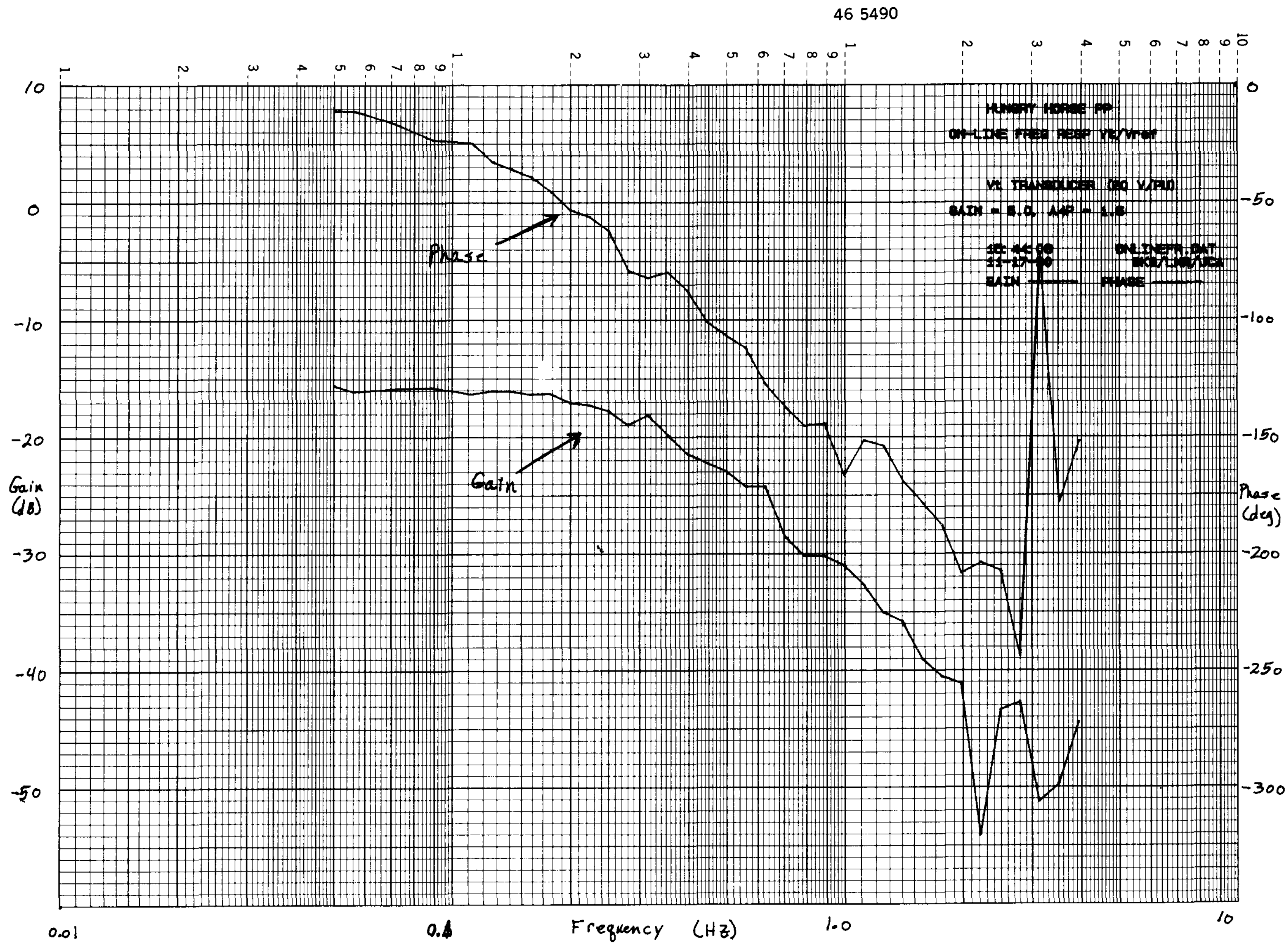

Figure 7. – Bode plot of the on-line voltage regulating system.

