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STARTUP CHARACTERISTICS OF PUMP-GENERATOR UNIT AT FLATIRON POWERPLANT

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16. ABSTRACT

This report consists of a presentation and analysis of the January 1984 pump startup investigations at Flatiron Powerplant in Colorado. The purpose of the investigations was to determine the possibility of starting the subject pump by means of a reduced voltage starting scheme. Startup records, test results, analysis, evaluations, and recommendations are presented.

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by
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Engineering and Research Center
Denver, Colorado

October 1984

SI METRIC

UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest 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 has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. Administration.

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Glossary of Abbreviations and Symbols

A	ampere
BFV	butterfly valve
CT	current transformer
dB	decibel
d.c.	direct current
fs	full scale
hp	horsepower
Hz	hertz
I	current
I_a	phase "a" current
I_b	phase "b" current
I_c	phase "c" current
P	power
ΔP_{max}	change in maximum power
$P3\phi$	3-phase power
PT	potential transformer
p-p	peak-to-peak
pu	per unit
Q	volt-amperes reactive
MQ	megavolt-amperes reactive
$Q3\phi$	3-phase, volt-amperes reactive
R_d	discharge resistor
R_f	field resistance
r/min	revolutions per minute
rms	root mean square
V	volts
kV	kilovolts
kV•A	kilovolt-ampere
mV	millivolts
V_{ab}	phase "a" to phase "b" voltage
V_{bc}	phase "b" to phase "c" voltage
V_{ca}	phase "c" to phase "a" voltage
V_{fs}	full scale voltage
V_{LL}	line-to-line voltage
V_{L8}	line-to-ground voltage
V_s	system voltage
MW	megawatts

INTRODUCTION

In the mid-1970's after 22 years of service, the Flatiron Power and Pumping Plant pump-generator unit No. 3 experienced several inservice failures. An analysis of the problem indicated the failures were related to metal fatigue in the end turns of the stator coils. Field tests indicated that the end turns vibrated during the initial startup period due to inadequate blocking of the winding in the end turn area.

Alternative solutions to the problem were reported on in 1976 and consisted of a reduced voltage starting scheme; use of an auxiliary starting motor; modification of the exciter to act as a starting motor; installation of a static starting system; and standard, normal, across-the-line starting in conjunction with the installation of a new, well-blocked winding. A synchronous starting scheme was not considered due to the inconvenience involved. At the time, it was decided that the best solution to the problem, economically and technically, would be to keep the standard across-the-line starting system and install a new, well-blocked winding. This decision was executed and supposedly eliminated the problem. However, in 1983, the pump-generator unit transformer failed in service. A temporary unit transformer was installed until a replacement could be procured.

The failure of the transformer, while unfortunate, presented an ideal opportunity to provide a reduced voltage starting scheme at minimum expense. Prior to actually specifying a special unit transformer with auxiliary reduced voltage starting capability, it was first necessary to verify that a reduced voltage starting scheme was feasible. To this end, the decision was made to perform a pump motor startup investigation at Flatiron in January 1984. The investigation included monitoring of winding end turn vibration during the startup tests. Startup tests were limited to watered starts since the design of the existing hydraulic turbine and butterfly valve was such that unwatered across-the-line starts cause excessive hydraulic system vibration. The startup investigation also provided an opportunity to study and resolve a synchronization problem reported by plant personnel.

CONCLUSIONS

Reduced voltage starting of the Flatiron pump-generator unit holds little promise for significantly reducing the startup stresses imposed on the motor winding end turns. The potential benefits of reduced voltage starting are significantly lessened by the fact that the test results indicate that the end turn vibration problem experienced on the original unit winding during normal system voltage startup no longer exists.

The synchronization problems are unrelated to the other motor starting problems and can be corrected quite easily with minor modifications to the field application circuit. Minor voltage regulator adjustments would also improve synchronization.

It may be possible to make unwatered motor starting a viable starting state by applying supplemental excitation control system equipment to reduce hydraulically induced transients. The same auxilliary control system may prove to be effective in improving turbine performance in the rough zone.

FLATIRON PUMP-GENERATOR UNIT

The pump generator is rather unique in that it was designed as a two-speed unit; there were originally two windings in the stator bore. The field was reconfigured through a switching network to obtain the necessary number of poles for proper operation at either speed. As a generator, the unit was rated at 13.8 kV, 8500 kV•A, 257 r/min, and with a unity power factor. As a pump motor, the unit was rated 13.8 kV, 10 158 kV•A, 300 r/min, and a unity power factor. Presently, the unit has only one stator winding and is capable of operating only at 300 r/min as either a motor or generator. The unit is operated primarily in the pump mode.

Since the unit operates as a pump motor, there is a butterfly valve in the hydraulic system instead of the usual wicket gate arrangement. The unit was originally designed for starting in either a watered or unwatered state. However, the unit never operated properly when started in the unwatered state due to hydraulic related problems during the initial opening of the butterfly valve. The pump did not always prime when starting and at times experienced violent vibration that actually damaged equipment. For this reason, the unwatered startup scheme has been eliminated from the standard operating procedures.

PRELIMINARY WORK

The initial request was to investigate reduced voltage starting as an alternative to across-the-line starting to minimize stator winding end turn stress. A reduced voltage start would in fact reduce the starting current and thereby limit the current-induced end turn forces. However, this would also reduce the starting torque and thereby increase the machine starting time and temperature. Therefore, a tradeoff of adverse effects must be considered. In reducing the amplitude of end turn stress, one must be willing to accept the longer duration stress periods at higher temperatures.

During our initial work, it was discovered that the unit had a history of long starting times, loud sounding startup surges, and occasional problems involving synchronization. In addition, synchronization would occur only in a very narrow range of applied voltage, making it difficult to start without first obtaining the proper system voltage.

To compound the problem, the manufacturer's original model data indicated that pumping against a closed valve would require about 70 percent of rated torque. Due to this rather high figure, there was some concern as to the validity of the original model data that were submitted in 1954. However, it was assumed that the high figure was valid and probably a compromise related in some way to the somewhat demanding high efficiency dual speed motor/generator operating requirements and the design methods of the 1950's.

Based on the numerous questions and uncertainties briefly presented in this section, it was decided to proceed with a detailed motor startup test investigation.

INSTRUMENTATION

The investigation basically consisted of instrumenting the unit and collecting data during several startup sequences. The instrumentation consisted of two 4-channel strip chart recorders, a lab grade instrumentation oscillograph, high-speed movie camera, and vibration monitoring equipment. The vibration equipment and movie camera were used to monitor, in various ways, stator coil end turn vibration and/or movement. The electrical and mechanical quantities monitored are listed in tables 1 and 2. Also included in these tables are the sources of the signals and the calibration data.

The vibration equipment and movie camera were set up to monitor stator coil end turn movement inside the air housing on the top of the unit. A special insulated fixture was built to couple the vibration equipment to a coil end turn.

Strip chart recorder signals were interfaced to the unit signals via various types of transducers. The voltage, current, watt, and var transducers were of the standard power system type. The var transducer was simply a watt transducer reconfigured to monitor vars.

The shaft torque transducer consists of a shaft-mounted strain gage and instrumentation package that transmits shaft torque data to a stationary instrumentation package. The torque instrumentation package frequency response is from direct current to either 1 Hz (3-dB point) or 80 Hz (3-dB point), and is switch selectable. All shaft torque records, except during test No. 7, were obtained

Table 1. – Strip chart recorder calibrations.

Channel No.	Signal	Scale	Calibration
1	V_{ab} machine	+2.5 V	15kV = 1.09 pu, fs
2	I_a machine	+2.5 V	4800 A = 11.3 pu, fs
3	P3ϕ	±25 mV	±10.15 MW = ±13 606 hp→±1.36 pu, fs
4	Q3ϕ	±50 mV	±47.88 MQ = ±4.72 pu, fs
5	Shaft torque	±0.125 V	Set to fs at rated pump load
6	Input torque	±5 V	Set to ±1 pu, fs at rated load
7	Speed	+10 V	Set to 1 pu at rated speed
8	Field V	±12.5 V	±2500 V_{fs}/±208.33 A, fs

with the torque instrumentation frequency response limited in bandwidth to 1 Hz. The device is calibrated in the pumping mode of operation. The method of calibration is straightforward and is based on the motor input power at synchronous speed. The motor losses were neglected in the calibration, but could be corrected for if needed.

The input torque signal is actually the input power divided by the unit speed. The transducer consists of signal conditioning circuits and a divider. The power and speed transducer signals, after conditioning, are divided to obtain a fast response input torque signal. This torque signal is slightly different from the shaft torque signal in that it also contains the torque component used to accelerate the motor mass. This signal and the resultant torque slip curve are somewhat inaccurate at high slip due to the motor losses which are disproportionately large at low speed. The motor stator losses were neglected, but could be included if required.

The speed transducer is a high-resolution, high-accuracy, fast-response instrument. The actual speed pickup sensor is an optical device that interfaces to the machine shaft.

The field voltage applied across the field discharge resistor during startup is monitored via the field voltage transducer. This transducer is basically a high-voltage, isolation amplifier with signal conditioning circuits. The isolation is required due to the high voltages induced across the floating field circuit during the startup period. The transducer is connected across the field winding. During starting, when the field is shorted by the discharge resistor, the measured field voltage is proportional to the field current. However, when field excitation is applied, after removing the resistor, the measured field voltage is no longer proportional to field current except in the steady-state case.

Table 2. – Oscillograph calibrations.

Trace	Signal	Primary/secondary quantities	CT/PT data	Oscillograph setup	Calibration
1	V_{ab} machine	13.8 kV_{LL}/115 V_{LL}	14.4 kV_{LL}/120 V_{LL}	115 V_{rms} = 0.8 inch, p-p	17.25 kV_{rms}/inch, p-p
2	V_{bc} machine	13.8 kV_{LL}/115 V_{LL}	14.4 kV_{LL}/120 V_{LL}	115 V_{rms} = 0.8 inch, p-p	17.25 kV_{rms}/inch, p-p
3	V_{ca} machine	13.8 kV_{LL}/115 V_{LL}	14.4 kV_{LL}/120 V_{LL}	115 V_{rms} = 0.8 inch, p-p	17.25 kV_{rms}/inch, p-p
4	I_a machine	2 kA/4.16 A	600:5 & 20:5	4 A_{rms} = 0.8 inch, p-p	2400 A_{rms}/inch, p-p
5	I_b machine	2 kA/4.16 A	600:5 & 20:5	4 A_{rms} = 0.8 inch, p-p	2400 A_{rms}/inch, p-p
6	I_c machine	2 kA/4.16 A	600:5 & 20:5	4 A_{rms} = 0.8 inch, p-p	2400 A_{rms}/inch, p-p
7	V_{ab} system	115 kV_{LL}/115 V_{LL}	Unit transformer, 13.8/115	115 V = 0.8 inch	143.75 kV_{rms}/inch, p-p
8	V_{bc} system	115 kV_{LL}/115 V_{LL}	PT 69 kV_{L8}/69 V_{L8}	115 V = 0.8 inch	143.75 kV_{rms}/inch, p-p
9	V_{ca} system	115 kV_{LL}/115 V_{LL}	PT 69 kV_{L8}/69 V_{L8}	115 V = 0.8 inch	143.75 kV_{rms}/inch, p-p
*10	P3ϕ	–	–	5V = 0.8 inch	1.25 pu/inch, peak
*11	Shaft speed	–	–	10 V = 0.8 inch	375 (r/min)/inch, peak
*12	Field V	–	–	10 V = 0.8 inch	2500 V/inch, peak (or 208.33 A/inch, peak)

* Same signals are on strip chart recorders.

The input torque transducer was specially developed by the Bureau for this field test investigation. The field voltage, speed, and shaft torque transducers were also developed by the Bureau for various other machine startup investigations.

Each of the eight transducer signals were recorded on the strip chart recorders. The three-phase power, shaft speed, and field voltage transducer output signals were also recorded on the oscillograph. The oscillograph was used to monitor the 13.8-kV unit line-to-line voltages and line currents as well as the 115-kV system line-to-line voltages.

An X-Y plotter was used to plot the motor input torque versus the motor speed, which resulted in the machine torque-slip curve automatically being plotted during each startup.

Noncontacting proximity probes were mounted orthogonally, roughly north and east, near the pump guide bearing and near the upper motor guide bearing to measure unit runout and radial vibration. A probe was mounted vertically above the coupling cover to measure vertical shaft vibration. A micarda rod with a steel washer on one end was tied to a coil to allow measurement of radial coil motion using one of the probes. The signals from the probes were recorded against time on a strip chart recorder and a frequency analyzer was used to search for and measure high-frequency vibration.

TEST SERIES DESCRIPTION

Eight tests were performed in the test series. Six of these tests involved monitoring unit startup under various starting conditions. The two remaining test runs consisted of monitoring operation of the unit during normal shutdown. The first startup test was basically used to set up and calibrate the instrumentation system. As a result, the information obtained was of limited use with respect to the analysis and evaluation of unit operation.

The startup test series consisted of three normal full system voltage starts, one reduced system voltage start, one reduced system voltage start with reduced field discharge resistance, and one normal system voltage start with reduced field discharge resistance. A description of the test series is shown in table 3.

The field discharge resistance was decremented from 12 to 10.43 ohms (87 percent of normal) for the reduced resistance startup testing. The normal system starting voltage, prior to actual startup, is 115.5 kV (measured at the operator's board). The system voltage was lowered to about 112.5 kV for the reduced system voltage testing. This is a decrease of only 2.5 percent. The

Table 3. – Test series description.

Test No.	Test description
1	Startup: Normal starting voltage and calibration run
2	Shutdown: Normal shutdown
3	Startup: Normal starting voltage
4	Startup: Normal starting voltage
5	Startup: Reduced voltage start
6	Startup: Reduced voltage start and reduced field discharge resistance
7	Startup: Normal voltage start and reduced field discharge resistance

purpose of reducing the voltage and discharge resistance during startup was not related to the primary purpose of investigating reduced voltage starting. Obviously, reduced voltage starting would require lowering the motor starting voltage considerably more than 2.5 percent. The purpose of reducing the starting voltage was to determine the reason why the unit would most often fail to synchronize at system starting voltages other than the critical 115.5-kV point. The field discharge resistance was reduced in an effort to determine if shifting the field winding startup induction torque peak closer to synchronous speed would result in proper synchronizing at system starting voltages below the critical 115.5-kV point.

The actual test records are shown in appendix B. Each record is labeled with the test series number, mode of unit operation, system starting voltage, value of the field dishcarge resistor, and the calibration data. The records for test 1 are not included because they were both incomplete and uncalibrated.

ANALYSIS OF TEST RESULTS

This analysis is based on the data summaries presented in tables 4 and 5. The information in the tables was taken from the oscillograph and strip chart records.

System Capacity

The test data analysis indicates that the 115-kV system voltage drop 1 second after both normal and reduced voltage startup ranges from 1.6 to 2.4 percent. The drop in the 13.8-kV machine terminal voltage at 15 seconds into the startup sequence ranges from 1.6 to 2.8 percent. The unit starting current at 15 seconds is about 4.75 per unit (2020 A). The actual current and voltage traces can be observed in the records provided in appendix B. In reviewing these data, it is obvious

Table 4. – Data summary.

Test No.	V_{ab} (115 kV) (Starting at t = 1 s, data from oscillograph)	V_{ab} (13.8 kV) (Starting at t = 15 s)	I_a (13.8 kV) (Starting at t = 15 s)	Power (Pumping) BFV open	Shaft torque (Pumping) BFV open	Shaft torque at sync –	Q (Starting)	Q at sync +	Comments
Start 3	98.4% Δ = 1.6%	13.5 kV $\frac{13.5}{13.86} = 97.4\%$ Δ = 2.6% $\frac{115.5}{115}(13.8) = 13.86$	2020 A	9.2 MW	33.5 div 92%	24.5 div 67% of torque at 95% speed	NA	3 MQ In	V_s at t– = 115.5 kV R_f = 12 Ω t_{sync} = 63 s
Start 4	98.4% Δ = 1.6%	13.5 kV $\frac{13.5}{13.86} = 97.4\%$	2020 A	8.6 MW	32.0 div 88%	23.0 div 63% torque at 95% speed	50 MQ In	1 MQ In	V_s at t– = 115.5 kV R_f = 12 M t_{sync} = 62 s
Start 5	97.6% Δ = 2.4%	13.2 kV $\frac{13.2}{13.51} = 97.7\%$ $\frac{112.6}{115}(13.8) = 13.51$ Δ = 2.3%	2020 A	NA	NA	23 div 63% torque at 93% speed	49 MQ In	NA	V_s at t– = 112.6 kV R_f = 12 Ω Unit failed to sync t_{sync} = 67 s
Start 6	97.6% Δ = 2.4%	13.35 kV $\frac{13.35}{13.56} = 98.5\%$ Δ = 1.6% $\frac{113}{115}(13.8) = 13.56$	2020 A	8.9 MW	NA	NA	50 MQ In	30 MQ In	V_s at t– = 113.0 kV R_f = 10.4 Ω t_{sync} = 67 s

Table 4. – Data summary. – Continued

Test No.	V_{ab} (115 kV) (Starting at t = 1 s, data from oscillograph)	V_{ab} (13.8 kV) (Starting at t = 15 s)	I_a (13.8 kV) (Starting at t = 15 s)	Power (Pumping) BFV open	Shaft torque (Pumping) BFV open	Shaft torque at sync –	Q (Starting)	Q at sync +	Comments
Start 7	97.7% Δ = 2.3%	13.5 kV $\frac{13.5}{13.88} = 97.2\%$ Δ = 2.8%	2020 A	8.4 MW	32 div 88%	22.5 62% torque at 93% speed	52 MQ In	3 MQ In	V_s at t– = 115.7 kV $R_f = 10.4\ \Omega$ $t_{sync} = 62$ s
Shutdown runs 2 and 8	These data used for torque transducer calibration			8.93 MW 8.93 MW	32 div, 88% 32 div, 88%				Shutdown runs for torque calibration
Calibration		300 V/div 1 pu = 13.8 kV	96 A/div 1 pu = 425 A	0.5761 MW/div 1 pu = 10.15 MW	0.0275 pu torque /div 1 pu torque=10.15 MW_{sync}		2 MQ/div 1 pu = 10.15 MQ		
	Torque calibration: $\frac{10.15\ MW}{8.93\ MW}(32\ div) = 36.4$ div = 1 pu torque						Note: Machine is underexcited.		

Note: Test No. 1 data not valid, set-up run only.
NA indicates "Not applicable".

Table 5. – Field voltage application data.

Test No.	System V at start, kV	Peak field V prior to sync	Field V at sync (–)	[2]$\Delta P_{max.}$ at sync (+)	Speed at sync – 1.75 s	Peak field V prior to t = sync – 1.75 s	Field V at t = sync – 1.75 s
3	115.5	+1050	+750↓	19.3 MW	95%	+1850	≈ 0 ↓[3]
4	115.5	+1250	+450↓	20.5 MW	95%	+1900	≈ 0 ↓
[1]5	112.6	+1400	–800↓	>31.7 MW	93%	+1900	≈ 0 ↓
6	113.0	+1150	+700↓	19.0 MW	94%	+1750	≈ 0 ↓
7	115.5	+1250	–300↓	19.0 MW	93%	+1850	≈ 0 ↓

[1] Test No. 5 did not syncronize when field voltage was applied.
[2] 10.15 MW = 1 pu power.
[3] ≈ 0 ↓ indicates approximately equal to 0 and going negative.

that the system is quite strong and the induction machine starting current requirements are moderate. Obviously, the system capacity is more than adequate with respect to both normal and reduced system voltage motor startup requirements.

Starting Time

The time from initial startup to synchronism is about 62 to 68 seconds. This is somewhat long and will contribute significantly to motor winding mechanical stress and heating. An unwatered start would greatly reduce the motor starting time and startup stresses. However, this is presently not feasible due to the severe vibration and resultant damage to the hydraulic system that can occur during unwatered starts. The hydraulic vibration problem occurs when the butterfly valve begins to open in the unwatered startup sequence.

Winding End Turn Forces

Since winding mechanical forces are proportional to the square of the current, startup winding (conductor) forces are about 22.6 times the normal operating forces. Reducing the starting voltage to 70 percent would also reduce the motor starting current requirements to 70 percent. This would reduce the winding startup forces to 49 percent but would also greatly extend the startup mechanical stress and heating period.

Shaft Runout and Vertical Shaft Motion

Severe, one per revolution, radial shaft vibrations were recorded from startup to opening of the butterfly valve. Maximum peak-to-peak runouts of up to 0.012 inch were observed at both the upper guide and impeller guide bearings. No significant vertical vibration was observed.

As no guide bearing problems have been reported since watered starts became the standard operating procedure in about 1980, the bearings must be capable of withstanding the severe runout for brief periods of time. However, the runout observed must reduce the fatigue life of the bearings and bearing housings or supports. To prolong the life of these components, time spent pumping against a closed discharge valve and frequency of pump starting should be minimized.

Stator Coil Movement

The proximity probe at the stator coils measured an acceptable, nearly linear radial outward movement of 0.036 inch during startup from a cold condition. Later starts recorded a movement of 0.029 inch. Movement against time data are plotted on figures 1, 2, and 3. Using the spectrum analyzer, a steady-state coil vibration of 0.0004 to 0.0005 inch occurring at 120 Hz was measured through the proximity probe.