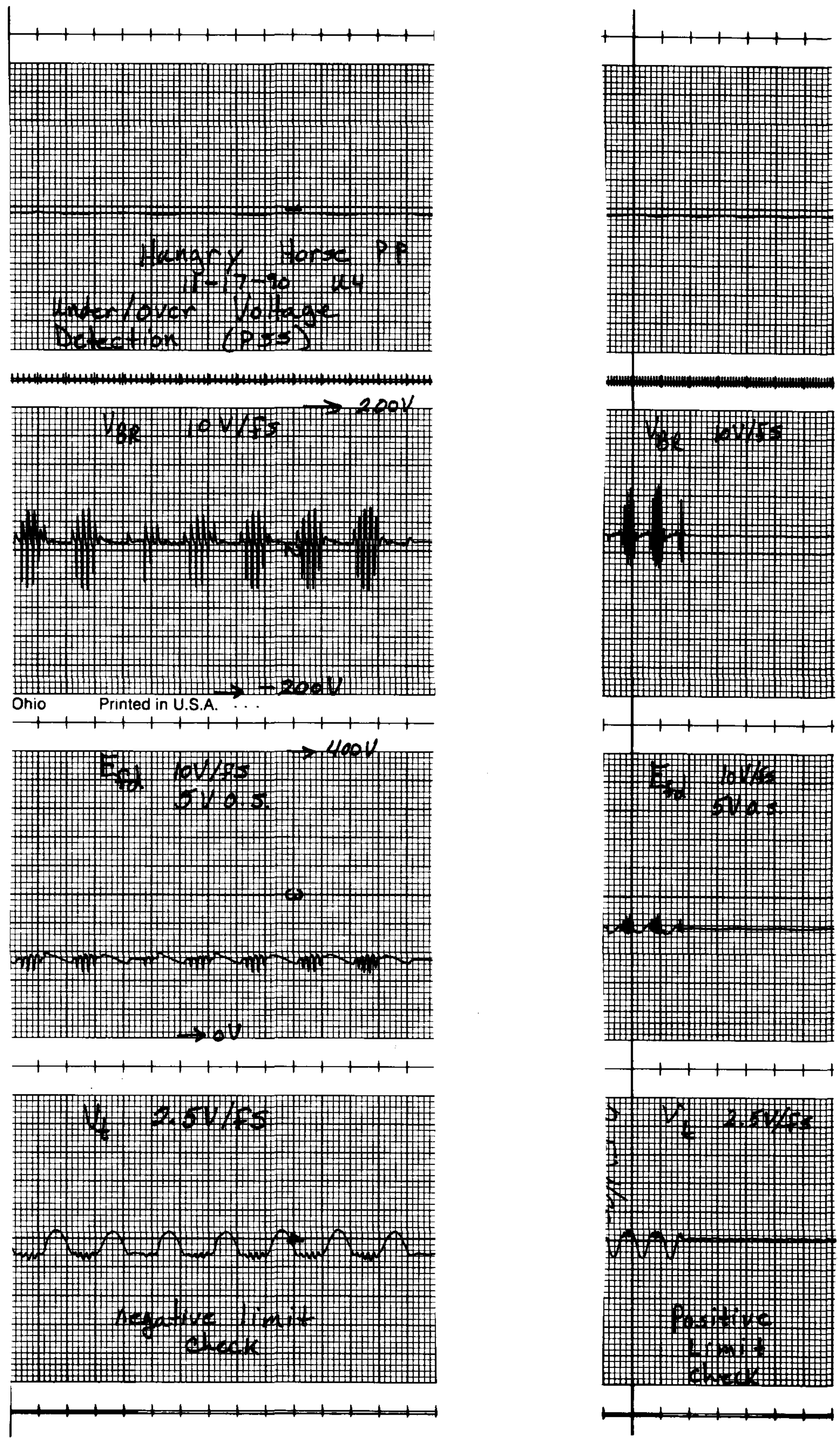

Figure 8. – Under-overvoltage detection test (PSS).