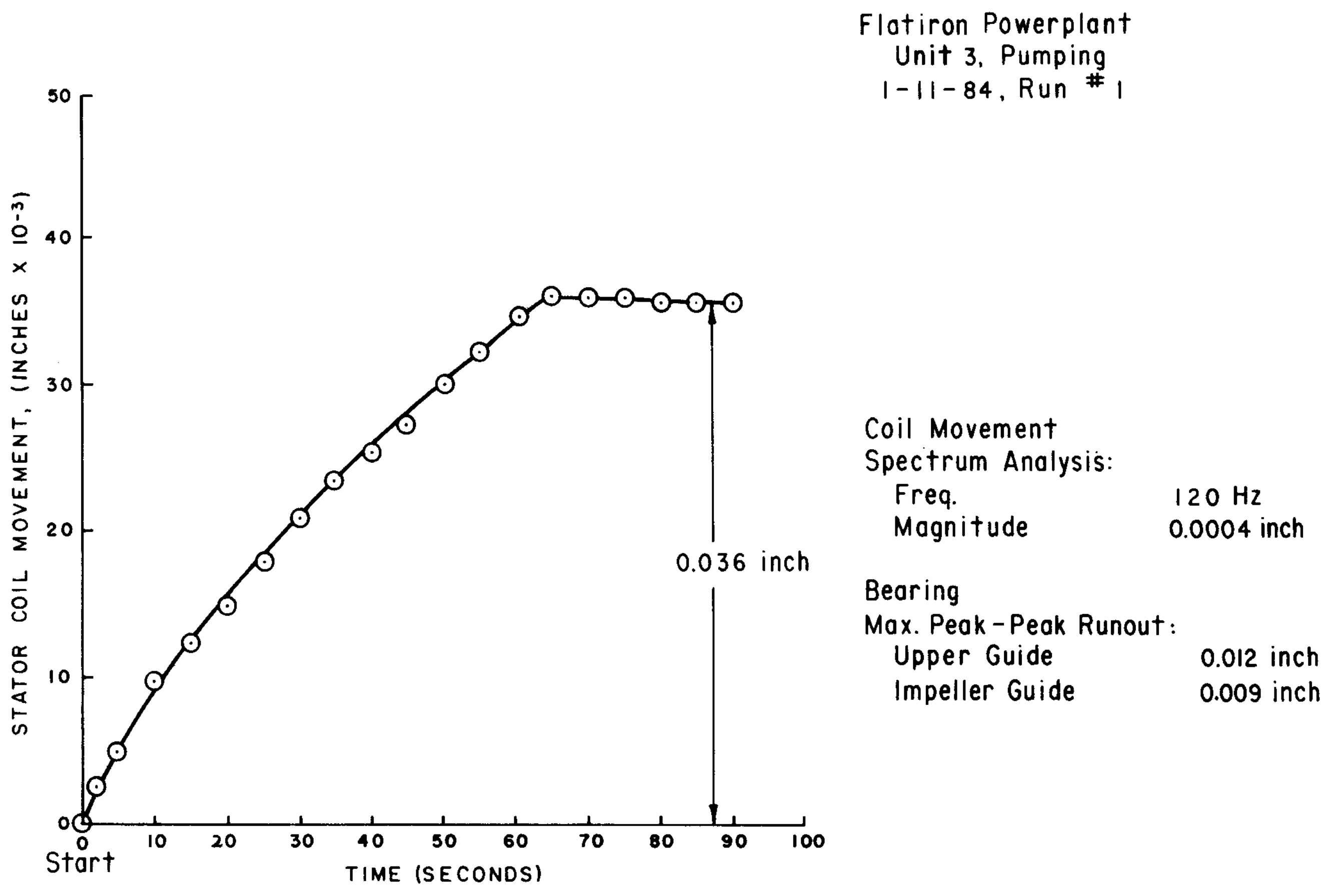


Figure 1. - Stator coil movement plot, run No. 1.

ANAYLSIS OF A REDUCED VOLTAGE STARTUP

To significantly reduce the winding end turn stresses would require the motor startup voltage to be reduced by about 30 percent. During a 70-percent reduced voltage start, the motor would only produce 49 percent of the starting torque that is available during a normal voltage start. At 80 percent speed, the torque required by the turbine pumping against a closed valve would be about 0.46 per unit. This is only 2 percent less than the torque output of the motor at 80 percent speed (see fig. 4). A slight decrease in the system starting voltage would result in insufficient motor torque to attain synchronous speed.

To ensure a successful start sequence when starting initially at 70 percent of normal voltage would require full voltage to be applied at 65 percent speed. This switchover speed point was selected to ensure proper startup for system voltage dips of up to 10 percent. All of the pertinent data for the selection were obtained from the test curves presented on figure 4. The 70-percent starting voltage level was selected to reduce the end turn stresses by 50 percent.

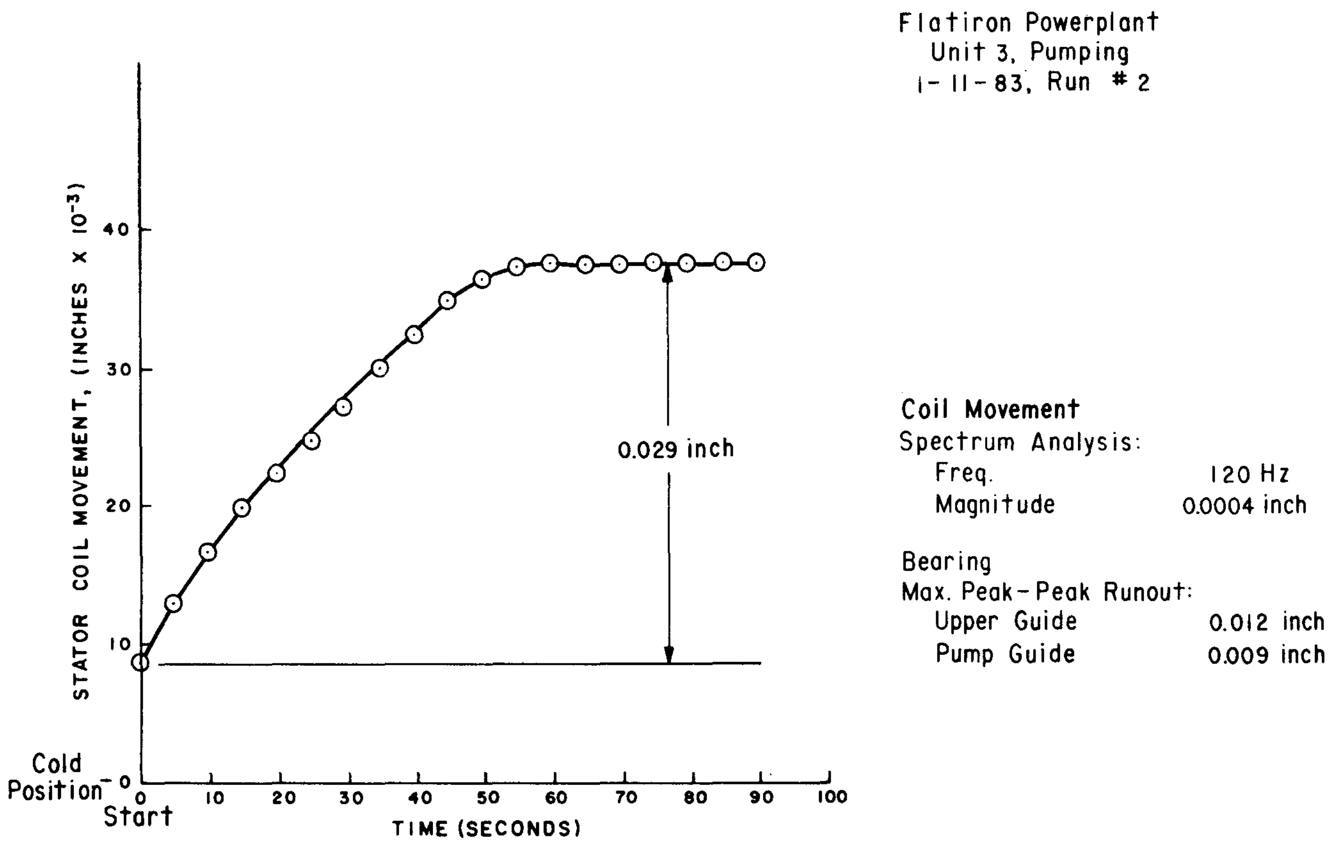


Figure 2. – Stator coil movement plot, run No. 2.

In a normal start, the 65-percent speed point is reached about 45 seconds into the 60- to 70-second start sequence (app. B, record 4B). Therefore, in a reduced voltage starting scheme, there will be at least a 15- to 25-second period in which full voltage would be applied to the motor. This period would be longer than in the normal startup sequence because the acceleration at the 65-percent speed point during a reduced voltage start would be considerably lower that the acceleration at the 65-percent speed point during a normal start. For the major part of this period that full voltage is applied to the motor, the starting current will be at its peak (test record 4B) and the coil end turn stresses at a maximum and equal to the same level reached during normal starts.

Therefore, there does not appear to be any clear advantage to a single stage reduced voltage starting scheme. This can be attributed primarily to the high closed valve torque requirement of the pump, which is about 70 percent of rating at synchronous speed. However, there would be a great advantage to reduced voltage starting if the machine could be started in the unwatered mode. In any event, the benefit to be gained in implementing the reduced voltage starting proposal is lessened by the fact that the photographic and vibration test results for the normal voltage startup tests did not give evidence of any significant movement of the coil end turns.

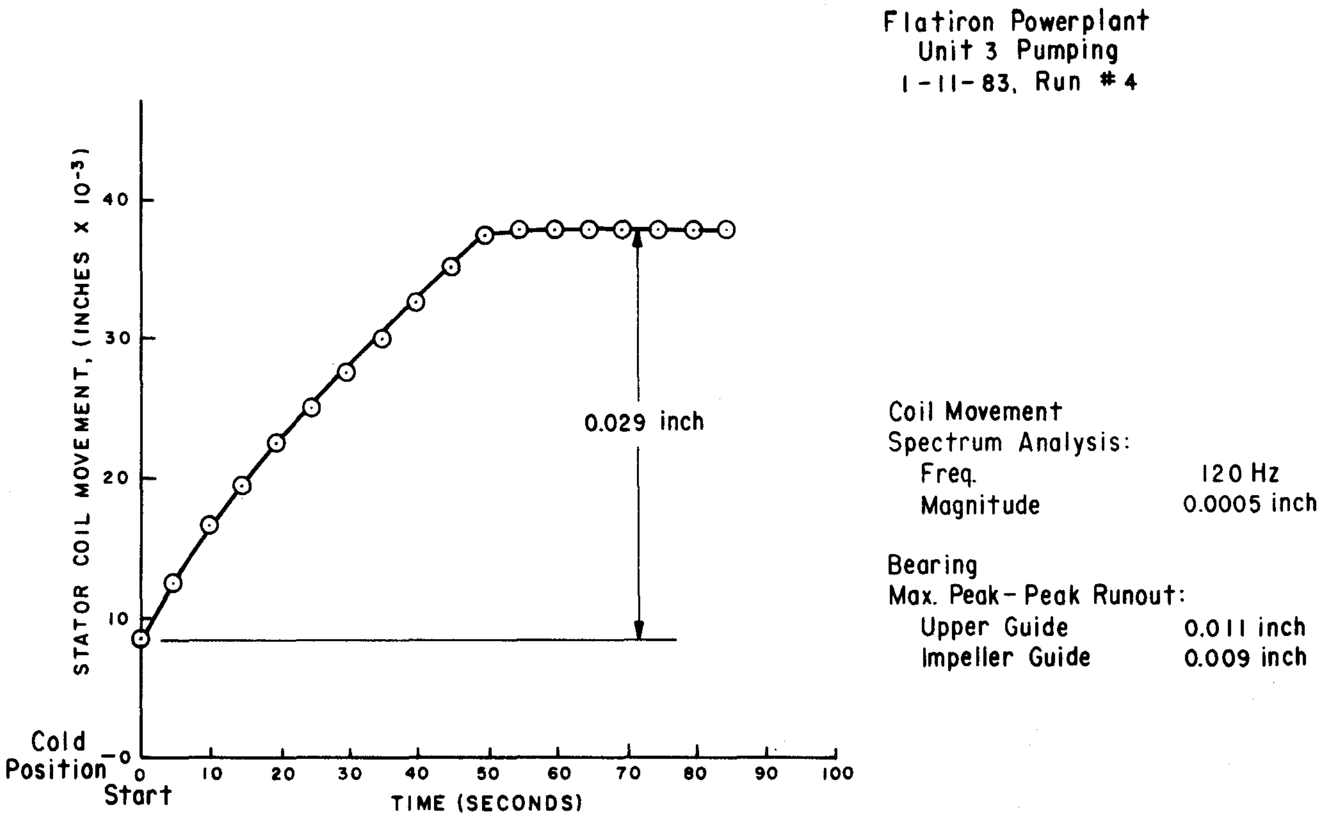


Figure 3. - Stator coil movement plot, run No. 4.

FIELD VOLTAGE APPLICATION (SYNCHRONIZATION)

Unit 3 at Flatiron has had a long history of problems involving synchronization. The standard operating procedure on starting is to preset the 115-kV bus voltage to 115.5 kV, which has been determined by plant operators to be the level required to ensure proper synchronization. An attempt (test 5) to start the motor at 113 kV resulted in failure of the machine to pull into step. The terminal voltage deviation of about 2.2 percent should not have affected the unit in such a manner. Based on the test data, the machine reached near synchronous speed in the normal manner and time and should have pulled into step.

The induced field voltage (per unit) just prior to each application of field excitation was plotted on the per unit sine wave curve of induced field voltage (fig. 5). From this curve, it can be seen that the failure to pull into step during test 5 was the result of applying the field voltage too late in the induction slip cycle. To pull the unit up to synchronous speed, the field excitation should be applied at or very near a negative going zero crossing on the induced field voltage waveform, see appendix A for a detailed analysis relating to this statement. However, due to the large field time constant of the motor and the transition conditions involved in going from induction to synchronous operation, the optimum time to apply excitation is just before the subject zero crossing.

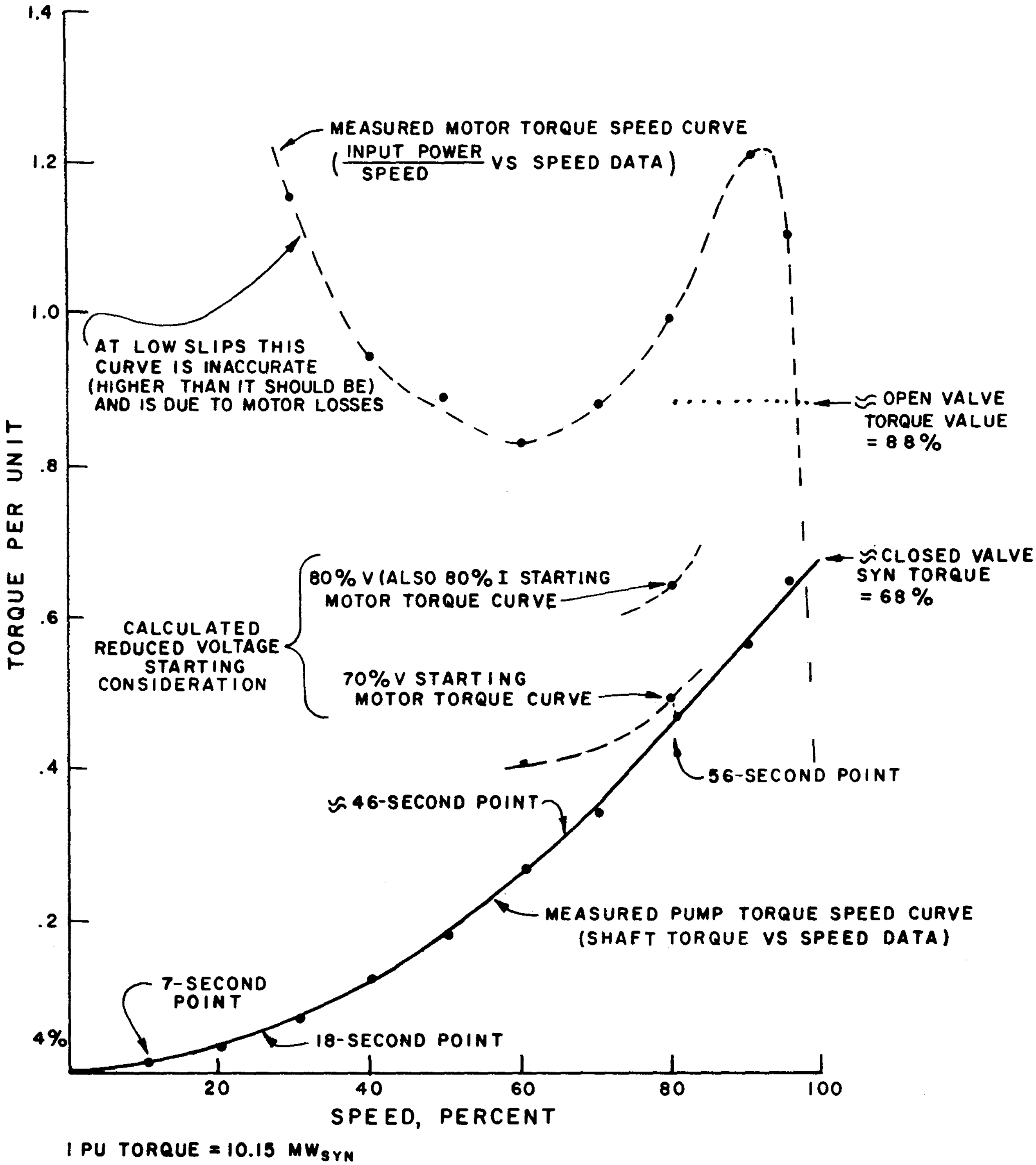
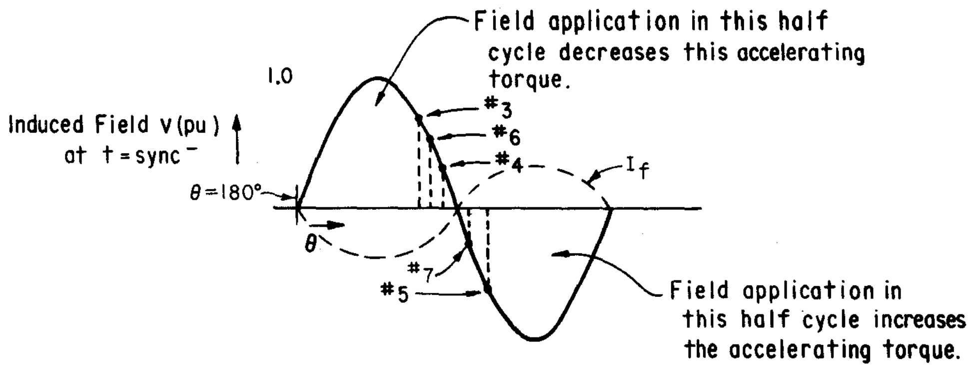


Figure 4. – Torque speed data obtained from test No. 5.



Curve data obtained from table 5

Figure 5. – Field application curve.

The field time constant prevents the current, and resultant flux, from building up instantaneously. Therefore, the lead time provides a head start for the transition and steady-state buildup of field current so that the maximum possible torque is developed to accelarate the rotor to synchronous speed.

It sould be noted that an analysis of the test records of field voltage just after field application does not give evidence of a field circuit time constant effect under transient conditions. Field voltage prior to field application is proportional to field current because of the field discharge resistor being in the circuit. However, after application of the excitation source, the field voltage waveform is proportional to the field current only during steady-state conditions.

A review of the field application control circuits revealed a 1.75-second timer installed between the field application relay and the field breaker. This timer delays the application of field excitation such that the field is no longer applied at the correct point on the induced voltage cycle. Apparently, the field application relay and timer were originally (and erroneously) set years ago by trial and error to produce reasonable results at a system starting voltage of 115.5 kV. This is why any deviation from the 115.5 kV starting point results in somewhat less than ideal conditions for synchronization. The 1.75-second delay timer does not belong in the circuit, and should be removed and the field application relay properly adjusted. If this relay is too difficult to adjust, it should be replaced with a more accurate and modern field application relay.

STARTUP EXCITATION LEVEL

Shortly after synchronization of the motor there is about 1 MQ flowing into the unit; that is, the motor is underexcited. The voltage regulator should be readjusted such that shortly after synchronization, the motor is either operating at unity power factor or is slightly overexcited. This will require a slightly higher excitation current on startup and will thereby increase the torque available during the pulling into step period of operation.

UNWATERED STARTS

With some considerations and modifications, it may be possible to eliminate the hydraulic related problems encountered in starting the unit unwatered. One alternative would be to replace the existing turbine runner with one of a new design. Since the original turbine design was developed for two-speed operation and the unit is now essentially a single-speed device, it is probable that substantial improvements could be obtained from a single-speed replacement turbine. However, this option is extremely expensive.

A second and more economical alternative would be the application of supplemental excitation control to damp the hydraulic transients during the initial valve opening period. During this operating period, the machine is synchronized to the line and operating essentially unloaded. Fast field current control would be used to modulate and damp the hydraulically induced mechanical transients. However, this scheme would require a fast acting modern excitation control system such as the one presently scheduled to be installed on the subject motor in the near future. Also required would be experimental supplemental control equipment. This equipment, with only slight modifications, could also be used to investigate the ability of supplemental control to damp rough zone hydraulic induced transients. A supplemental excitation control system research project to investigate damping in the rough zone was recently proposed by personnel from the Hydraulics Branch in the Bureau's Division of Research and Laboratory Services.