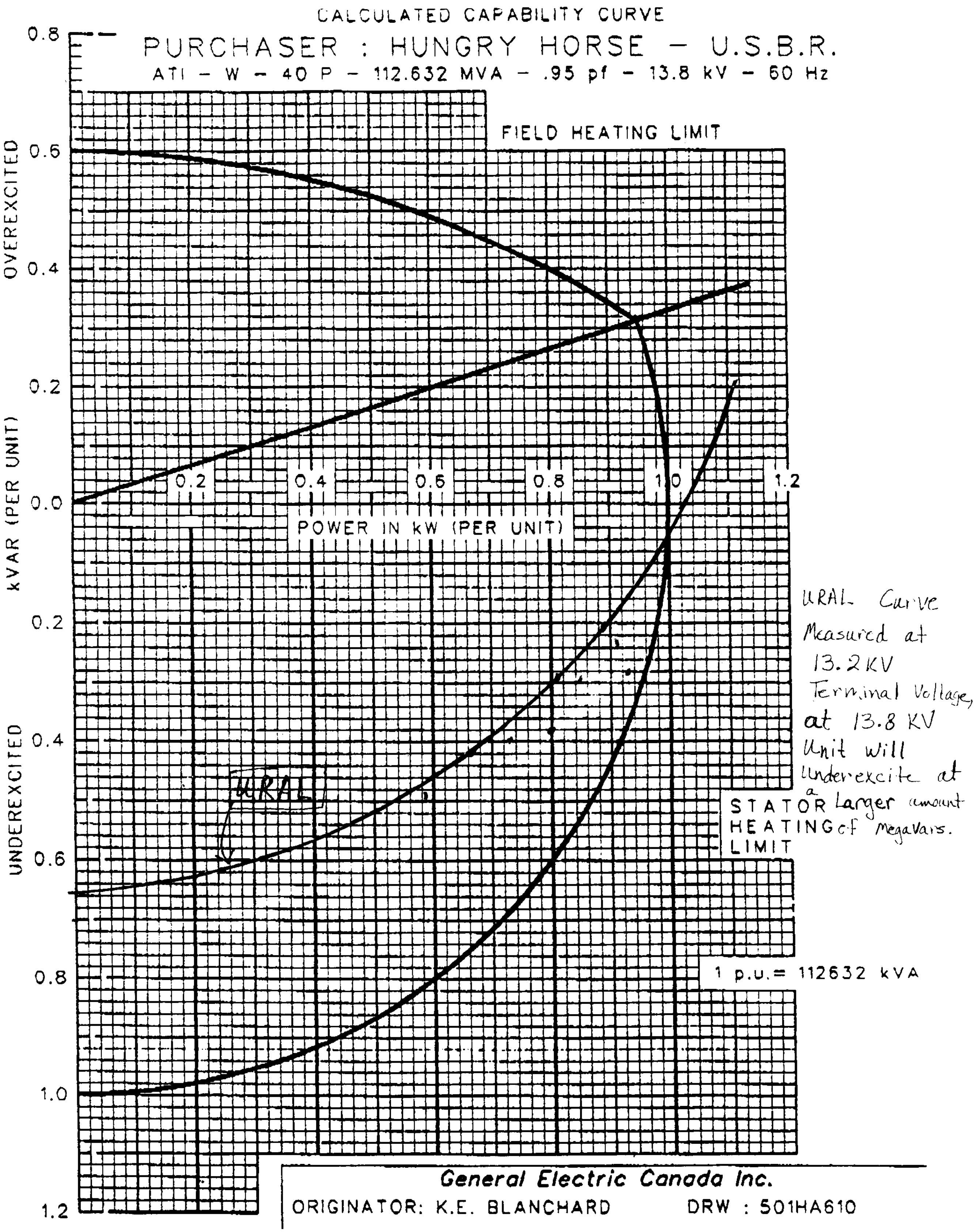

Figure 9. – Generator capability curve with the URAL curve.