APPENDIX A

FIELD APPLICATION CONSIDERATIONS

APPENDIX A

FIELD APPLICATION CONSIDERATIONS

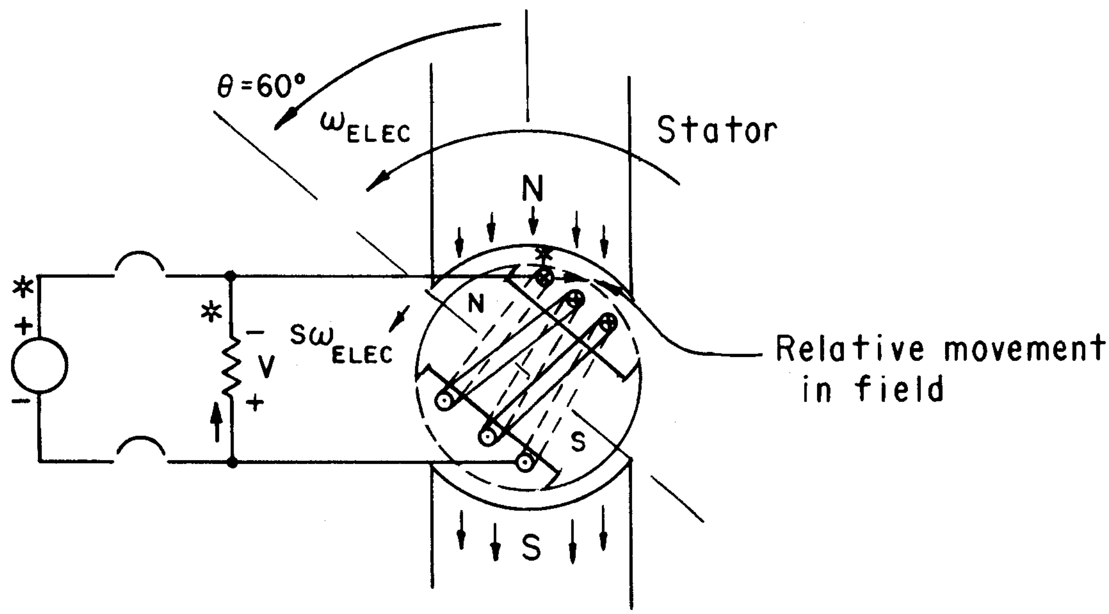
Figures A-1 through A-4 show various instances relating rotor position to the induced voltage in the field winding. The rotor north-south designation is shown on all four figures as it would be if the rotor was energized from the exciter. This is not the magnetic polarity as generated by the induction effect at subsynchronous speed. Rotor position is designated by θ from the 12 o'clock position in a counterclockwise direction. This unit is being operated as a motor in the counterclockwise direction. Near synchronous speed (small slip), it is obvious that the stator magnetic field is also rotating in a counterclockwise direction, but at a speed (synchronous at that) only slightly greater than that of the rotor. As a result, the relative motion of the shorted field conductors with respect to a stationary stator field is in a clockwise direction. The induced direction of current in accordance with the Fleming convention is shown on each figure. The polarity of the voltage induced across the discharge resistor is also shown.

By inspection, it can be seen that energizing the field with the rotor in the position shown in either figure A-1 or A-2 will result in increasing the rotor magnetic field strength, and thereby cause the rotor to accelerate. Energizing the field with the rotor in the position shown in either figure A-3 or A-4 will result in a demagnetizing effect which will cause the rotor to decelerate. Obviously, energizing the rotor field at $\theta = 180°$ would appear to result in a maximum acceleration effort. However, the field time constant would prevent field current from building up instantaneously in both the transition period (going from induction to synchronous mode of operation) and in the synchronous period involving field current build up. Therefore, energizing the field slightly prior to $\theta = 0$ will provide sufficient lead time to allow current to build up from zero so that maximum torque can be generated to pull the motor into synchronism.

Figure A-5 is a plot of the flux linking the field winding as a function of rotor angle θ. From this plot, figure A-6 can be obtained, which shows the time rate of change of flux (which is proportional to the induced rotor field voltage) as a function of rotor angle θ. The induced voltages at the rotor positions shown on figures A-1 through A-4 are also shown on figure A-6 as well as several other pertinent relationships.

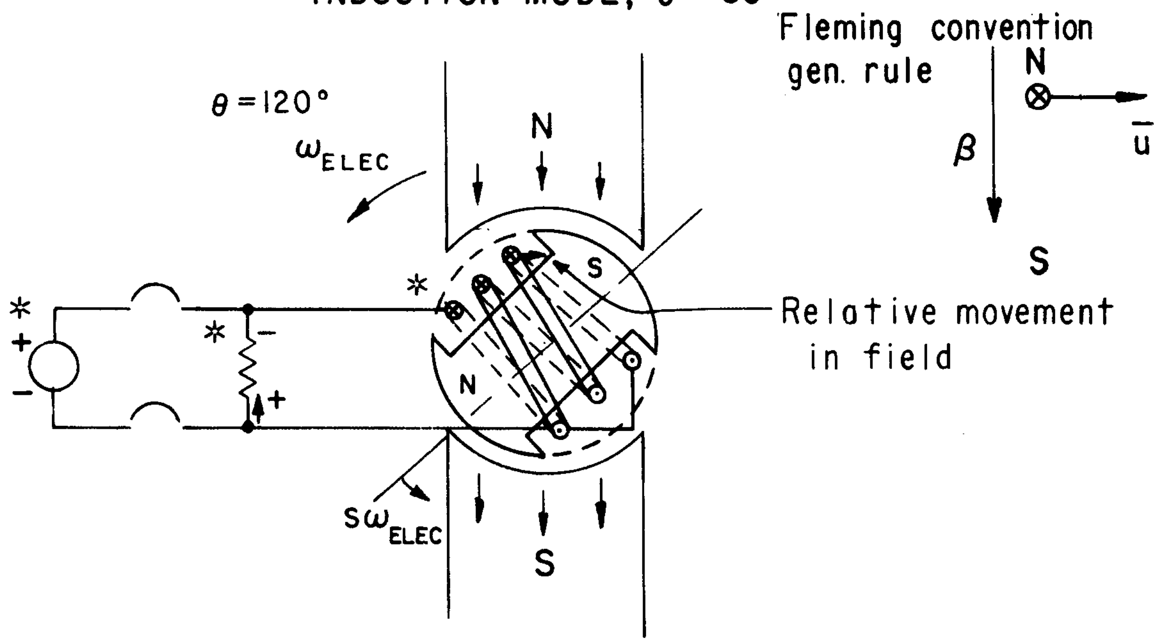
Figure A-6 shows the field current response starting at the time of field voltage application. The unsaturated field time constant is 5.3 seconds, the time constant corrected for saturation at unity voltage is 4.6 seconds, and the actual measured time constant is 3.1 seconds. The actual time constant of 3.1 seconds is considerably lower than 4.6 seconds, and is due to the high internal transient voltage of the machine further contributing to saturation effects. It should be noted that during this field buildup period the stator current is in a transient state, decaying from 2.7 to 0.7 per unit.

The 290-A, 1-second field current pulse at the beginning of the trace is due to the transient conditions in accelerating the motor from subsynchronous (induction) operation to synchronous operation.



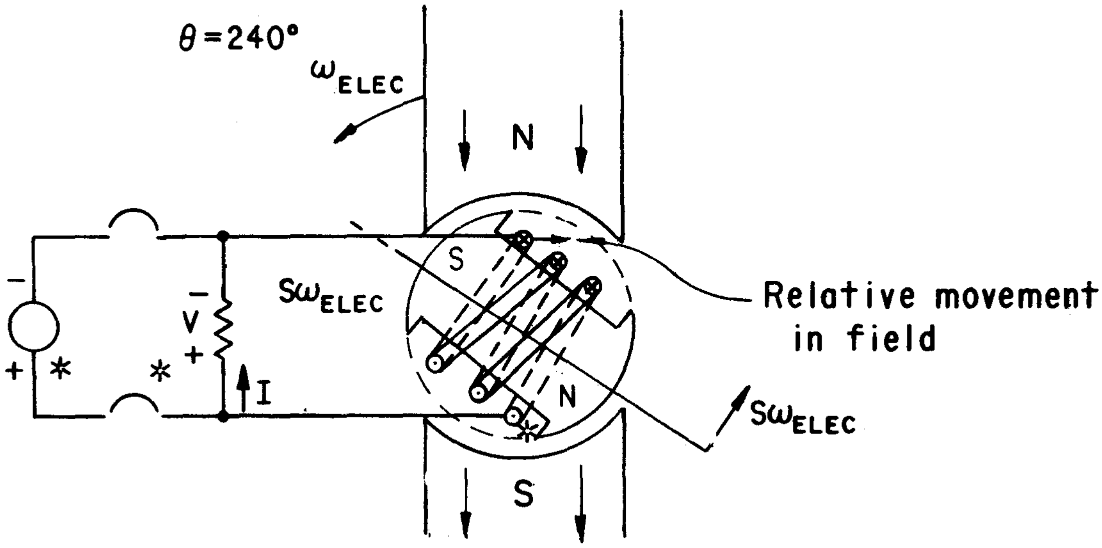
Comments: Machine most likely will not pull into step.

FIGURE A-1 - SYNCHRONOUS MACHINE START UP INDUCTION MODE, $\theta = 60°$



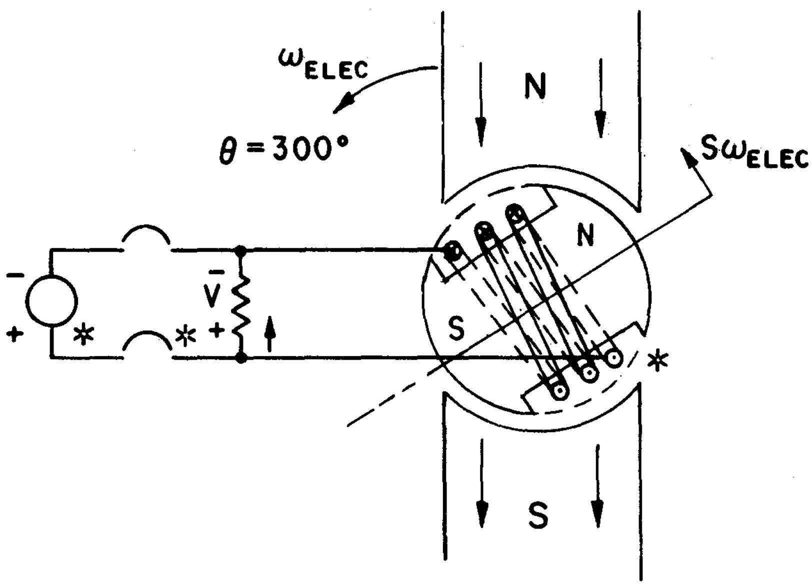
Comments: Machine most likely will pull into step.

FIGURE A-2 - SYNCHRONOUS MACHINE START UP INDUCTION MODE, $\theta = 120°$



Comments: Machine
most likely will pull
into step.

FIGURE A-3 - SYNCHRONOUS MACHINE START UP, INDUCTION MODE, $\theta=240°$



Comments: Machine most likely
will not pull into step.

FIGURE A-4 - SYNCHRONOUS MACHINE START UP, INDUCTION MODE, $\theta=300°$

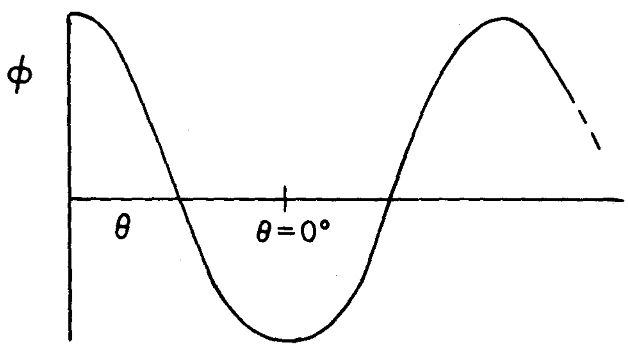
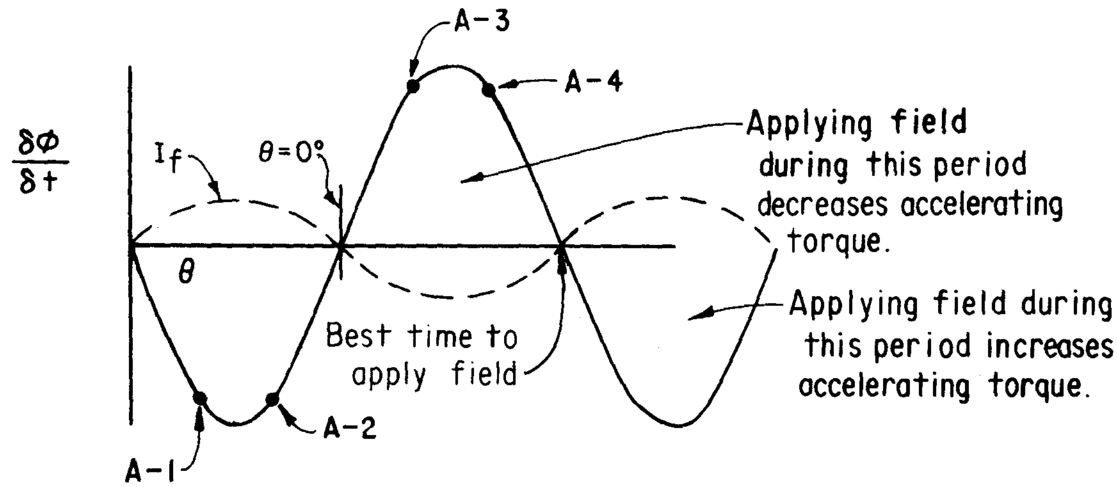


FIGURE A-5 PLOT OF FLUX ϕ LINKING THE FIELD WINDING AS A FUNCTION OF THE ANGLE OF ROTATION



NOTE: 1. V_f induced α $\delta\phi/\delta t$

2. Points D-1 through D-4 correspond to the voltages induced in the winding for the various rotor positions shown in figures A-1 through A-4.

FIGURE A-6 PLOT OF $\frac{\delta\phi}{\delta t}$ AS A FUNCTION OF THE ANGLE OF ROTATION θ

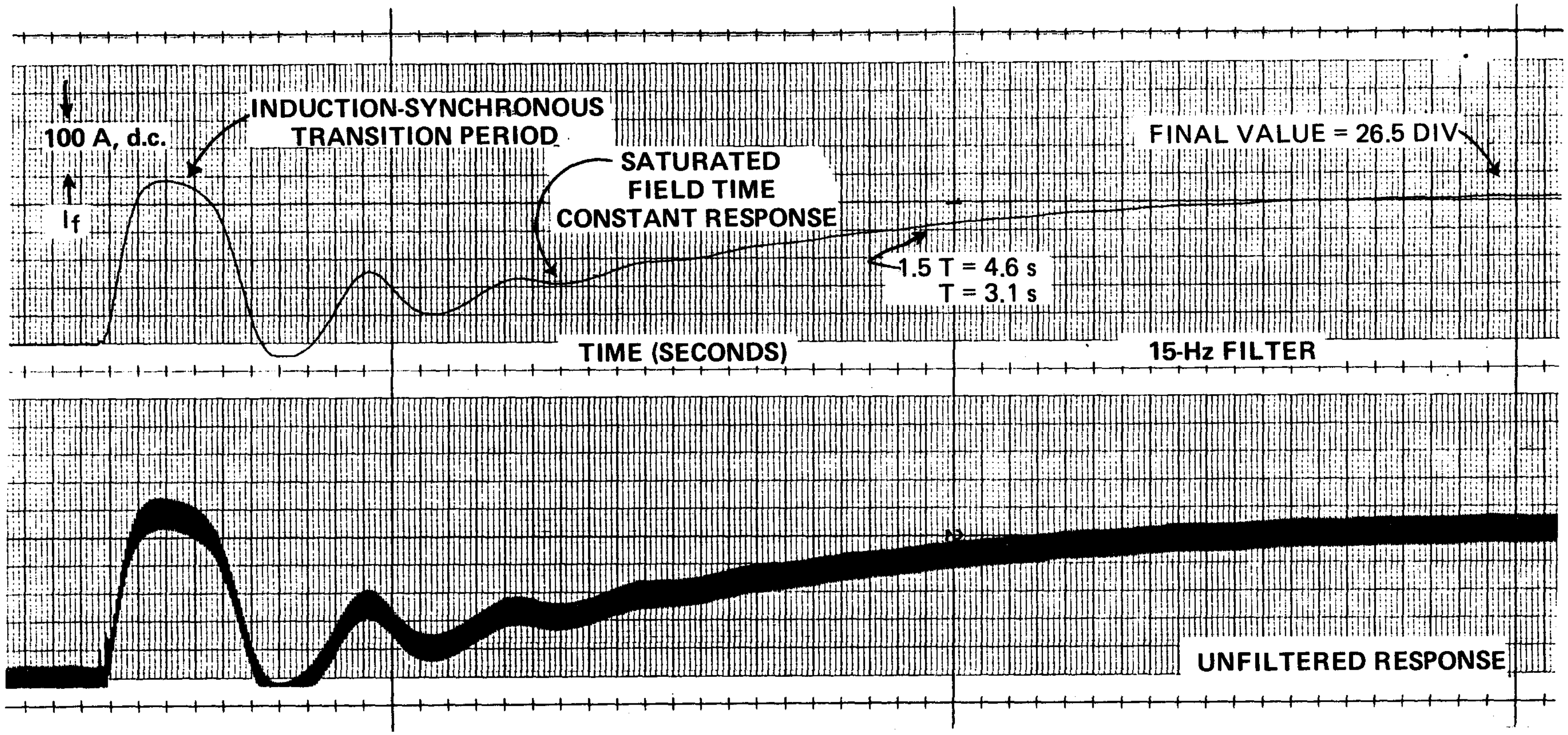


Figure A-7. – Field current response at time of field application.

APPENDIX B

TEST RECORDS

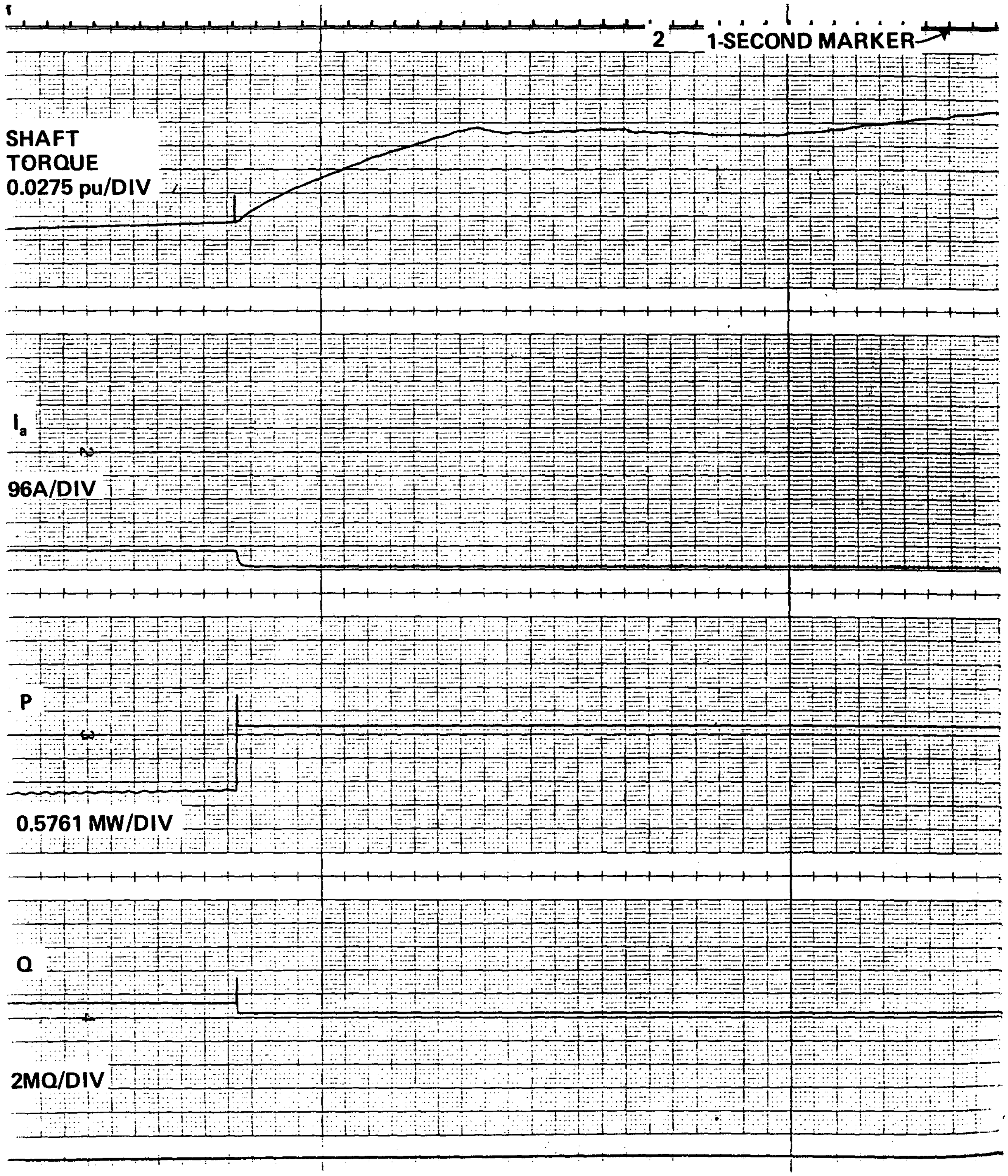


Figure B-1. – Test 2, shutdown (sheet 1 of 2).