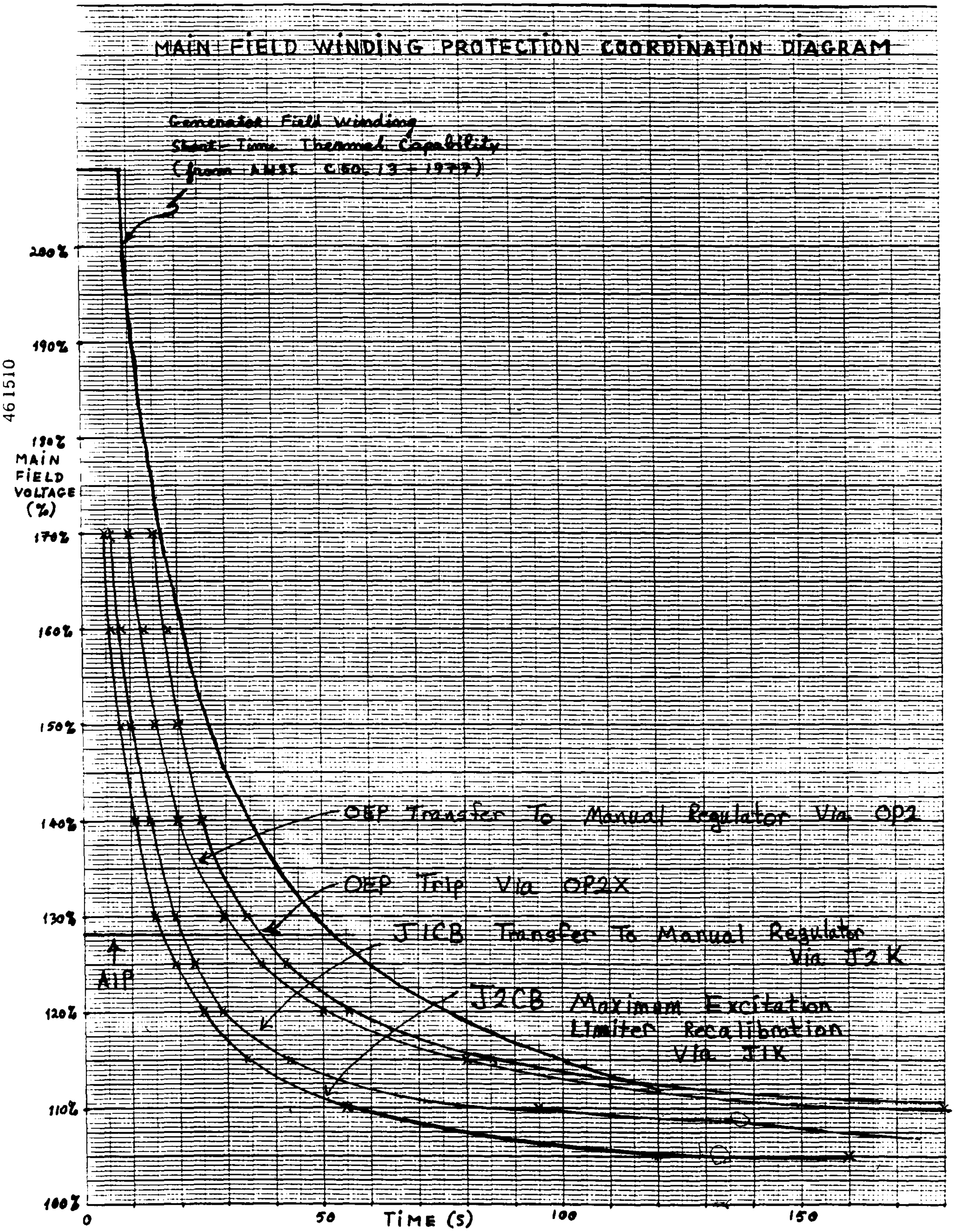

Figure 10. – Main field winding protection coordination diagram.

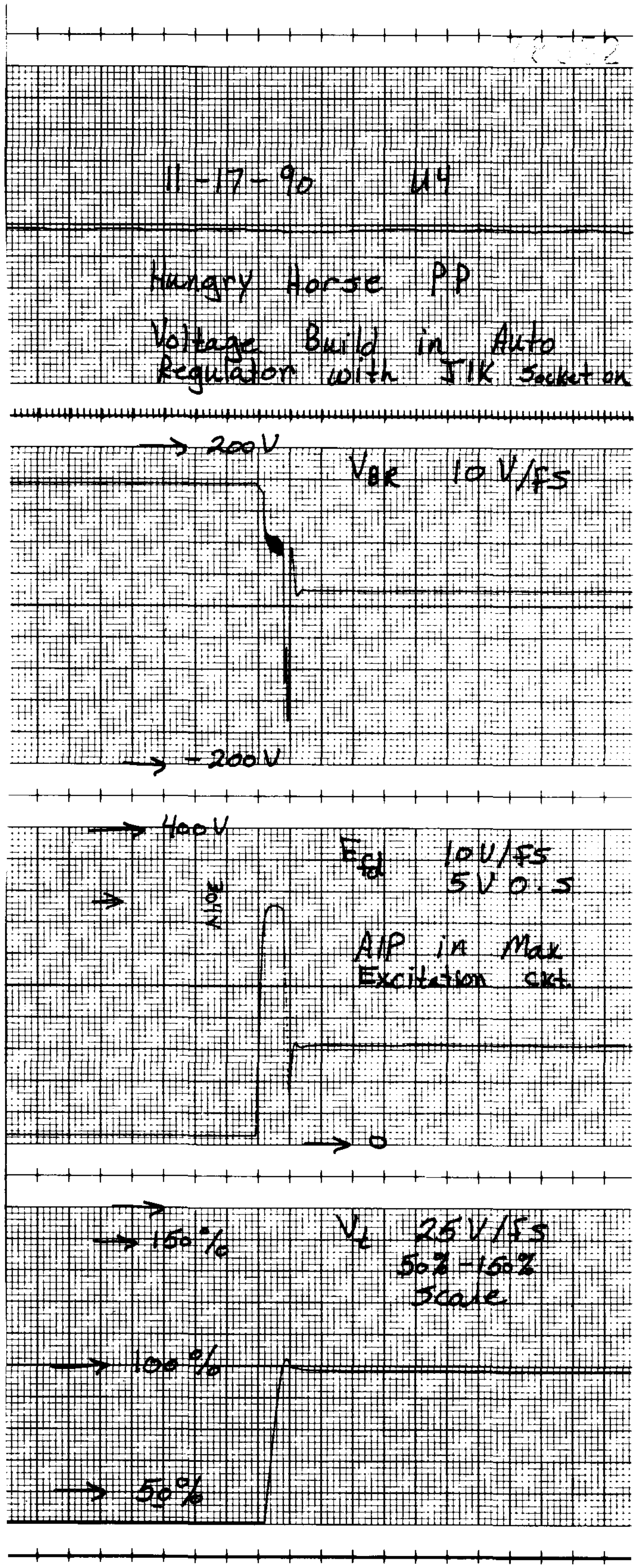

Figure 11. – Typical startup.