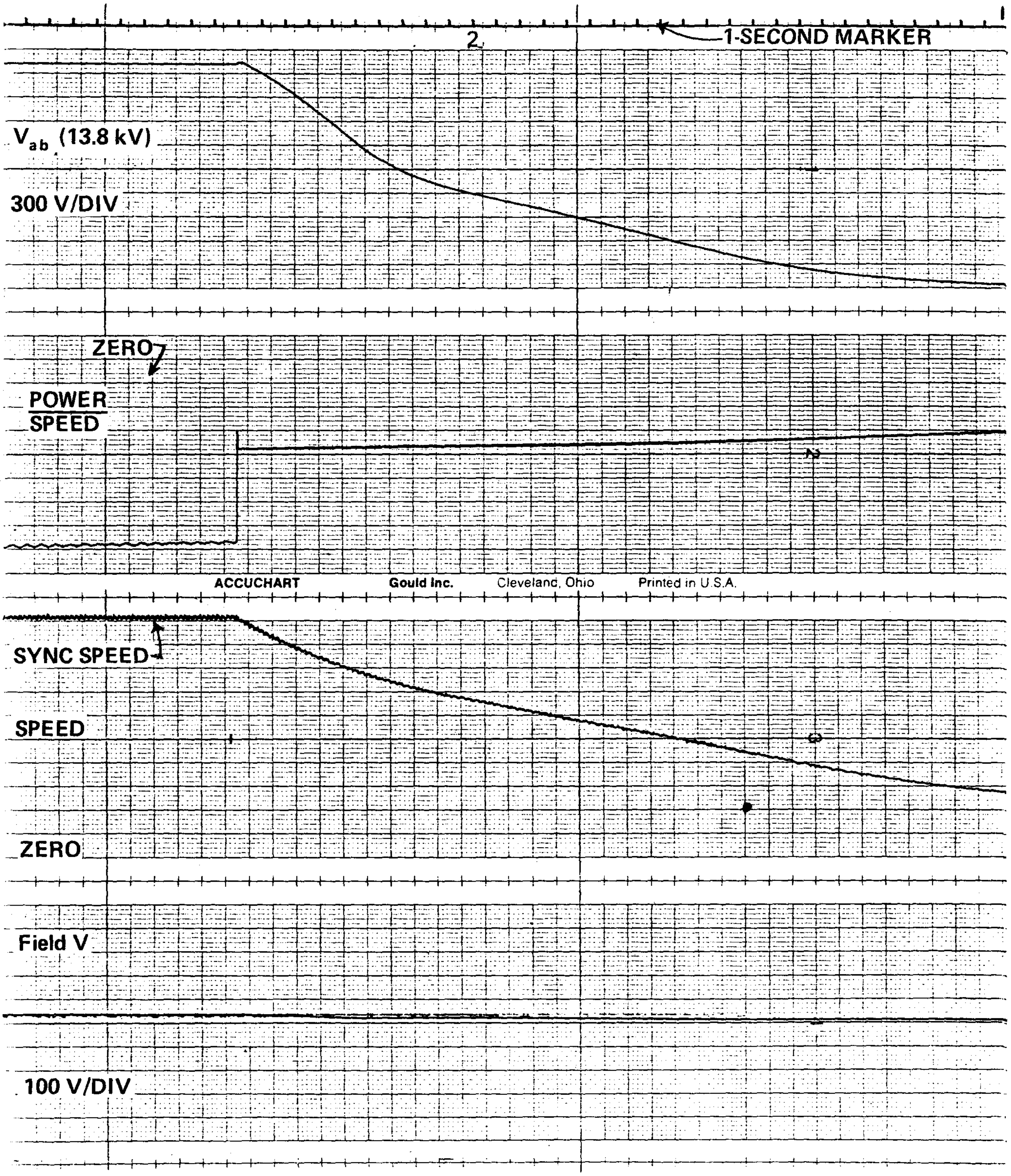


Figure B-1. – Test 2, shutdown (sheet 2 of 2).

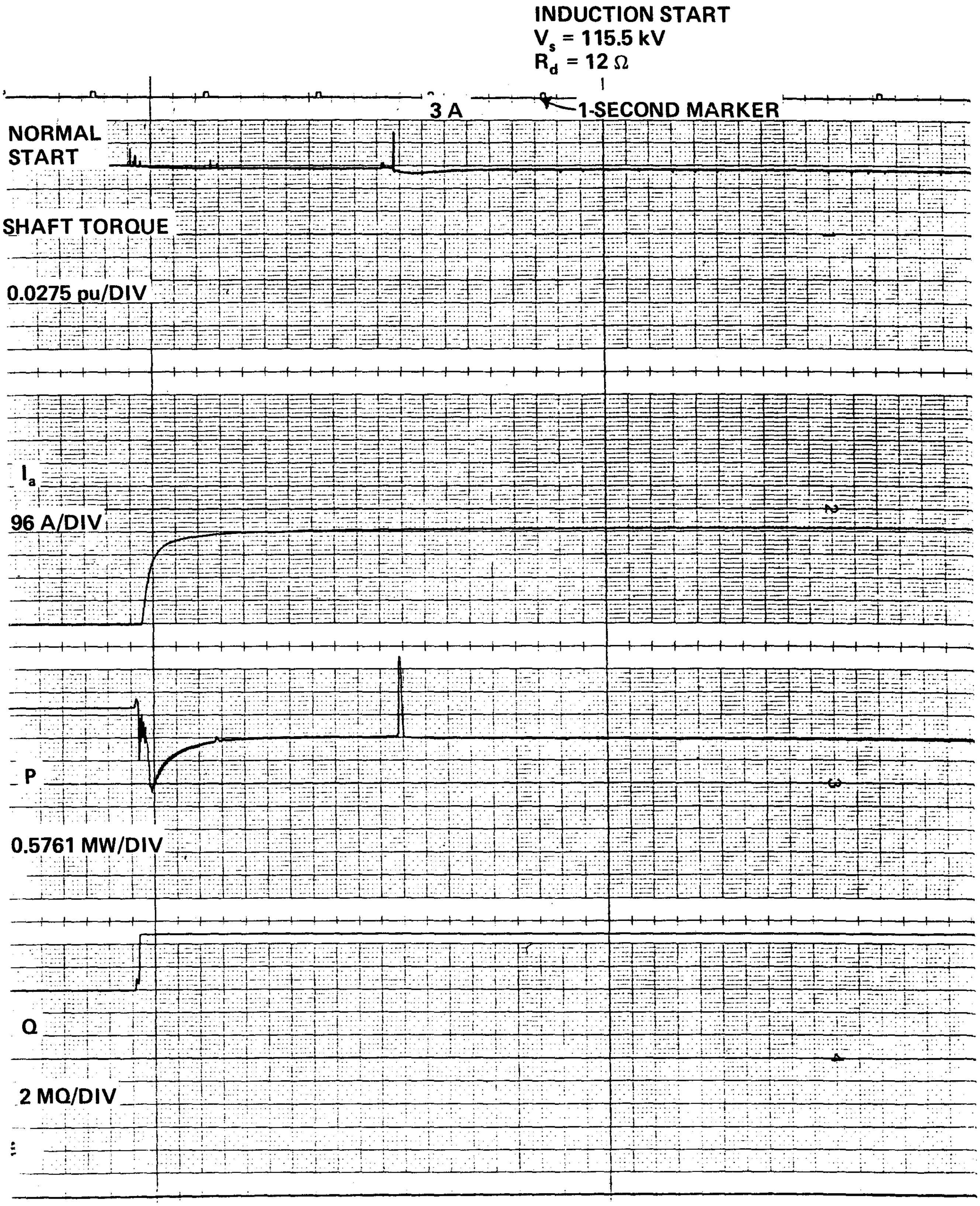


Figure B-2. – Test 3, induction start (sheet 1 of 2).

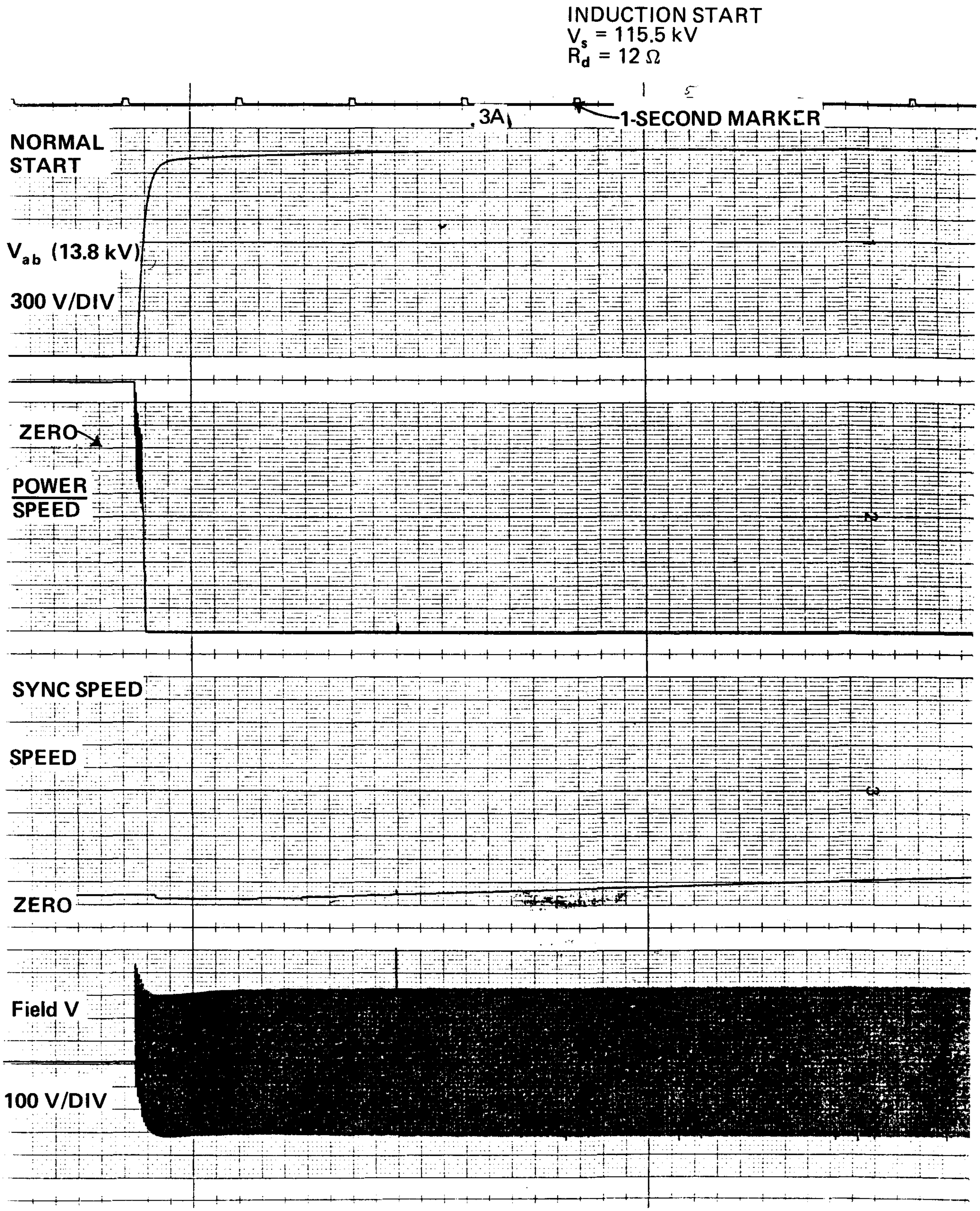


Figure B-2. – Test 3, induction start (sheet 2 of 2).

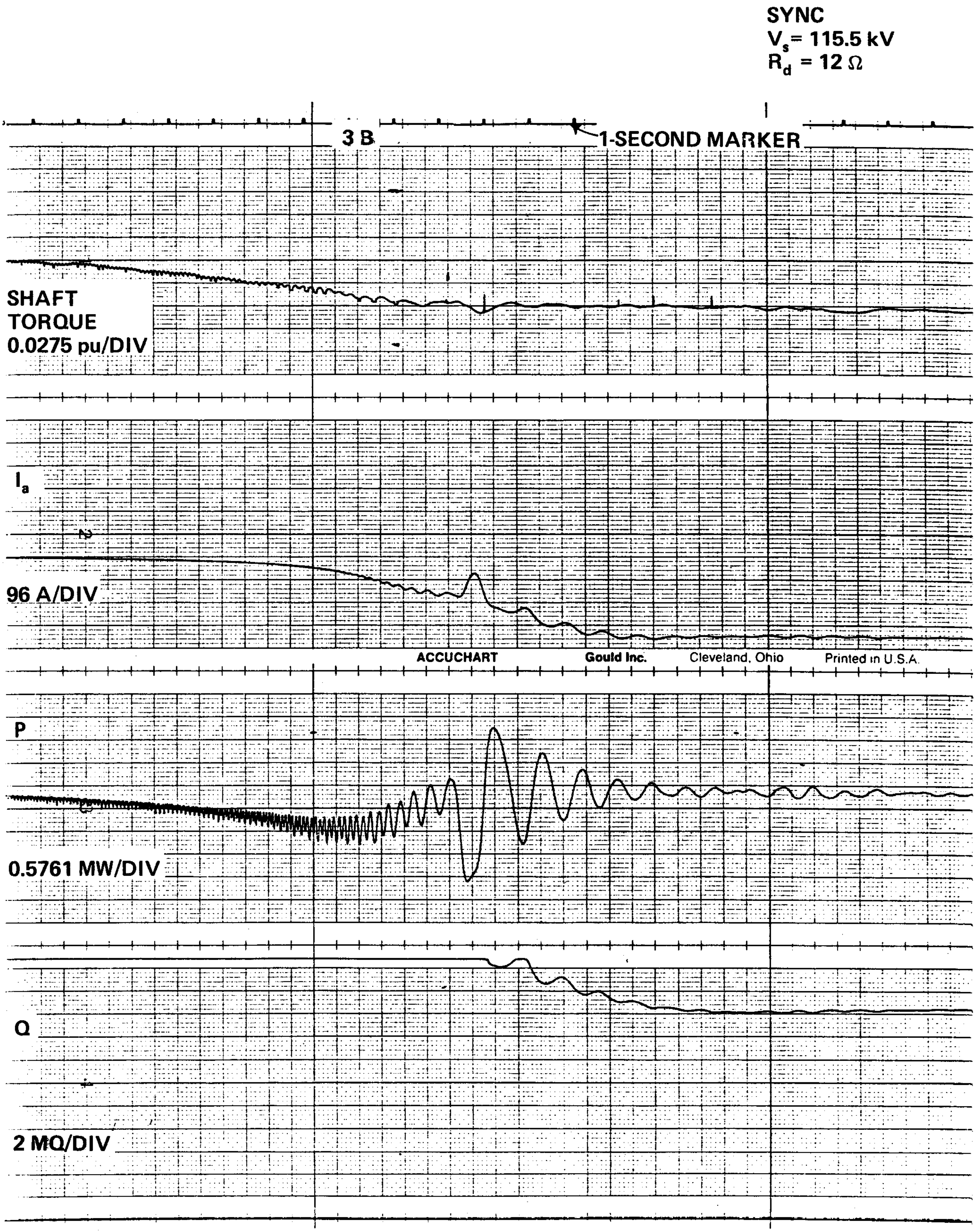


Figure B-3. – Test 3, synchronization (sheet 1 of 2).

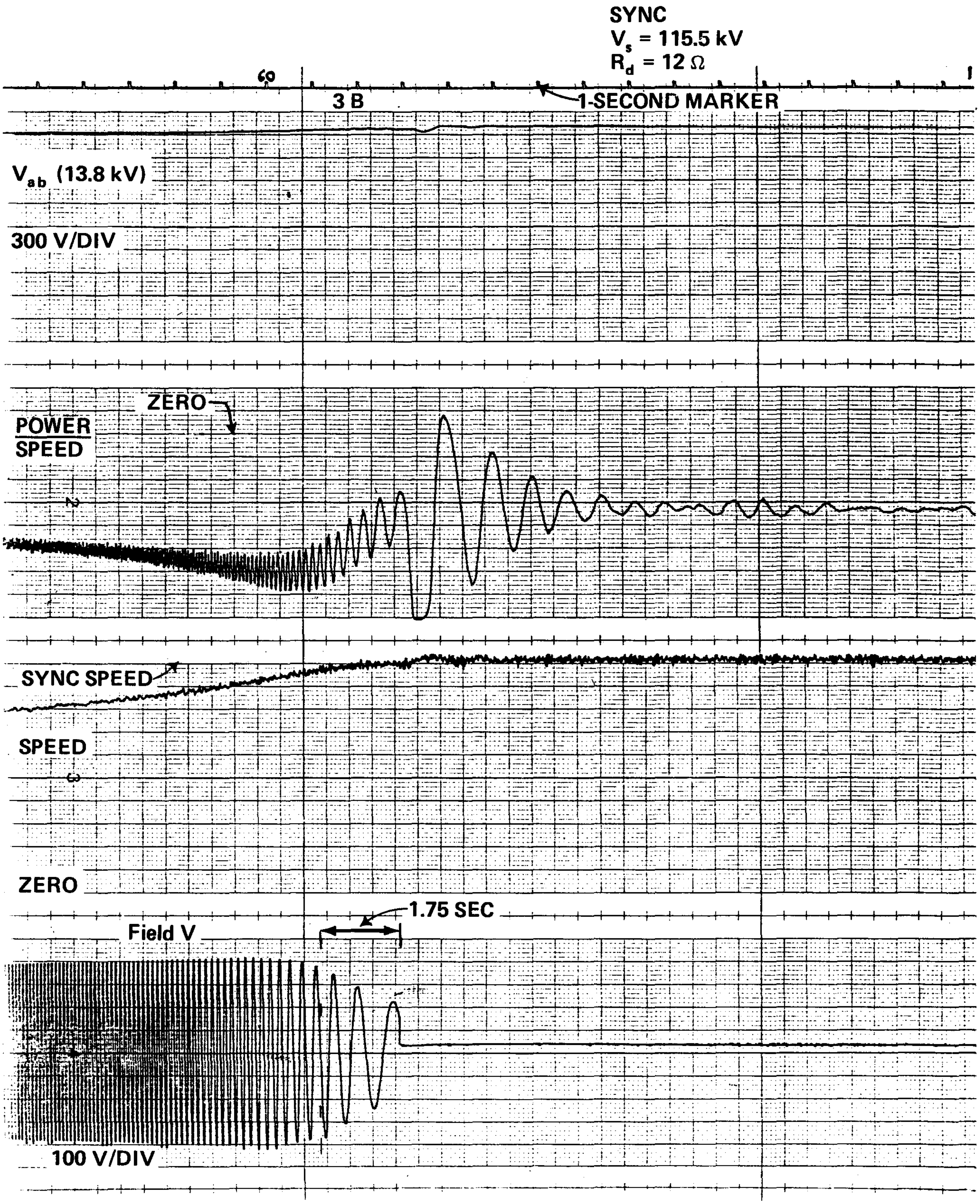


Figure B-3. – Test 3, synchronization (sheet 2 of 2).

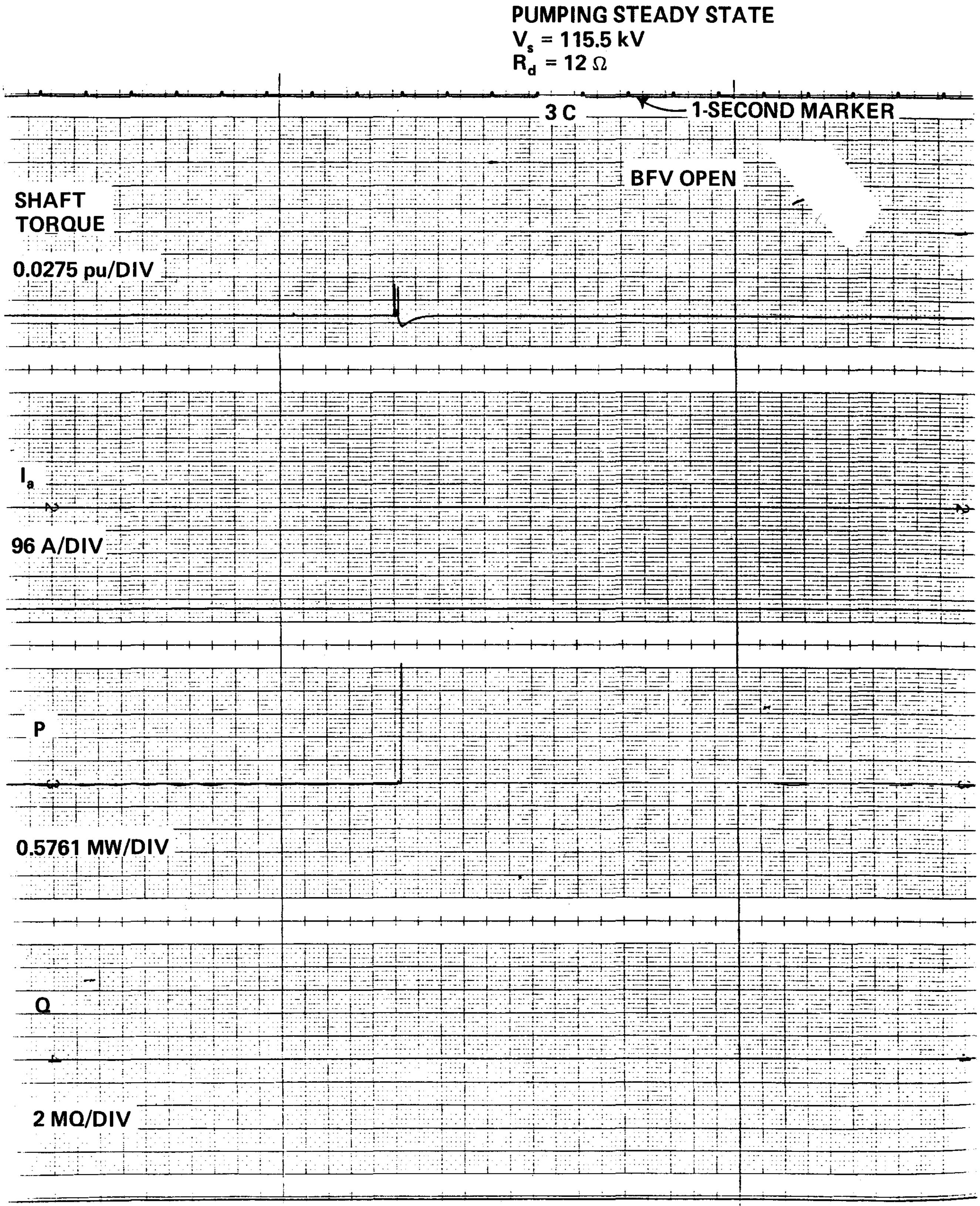


Figure B-4. – Test 3, pumping–steady state (sheet 1 of 2).