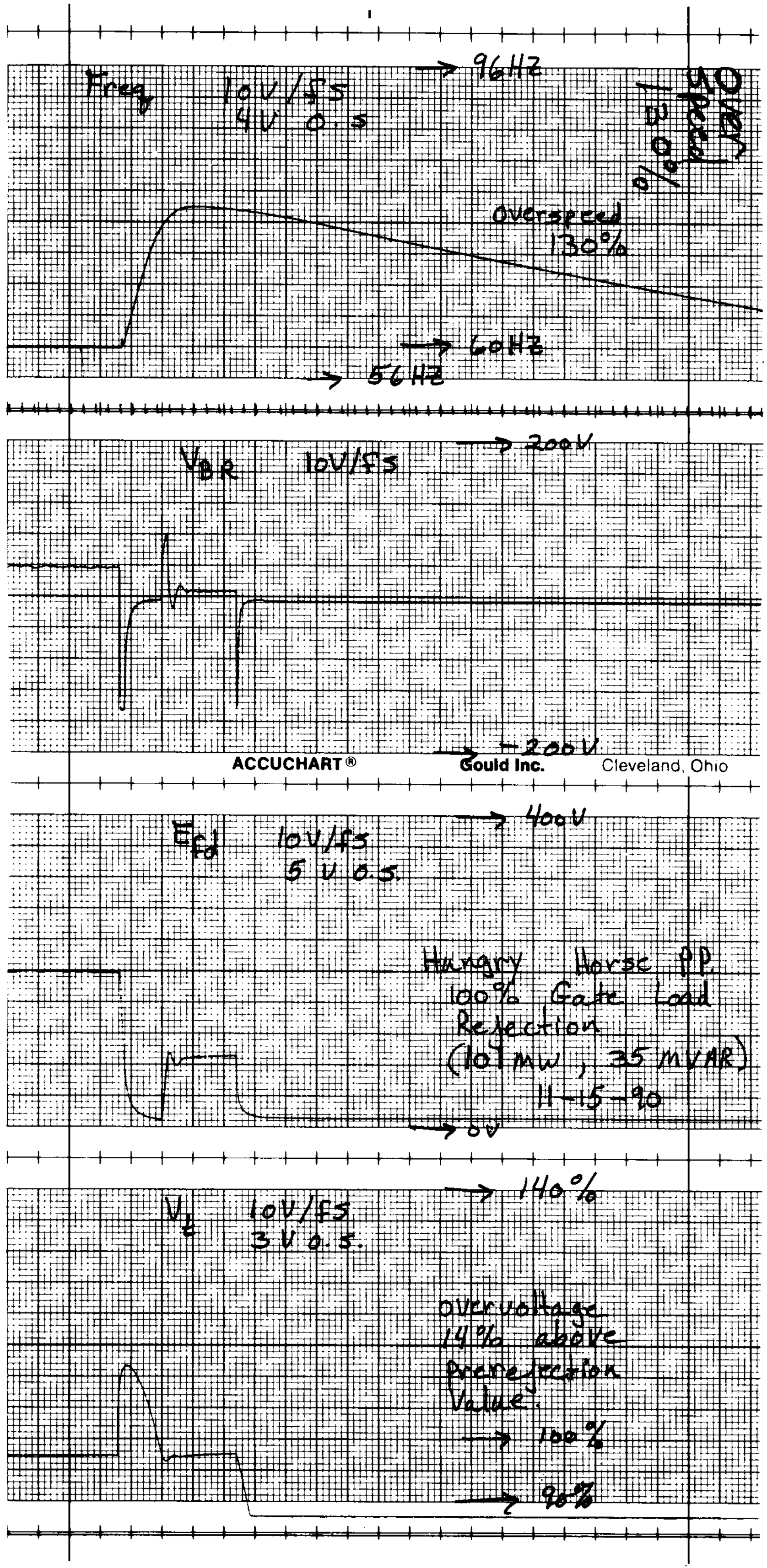

Figure 12. – Rated load rejection.

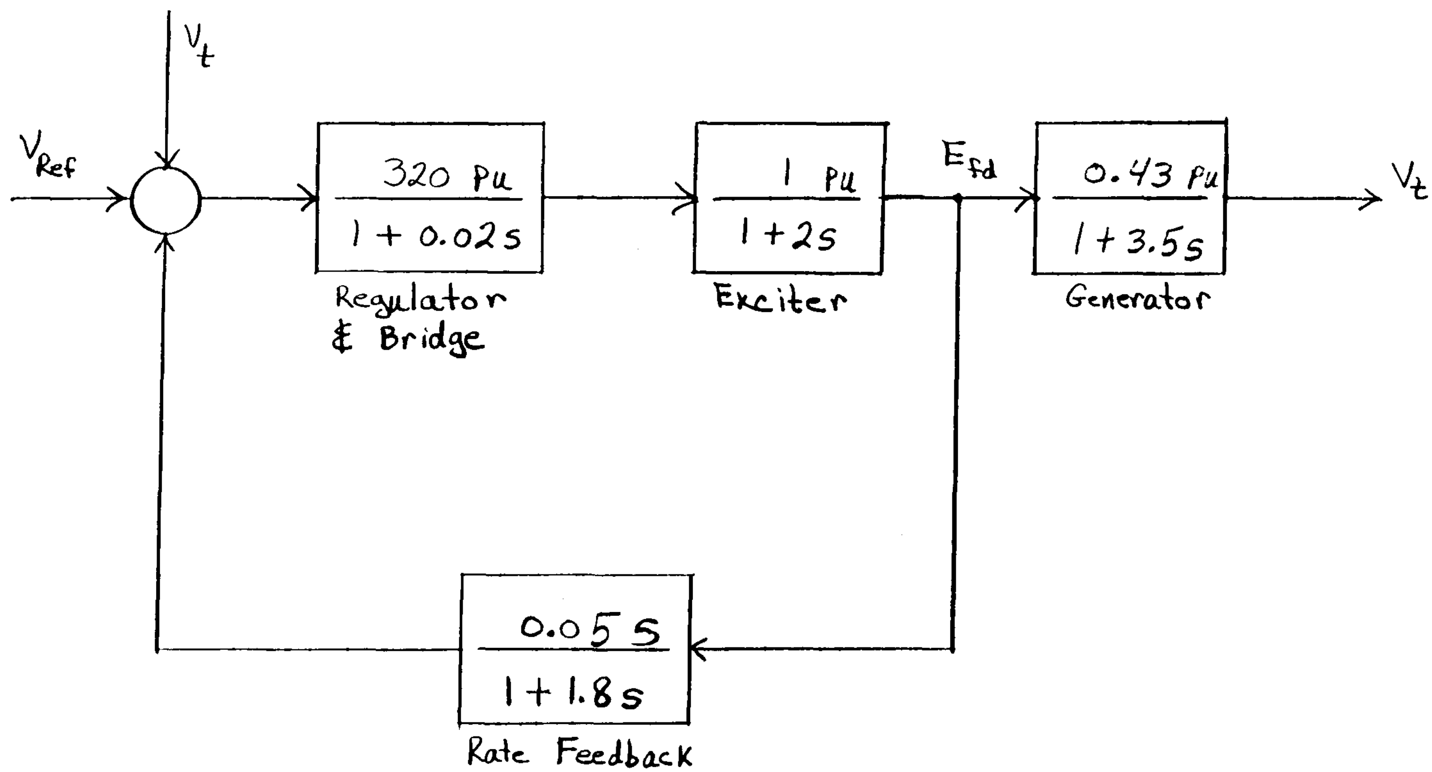

Figure D-1. – Small signal off-line model.

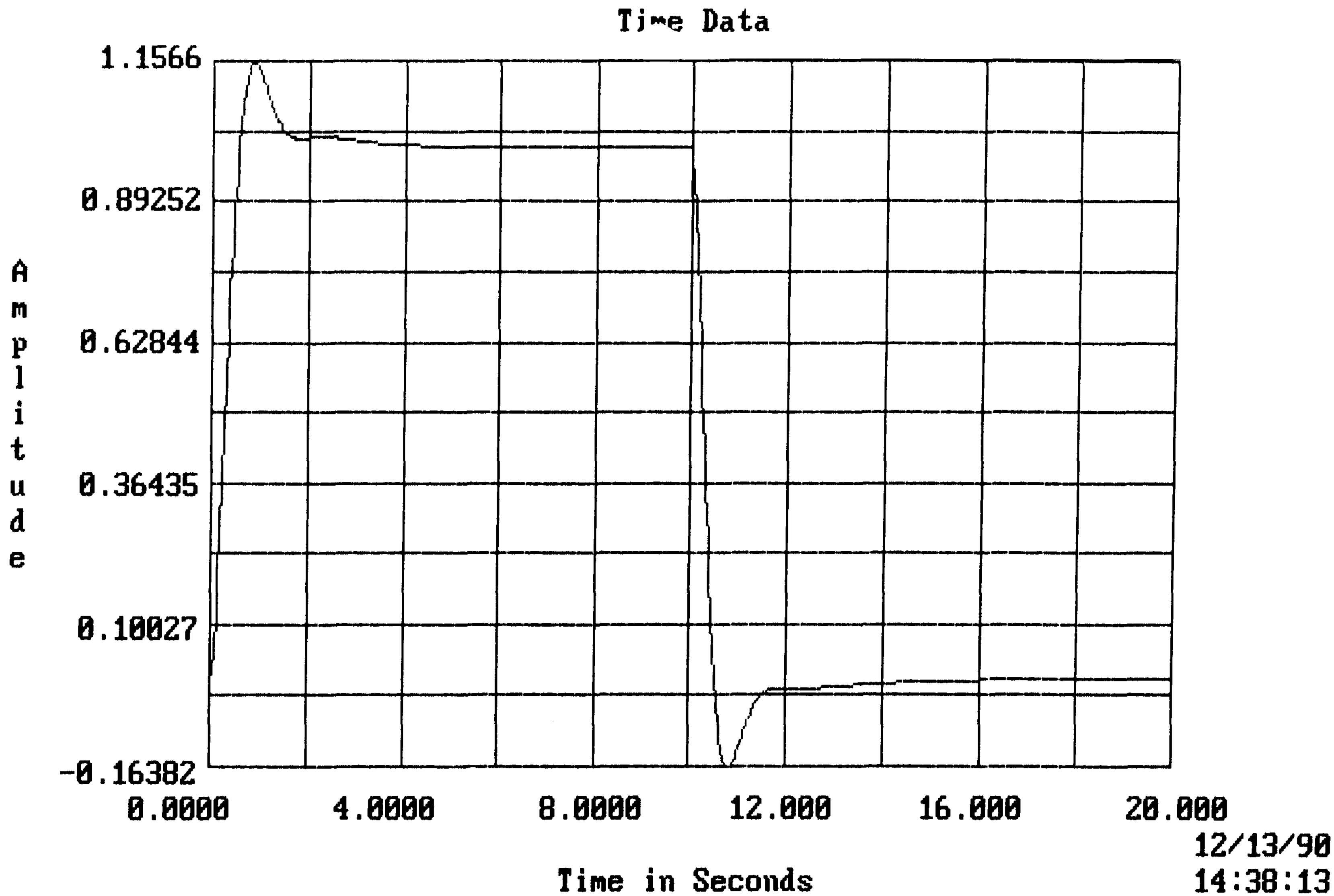

Figure D-2. – Time data.