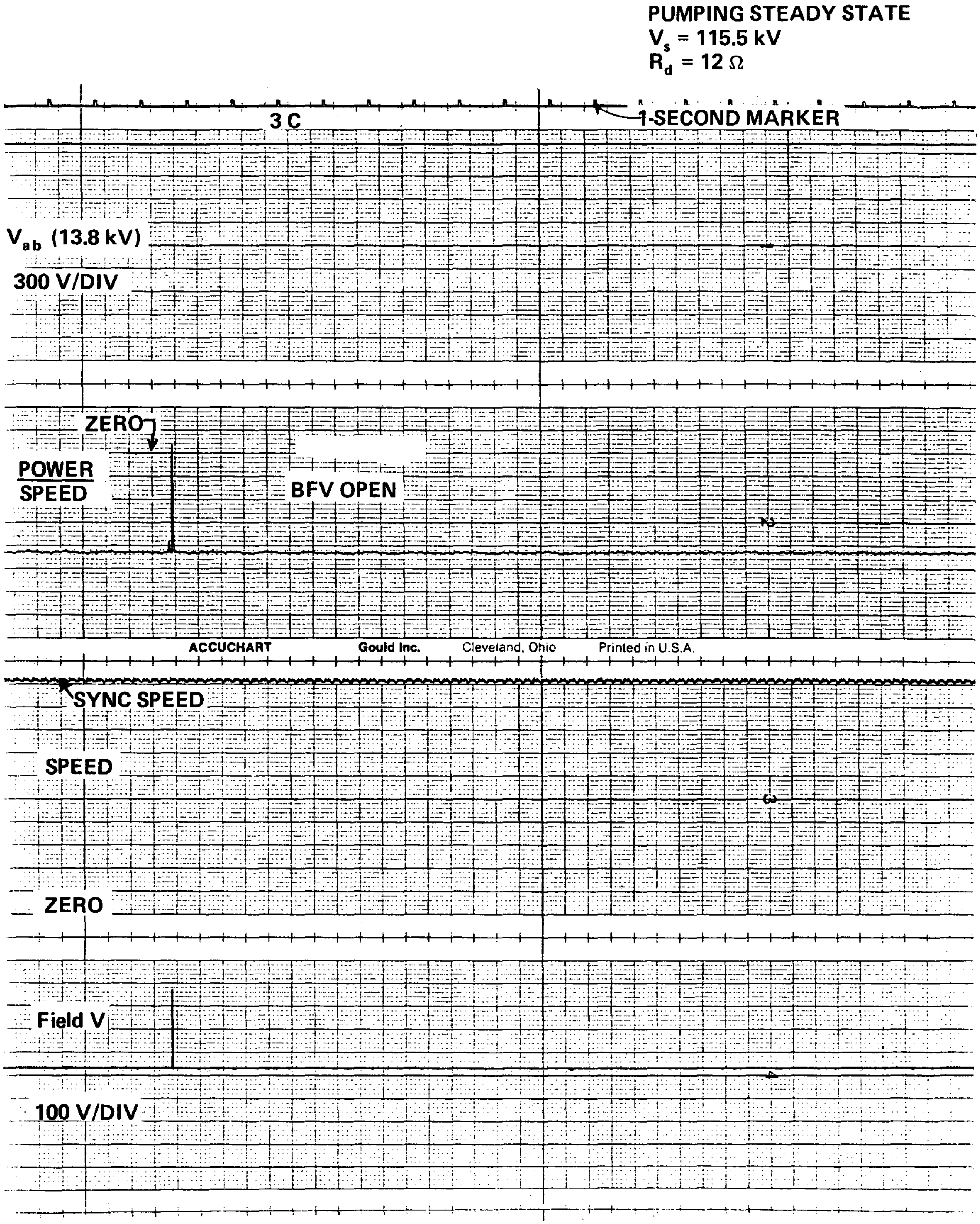


Figure B-4. – Test 3, pumping–steady state (sheet 2 of 2).

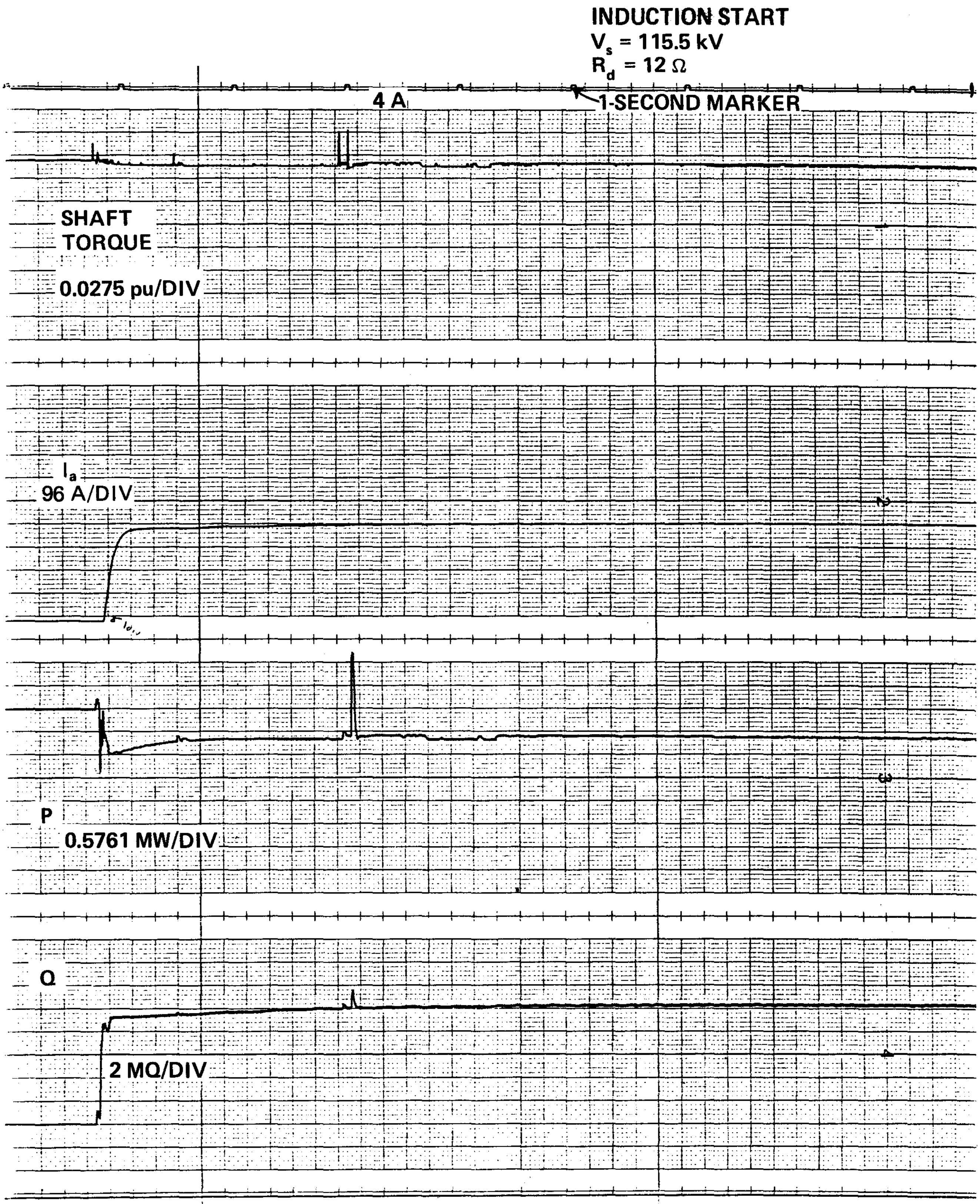


Figure B-5. – Test 4, induction start (sheet 1 of 2).

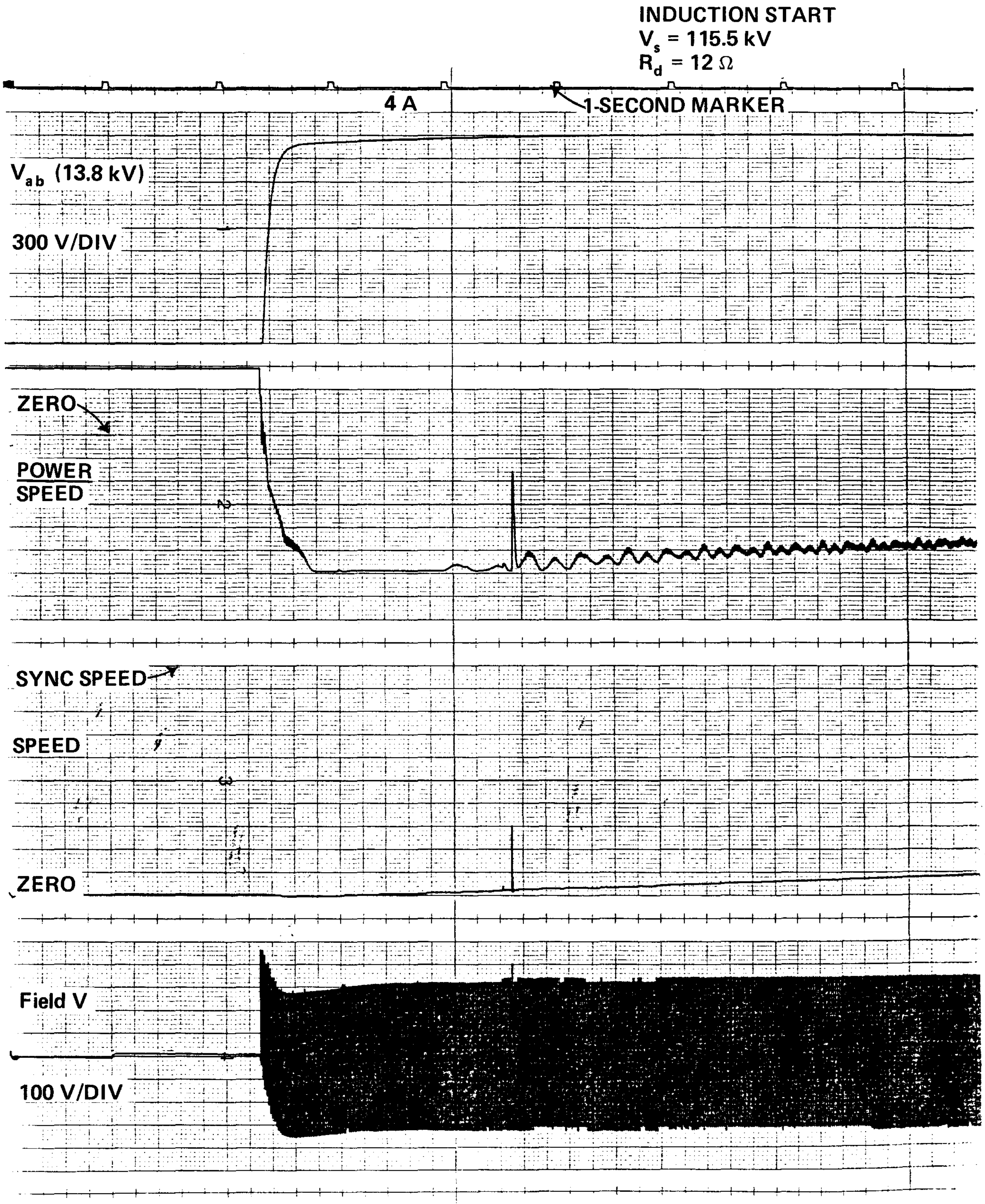


Figure B-5. – Test 4, induction start (sheet 2 of 2).

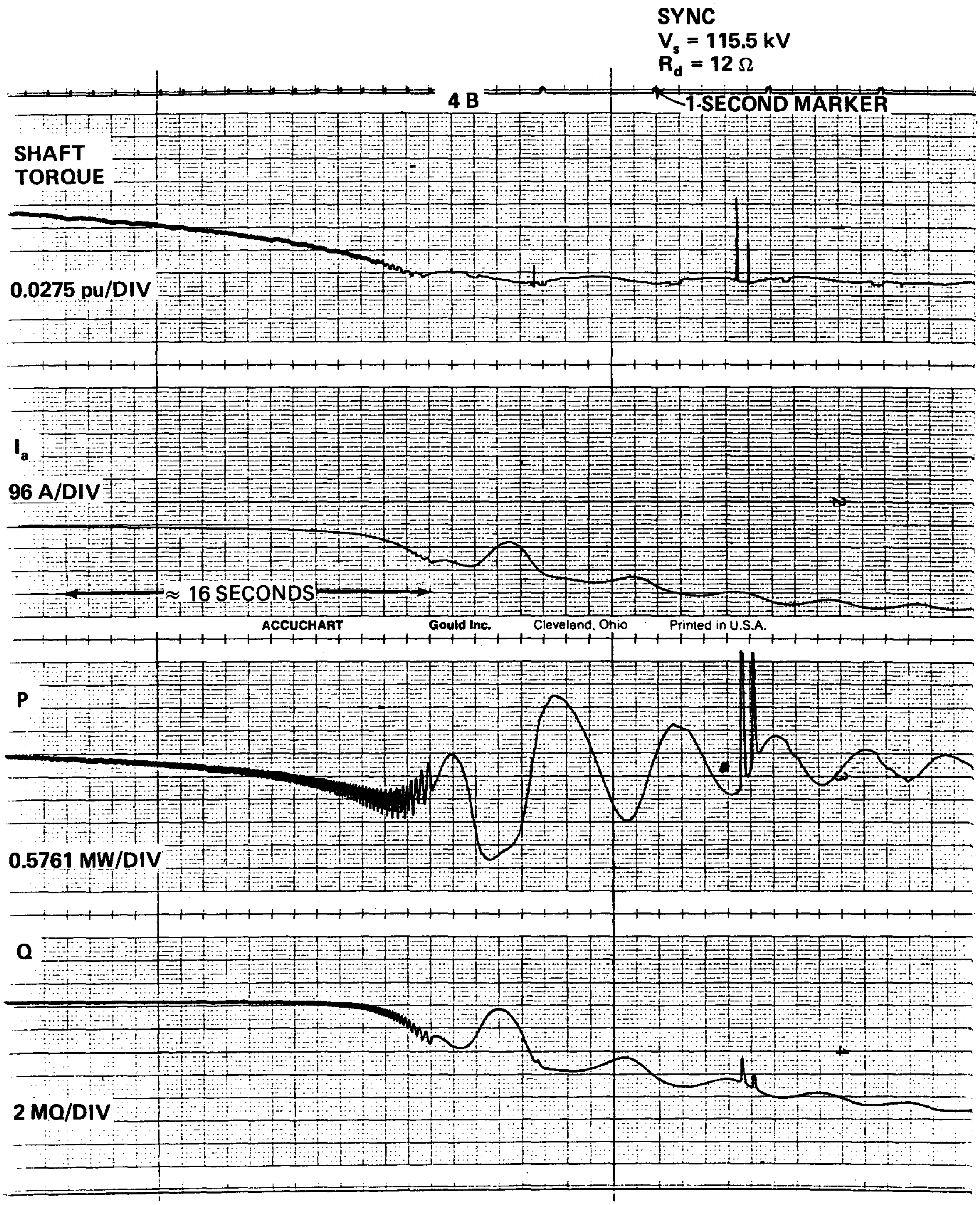


Figure B-6. – Test 4, synchronization (sheet 1 of 2).

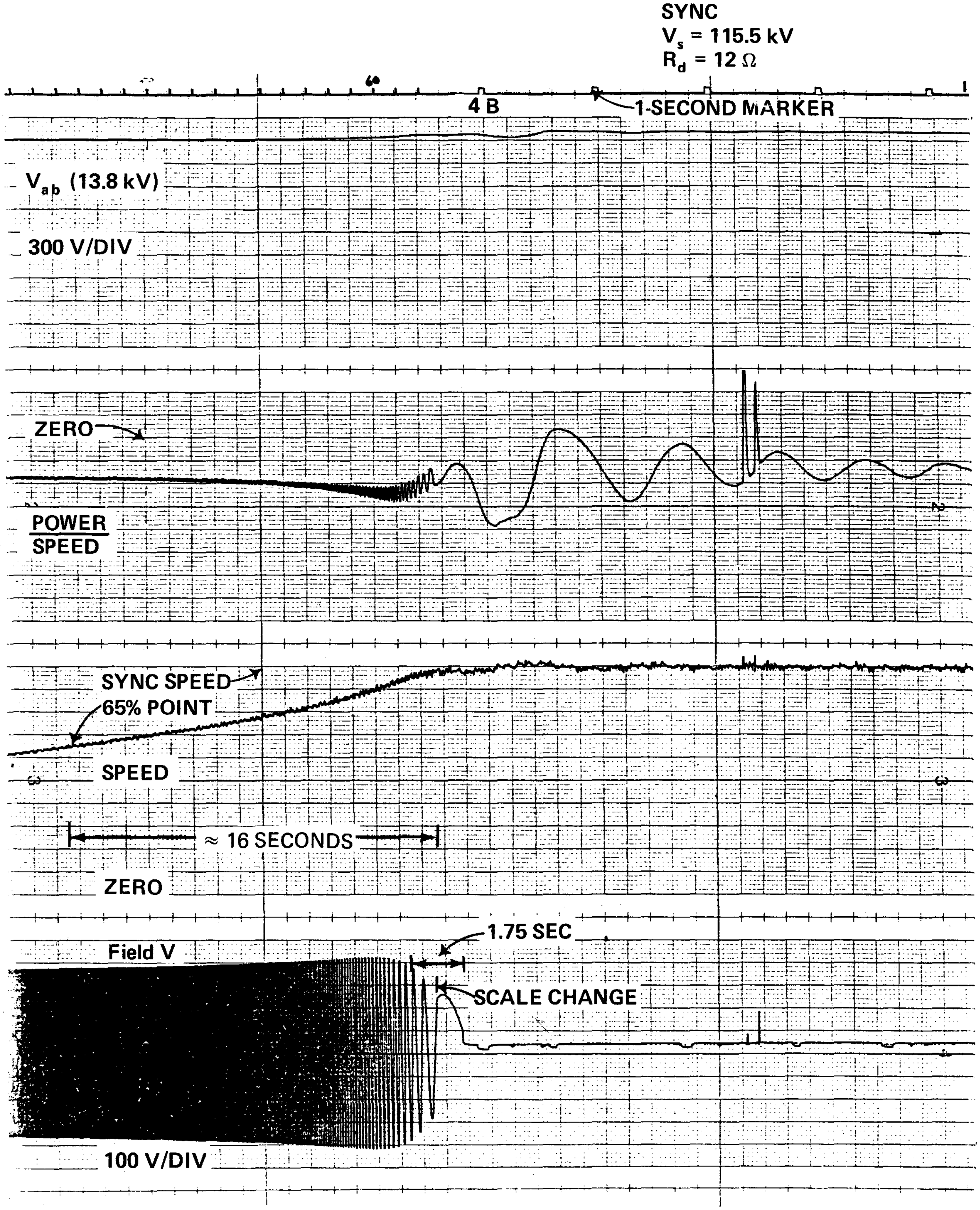


Figure B-6. – Test 4, synchronization (sheet 2 of 2).

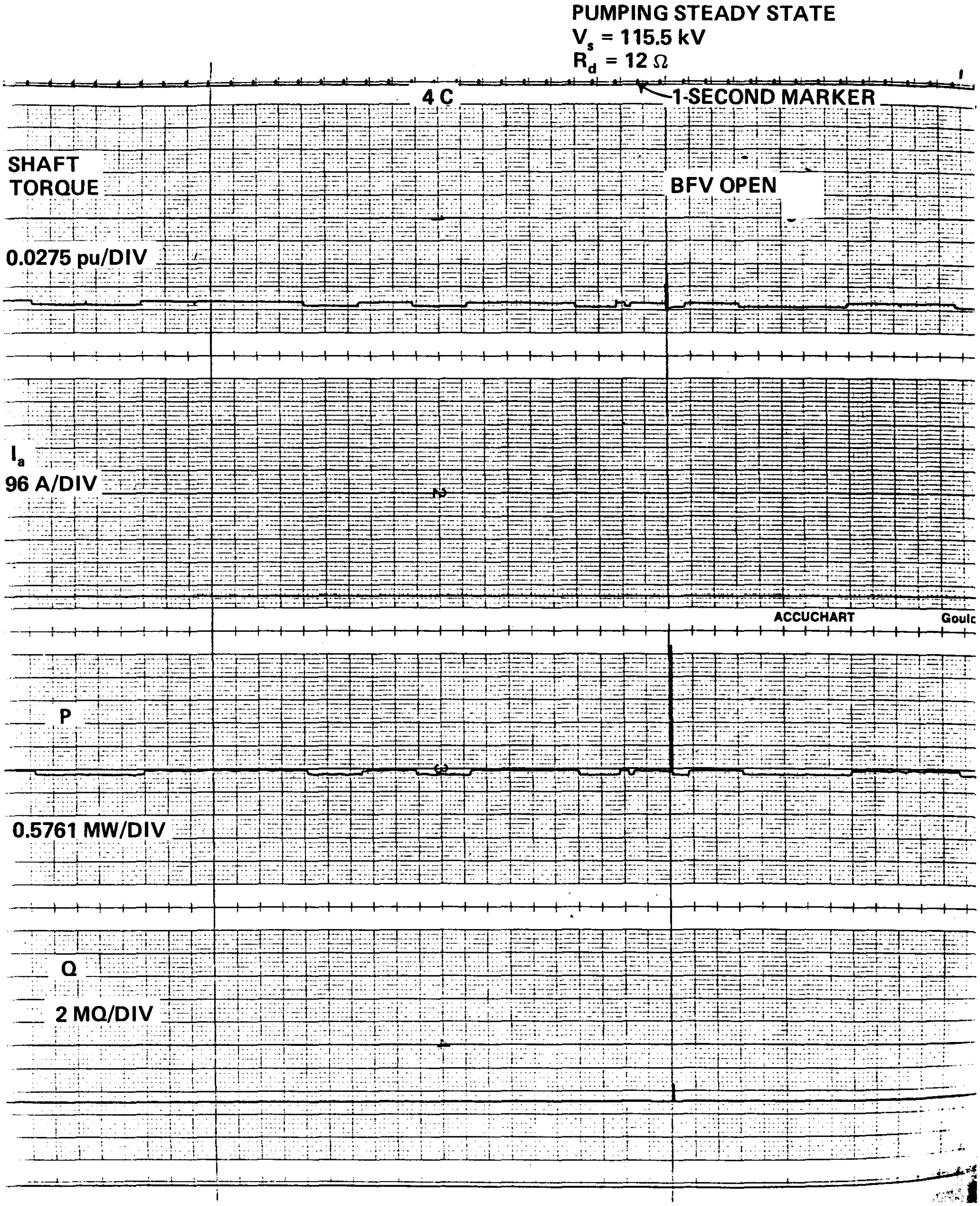


Figure B-7. – Test 4, pumping–steady state (sheet 1 of 2).

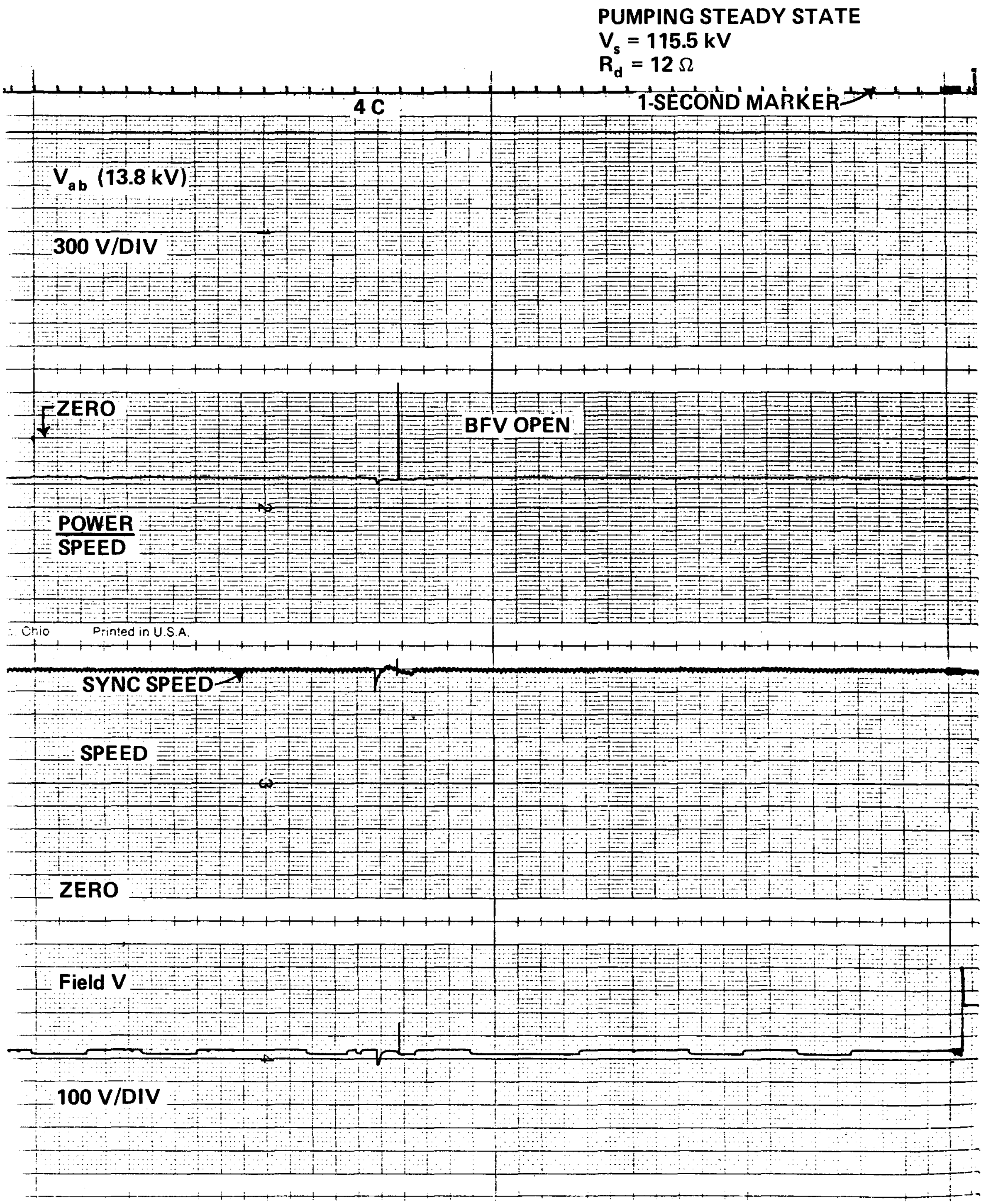


Figure B-7. – Test 4, pumping–steady state (sheet 2 of 2).

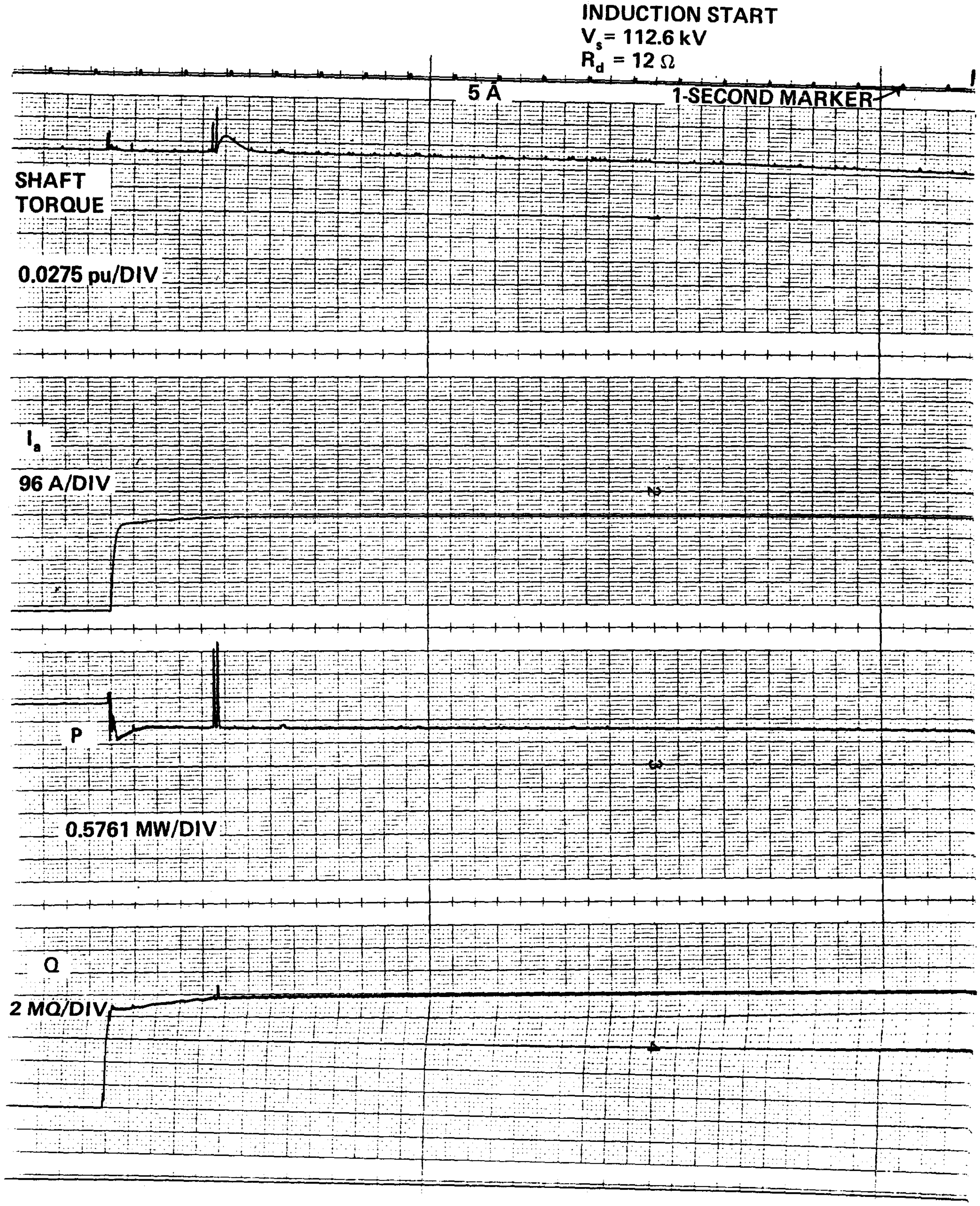


Figure B-8. – Test 5, induction start (sheet 1 of 2).

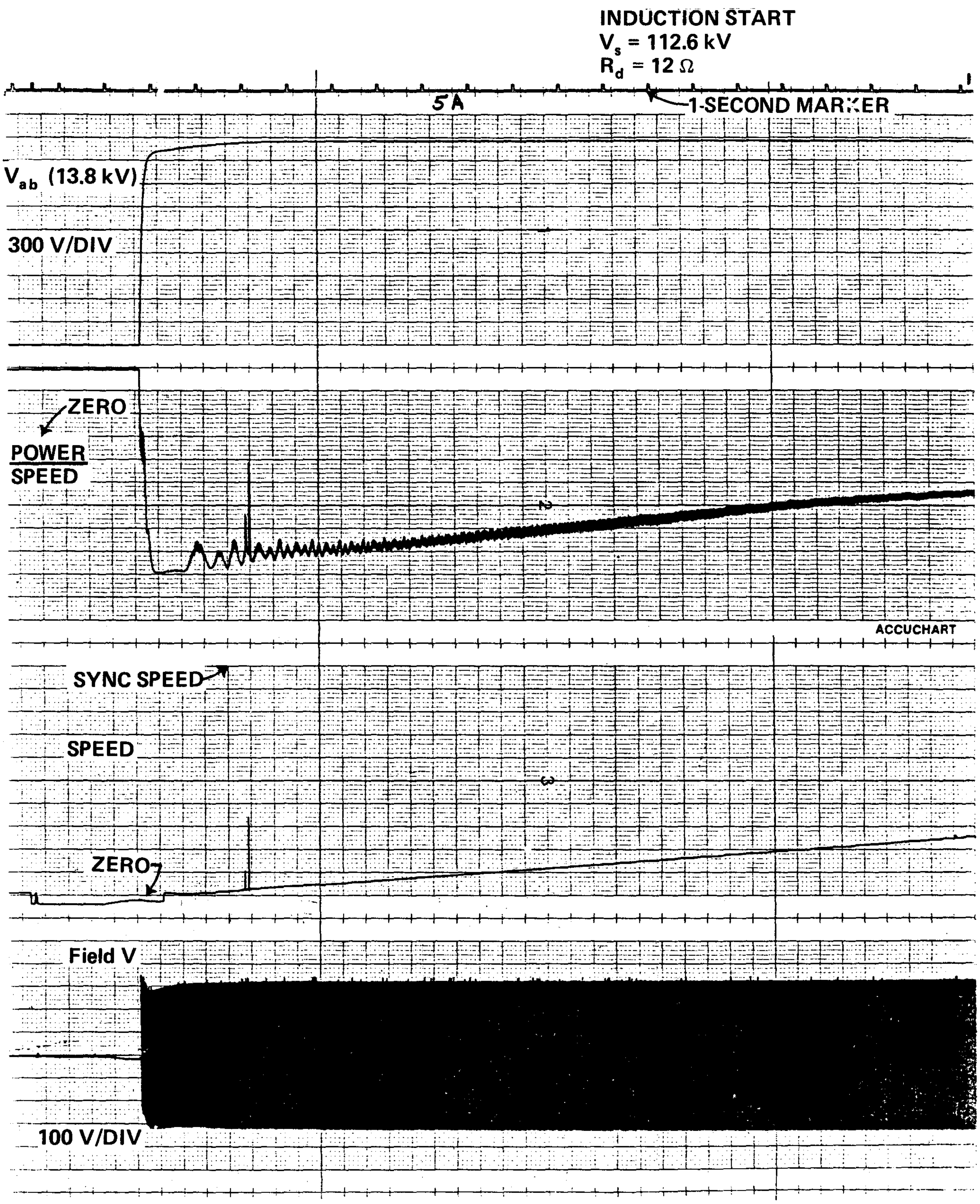


Figure B-8. – Test 5, induction start (sheet 2 of 2).

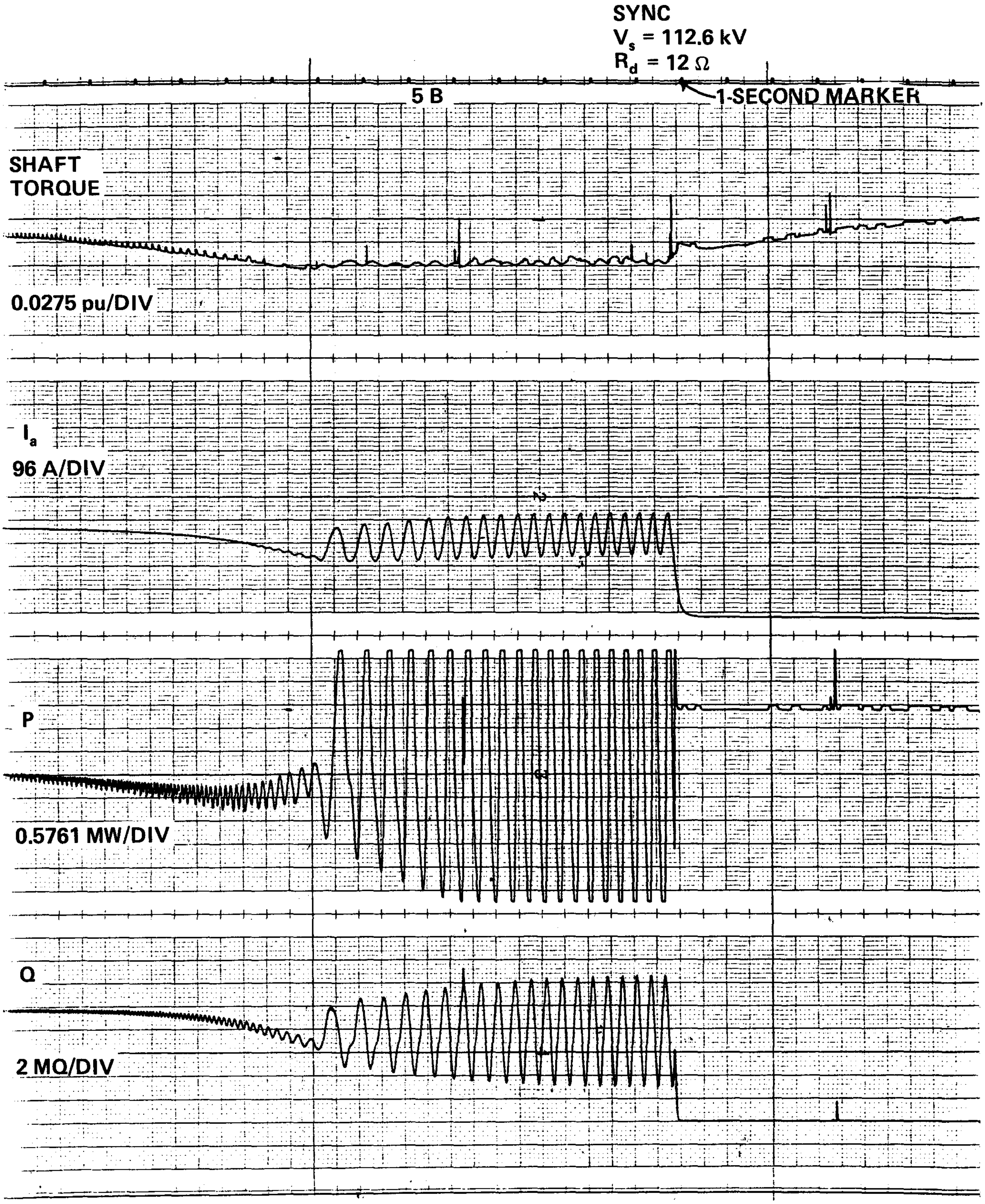


Figure B-9. – Test 5, synchronization (sheet 1 of 2).

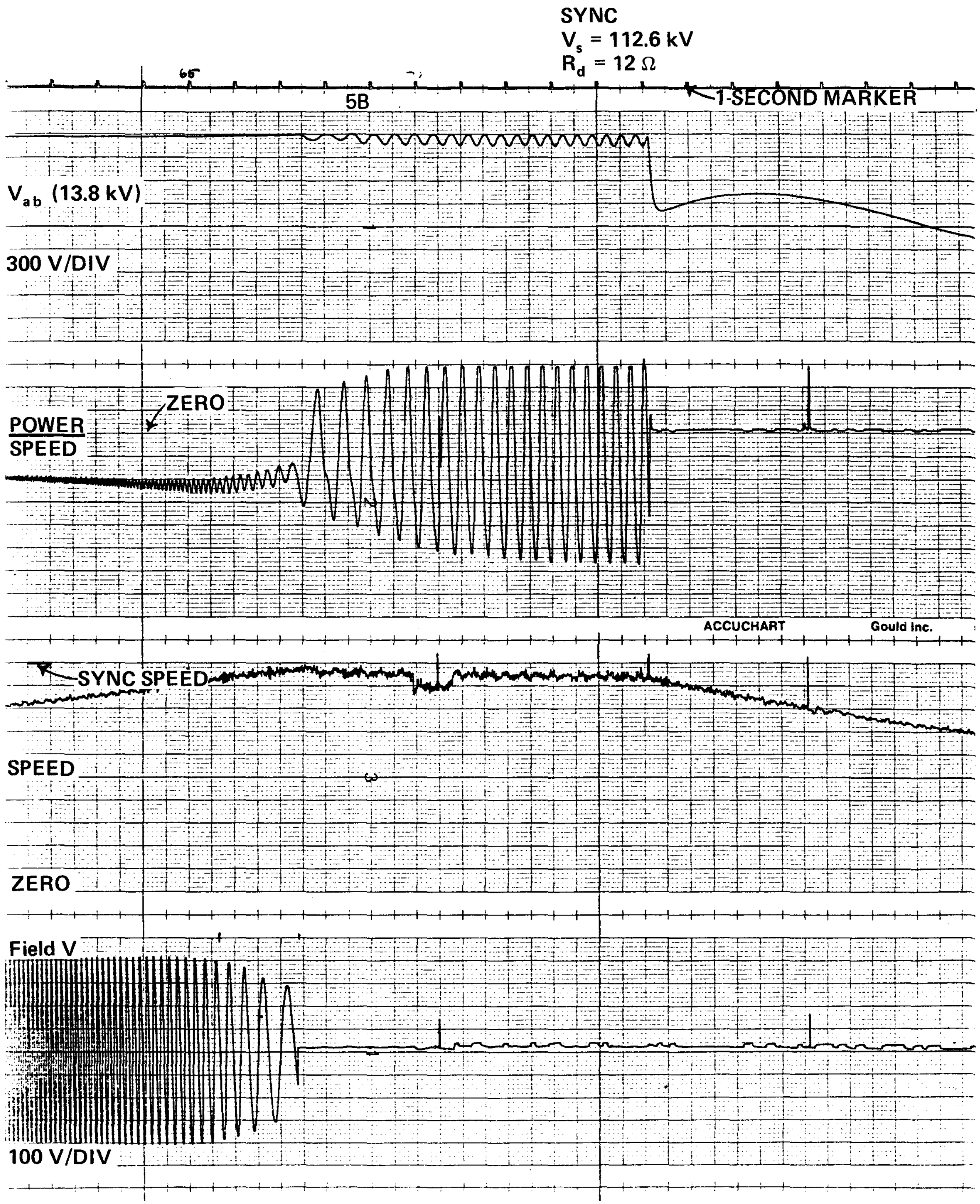


Figure B-9. – Test 5, synchronization (sheet 2 of 2).

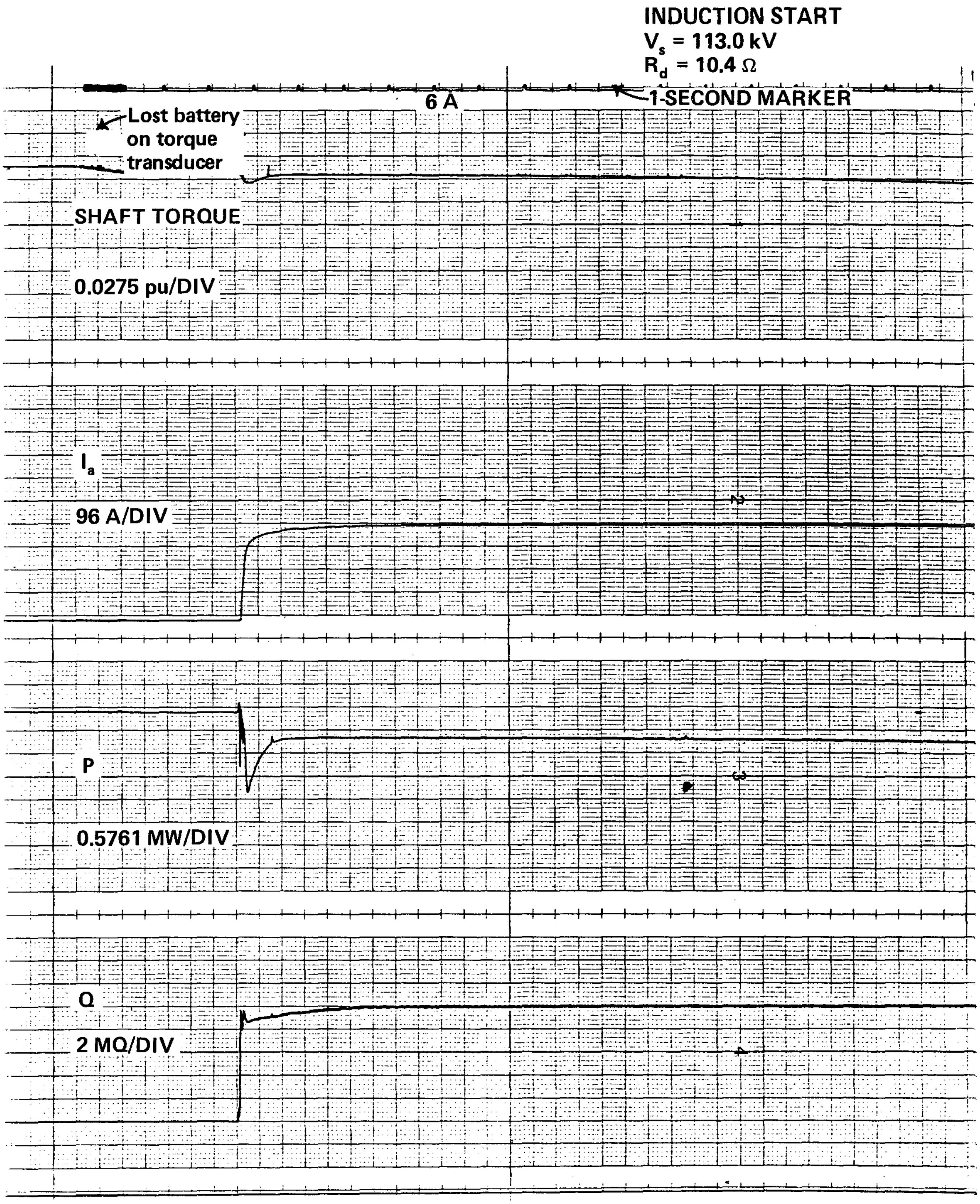


Figure B-10. – Test 6, induction start (sheet 1 of 2).