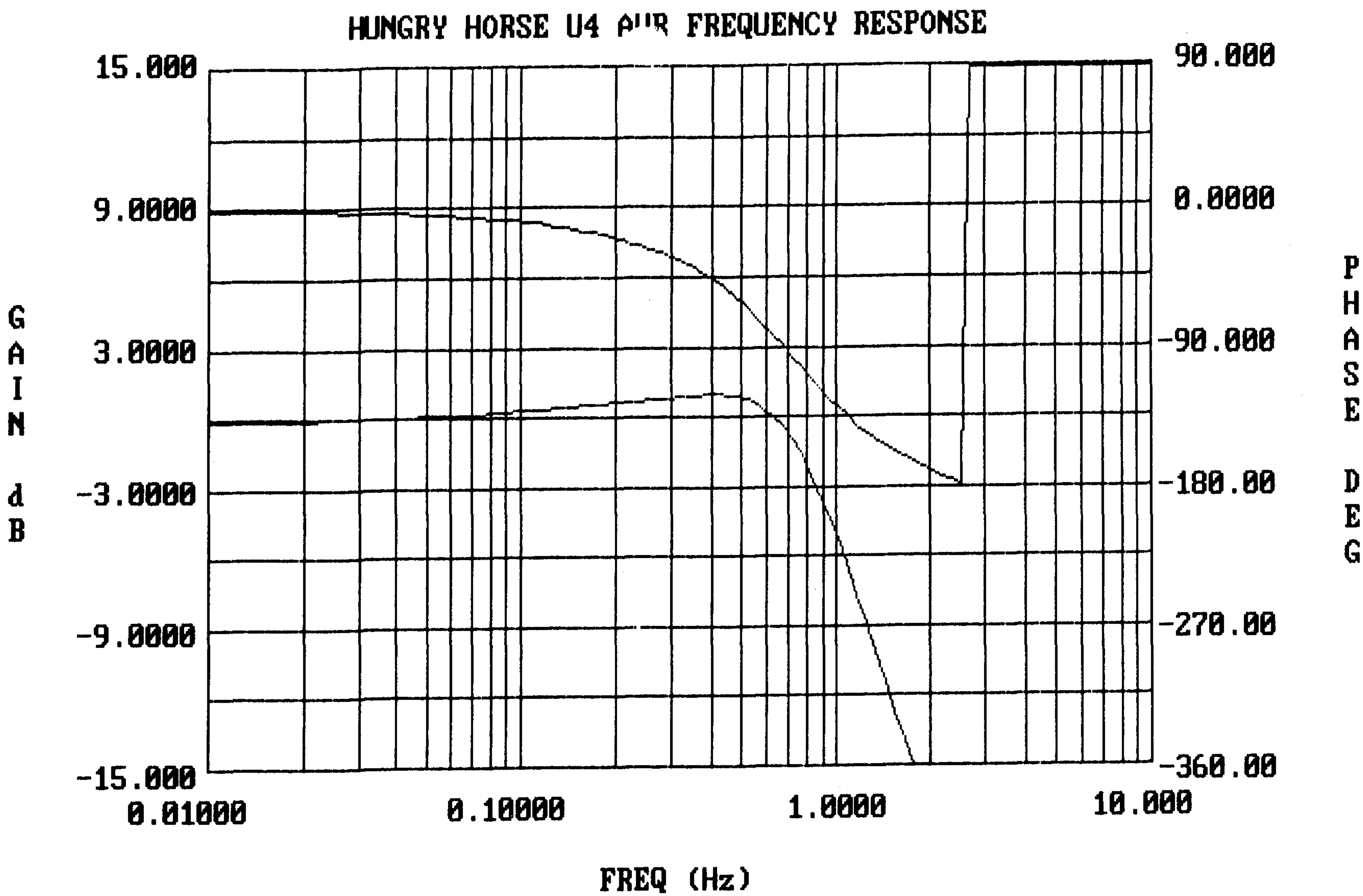

Figure D-3. – U4 air frequency response.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1992—673-185/60,007 REGION 8

Mission

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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.