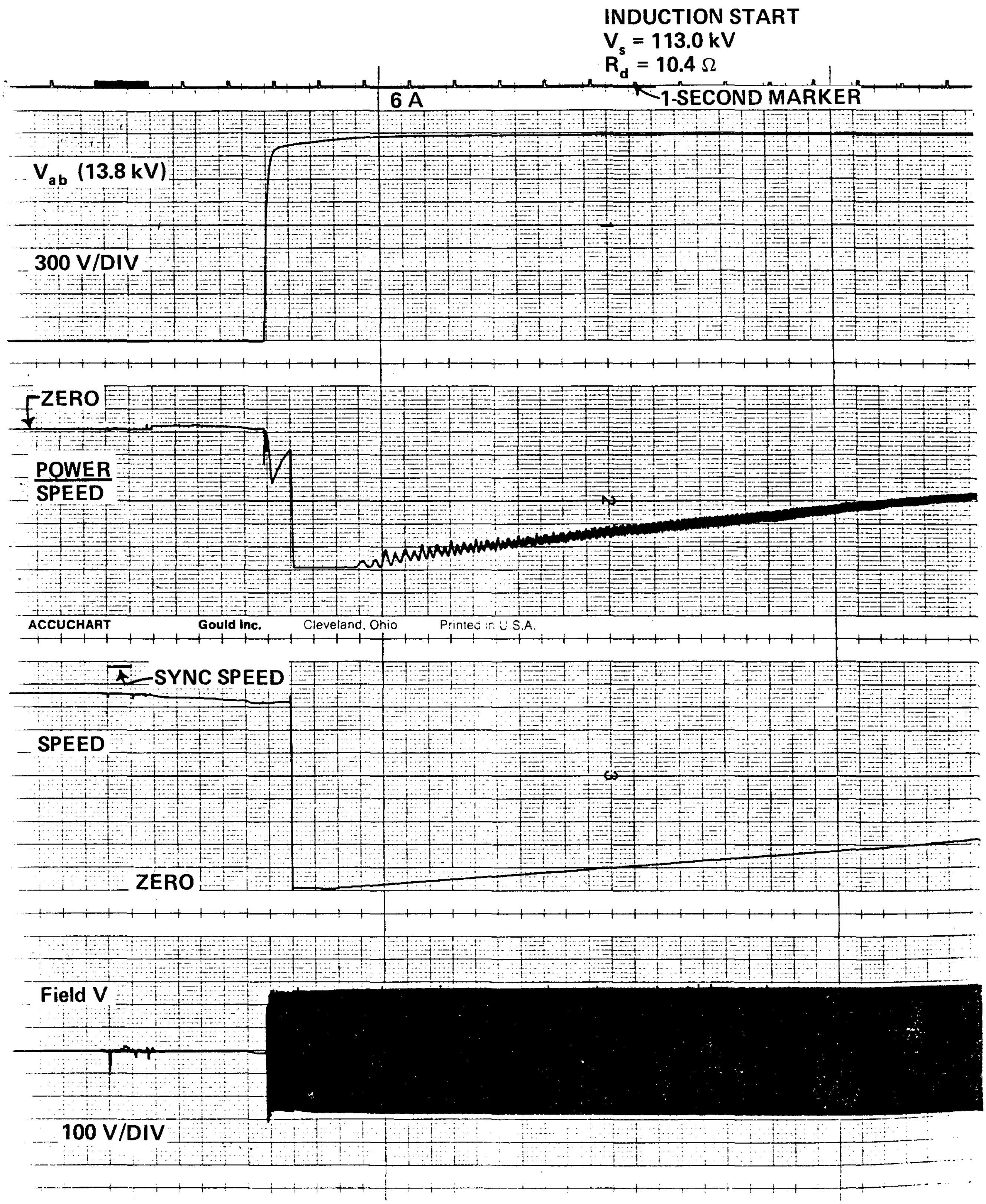


Figure B-10. – Test 6, induction start (sheet 2 of 2).

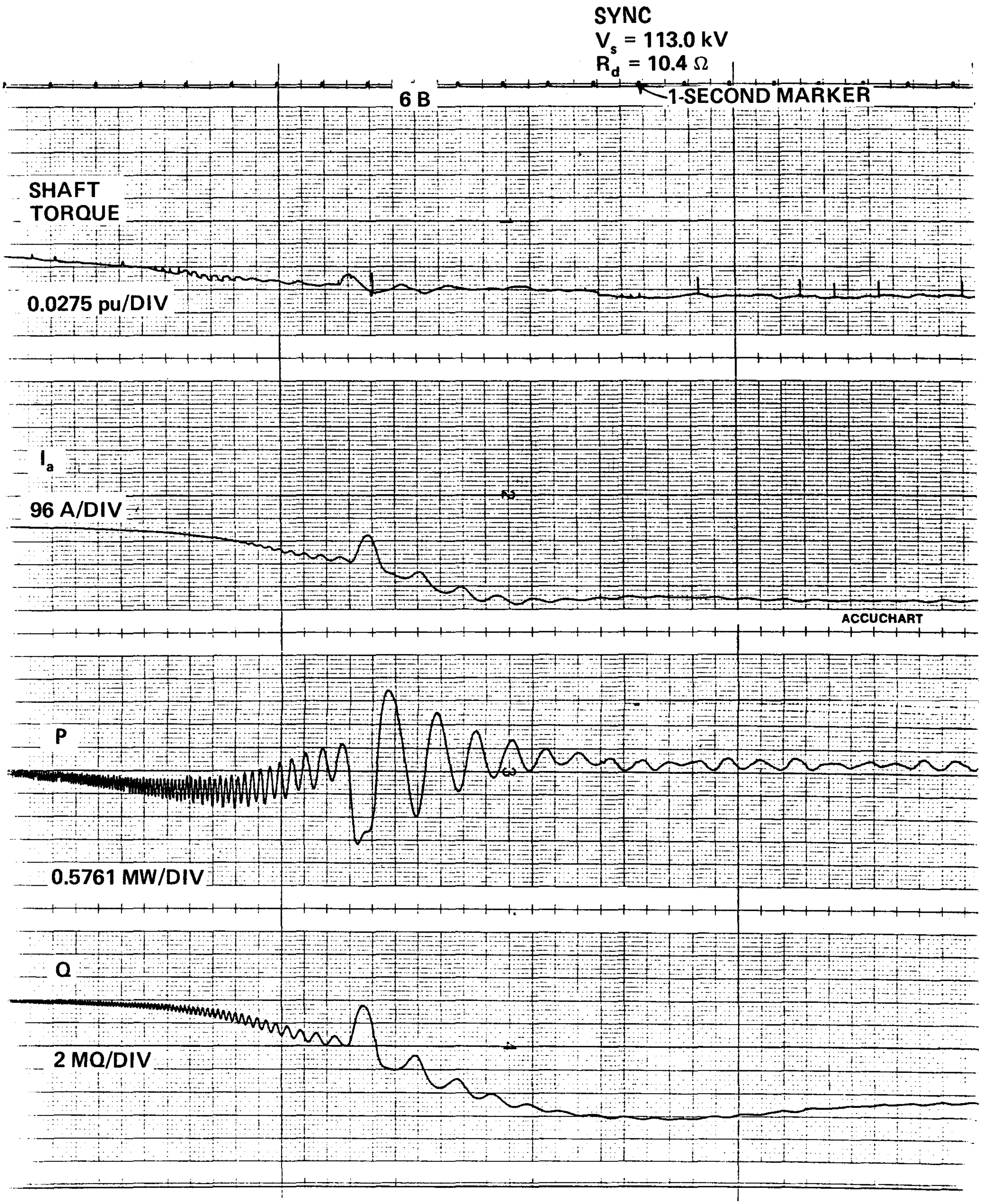


Figure B-11. – Test 6, synchronization (sheet 1 of 2).

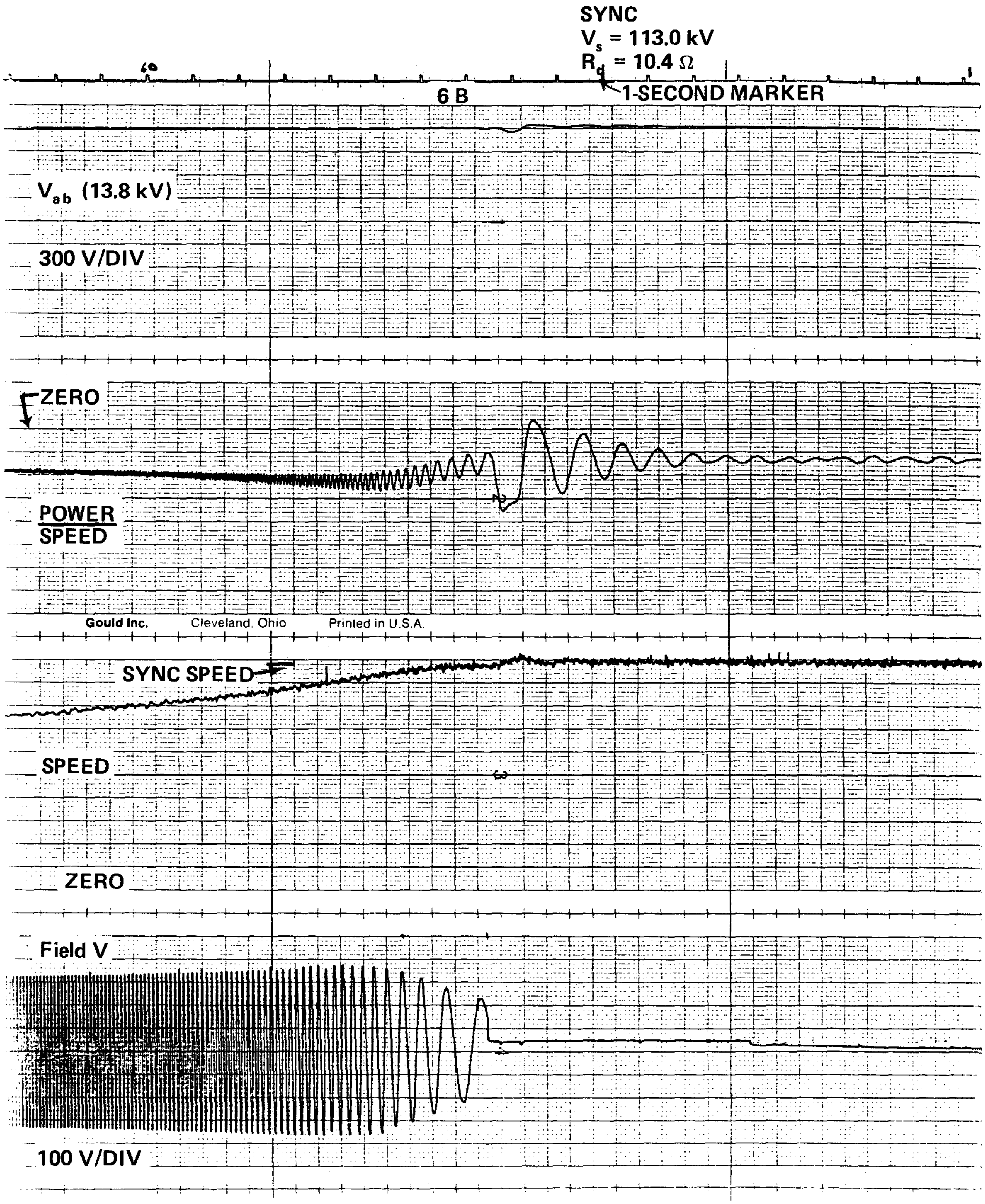


Figure B-11. – Test 6, synchronization (sheet 2 of 2).

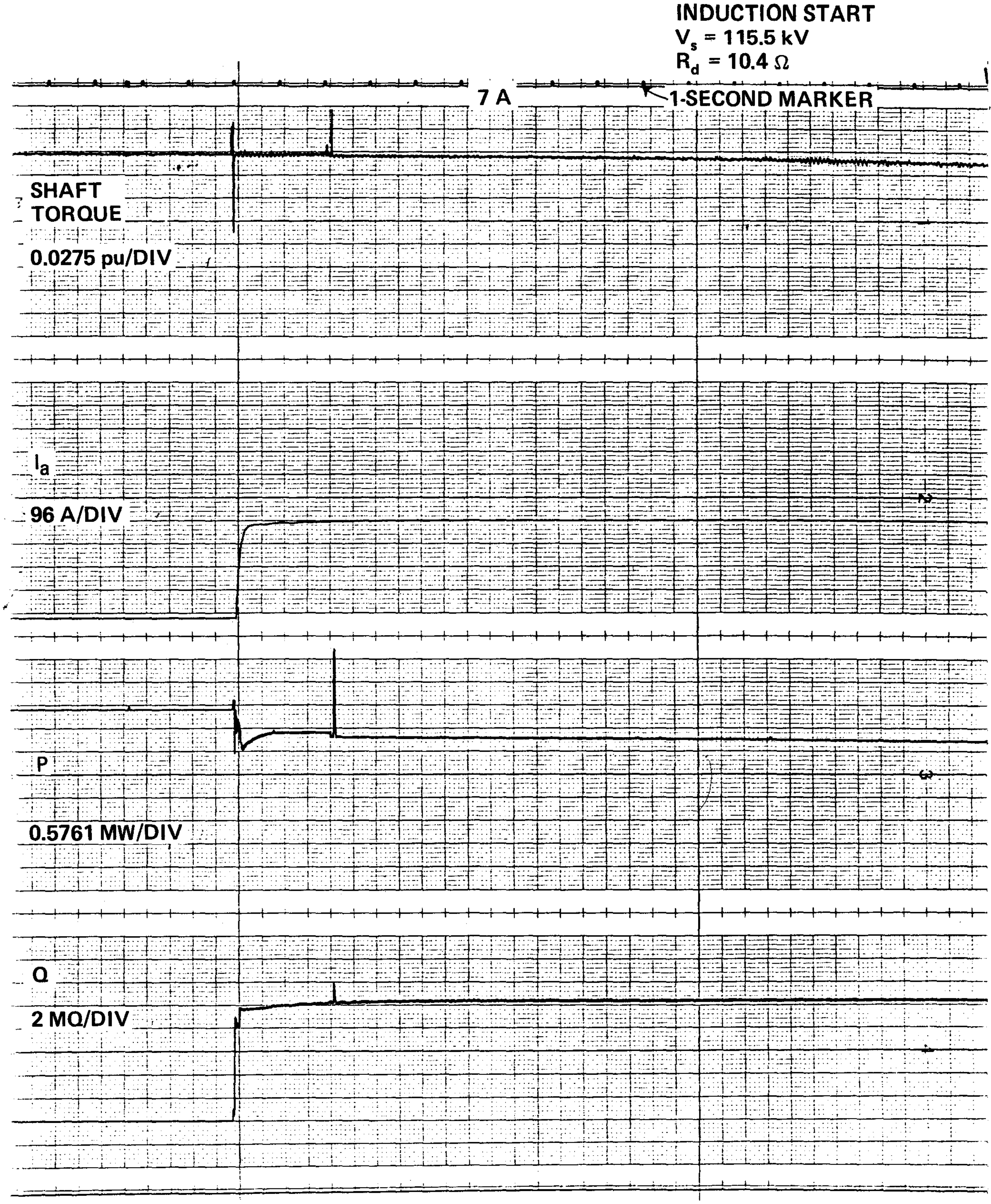


Figure B-12. – Test 7, induction start (sheet 1 of 2).

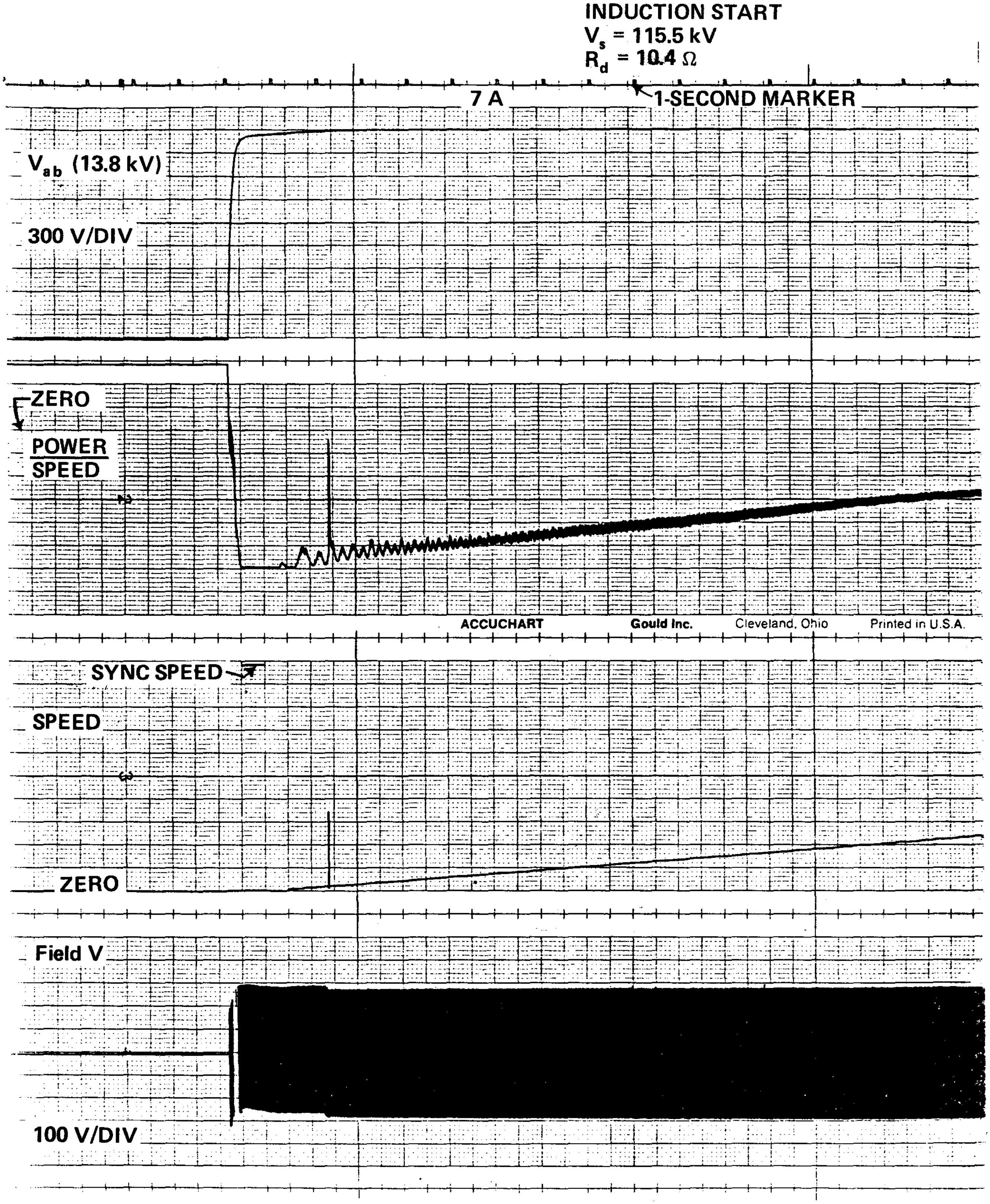


Figure B-12. – Test 7, induction start (sheet 2 of 2).

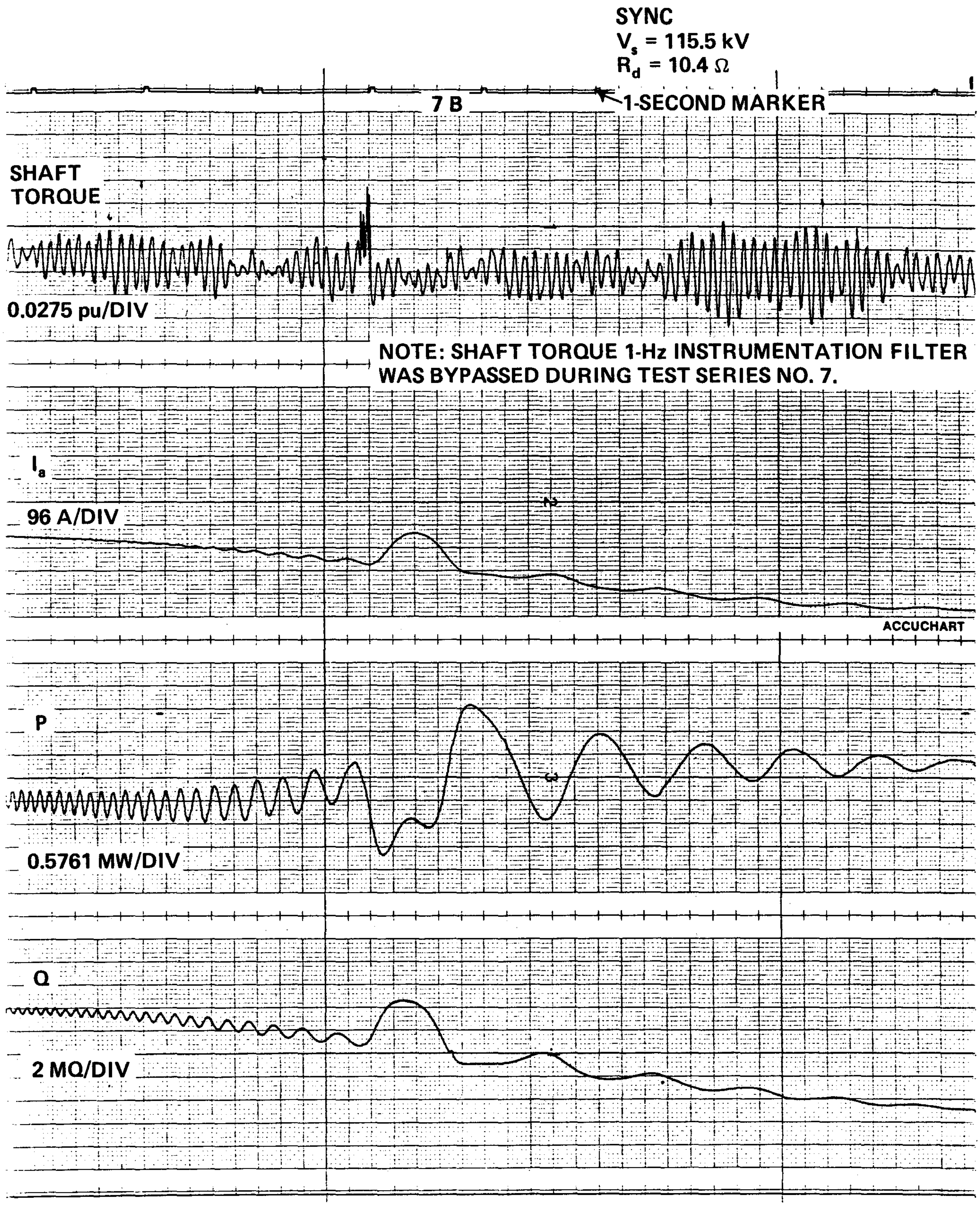


Figure B-13. – Test 7, synchronization (sheet 1 of 2).

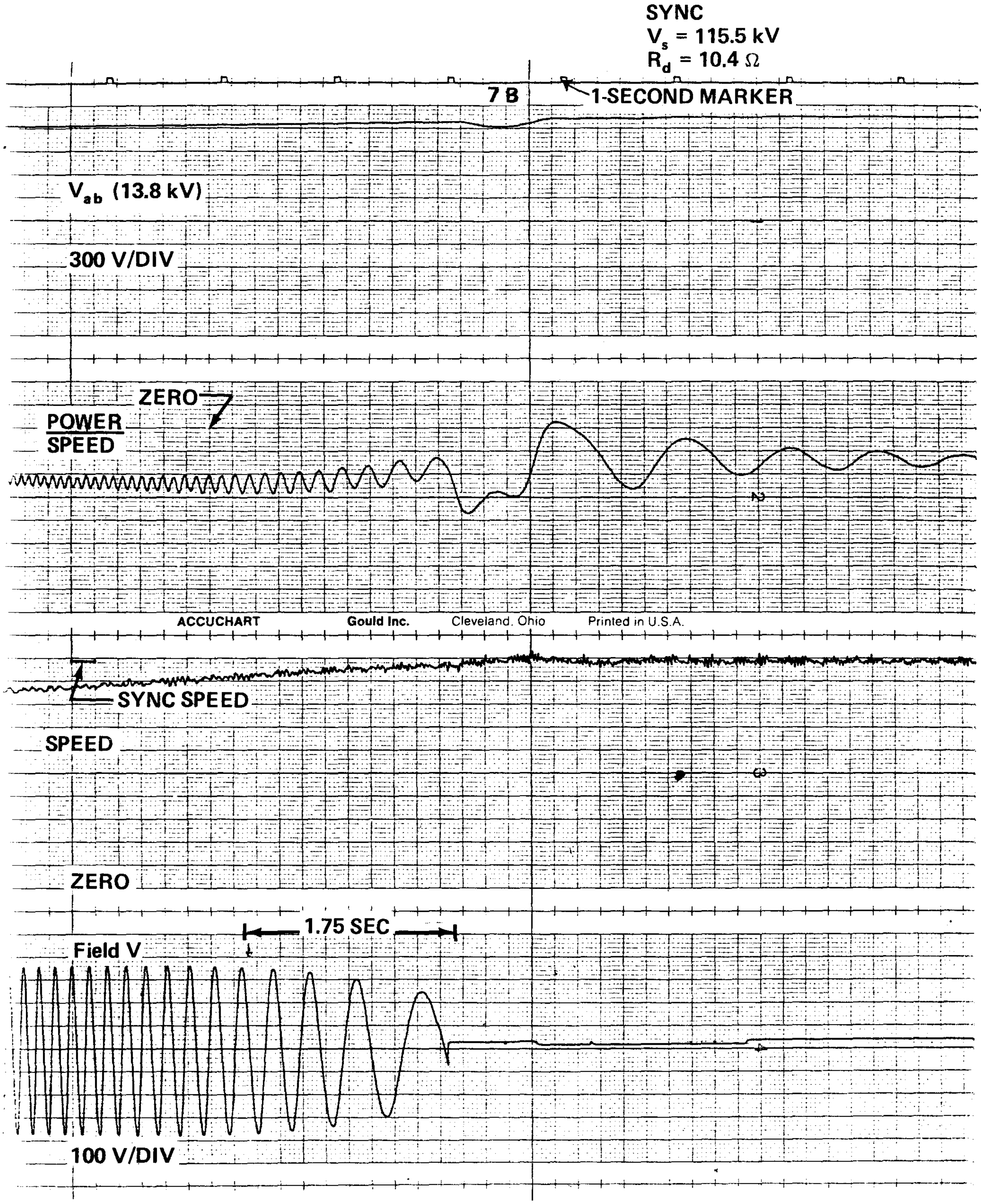


Figure B-13. – Test 7, synchronization (sheet 2 of 2).

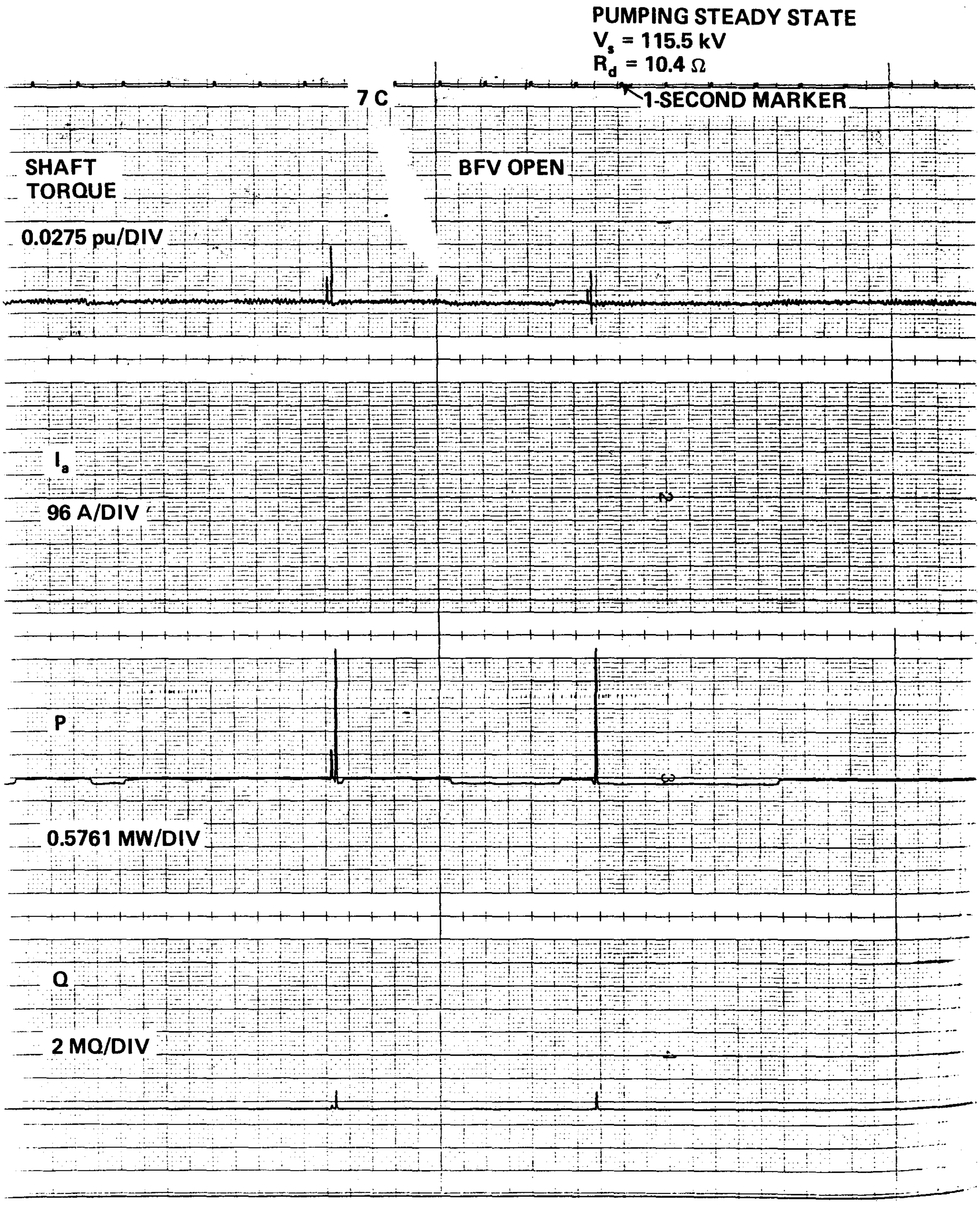


Figure B-14. – Test 7, pumping–steady state (sheet 1 of 2).

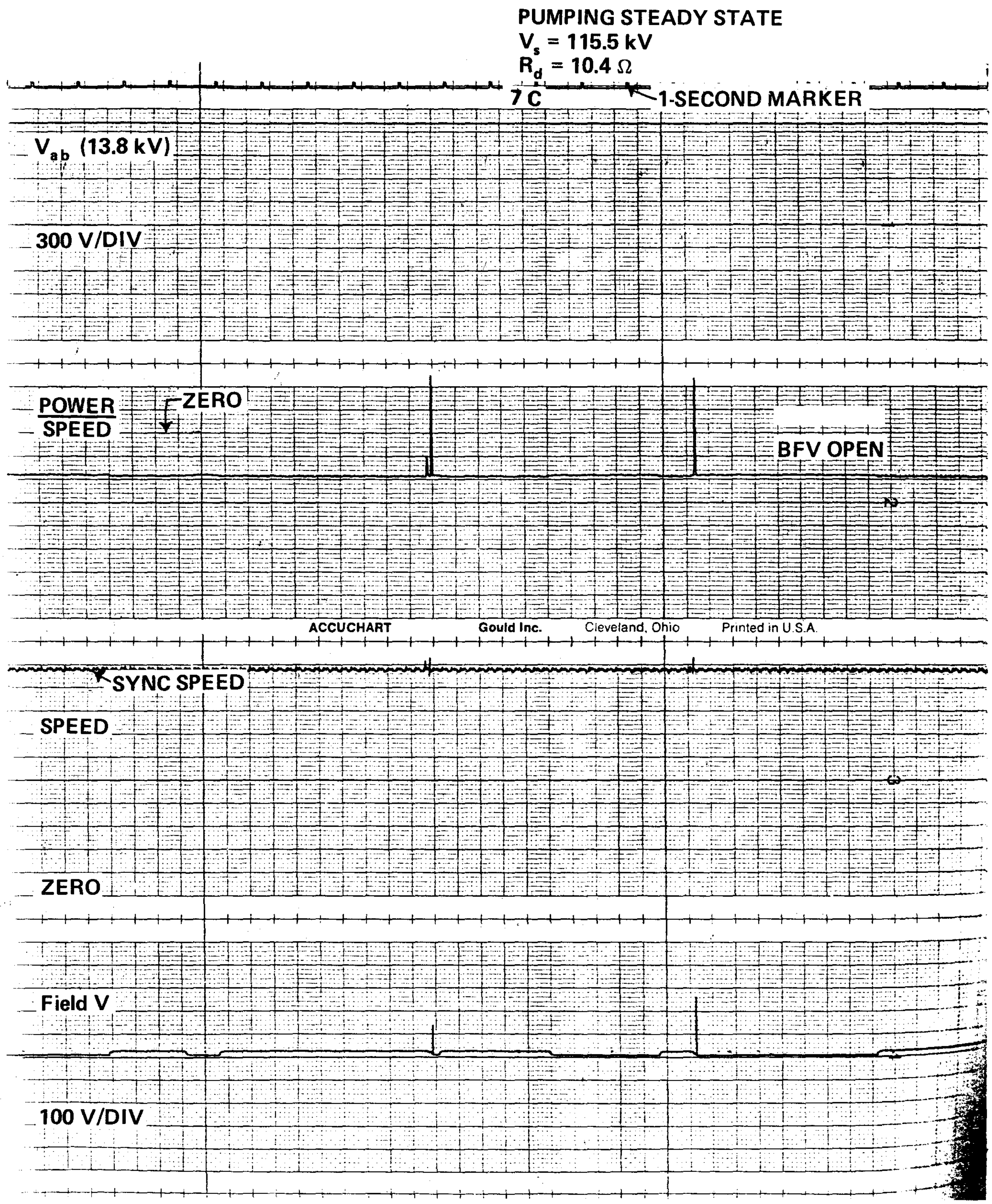


Figure B-14. – Test 7, pumping–steady state (sheet 2 of 2).

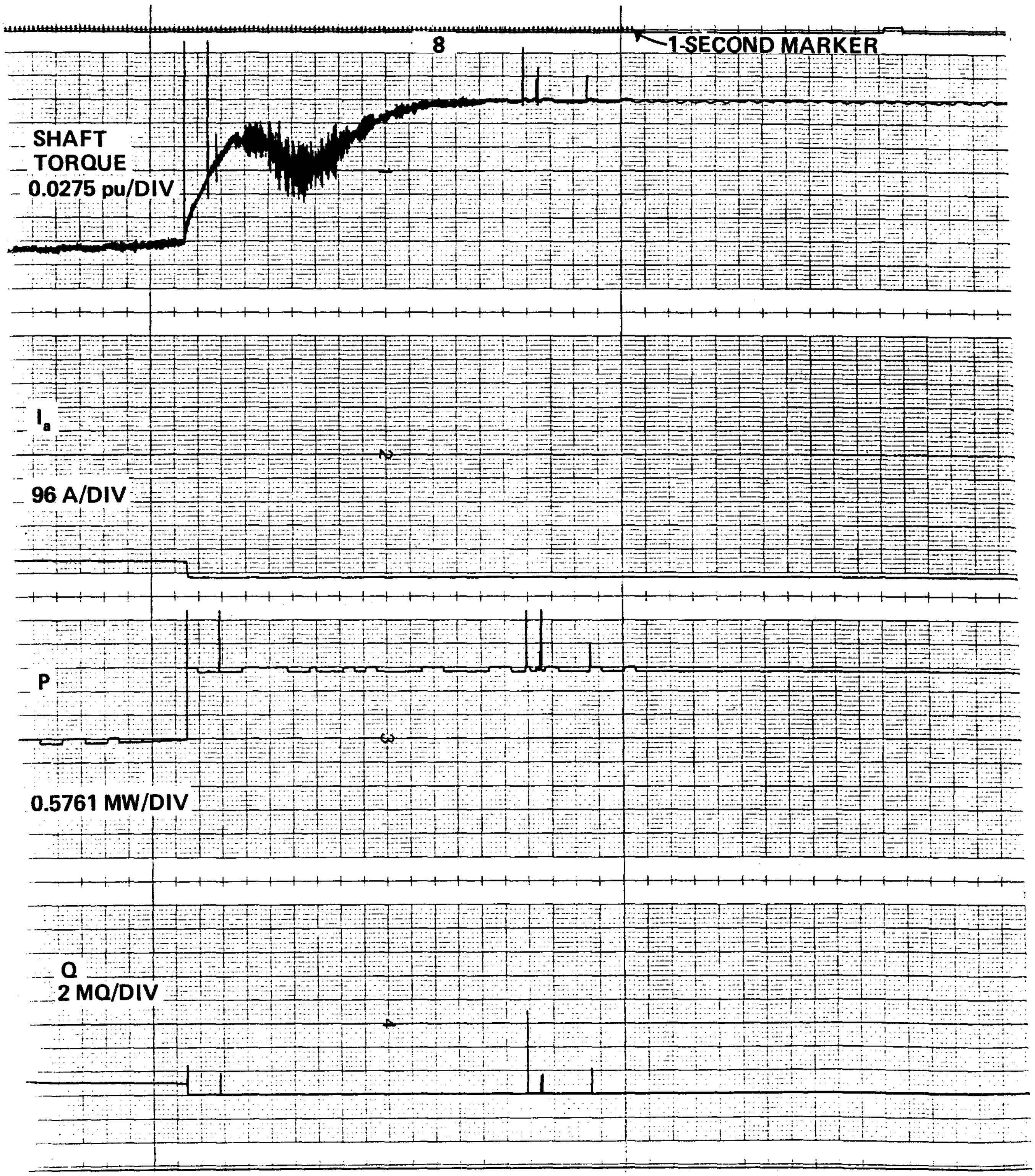


Figure B-15. – Test 8, shutdown (sheet 1 of 2).

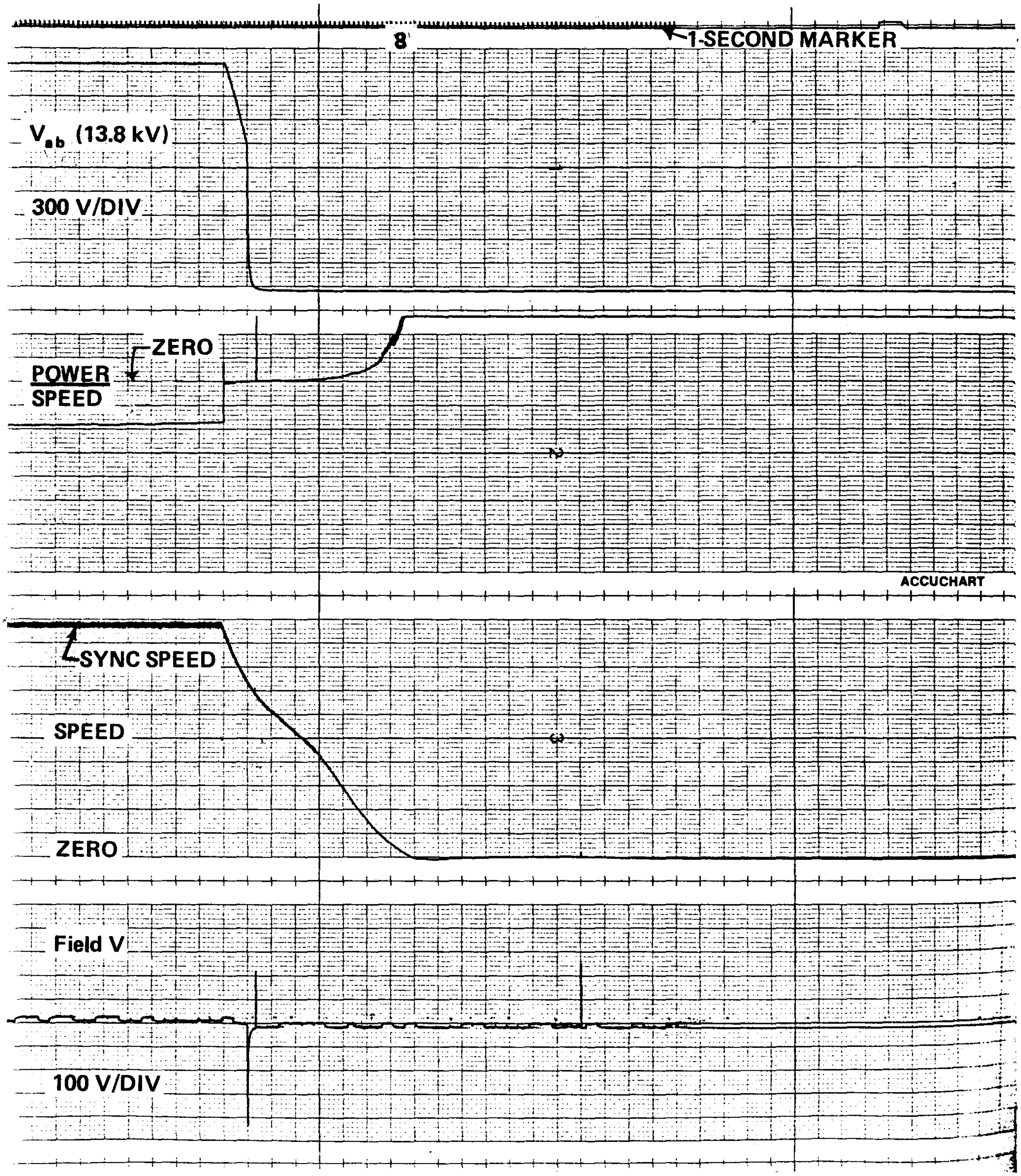


Figure B-15. – Test 8, shutdown (sheet 2 of 2).

GPO 847 – 635

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.