GR-82-2

DYNAMICS OF LOADS ON POWER SYSTEMS USING FIELD MEASUREMENTS

May 1984

Engineering and Research Center

U. S. Department of the Interior
Bureau of Reclamation
Division of Research and
Laboratory Services
Power and Instrumentation Branch

7-2090 (4-81)
Bureau of Reclamation

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.
GR-82-2

2. GOVERNMENT ACCESSION NO.

3. RECIPIENT'S CATALOG NO.

4. TITLE AND SUBTITLE
Dynamics of Loads on Power Systems Using Field Measurements

5. REPORT DATE
May 1984

6. PERFORMING ORGANIZATION CODE
D-1550

7. AUTHOR(S)
J. R. Schurz and T. R. Whittemore

8. PERFORMING ORGANIZATION REPORT NO.
GR-82-2

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Bureau of Reclamation
Engineering and Research Center
Denver, Colorado 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

15. SUPPLEMENTARY NOTES
Microfiche and/or hard copy available at the Engineering and Research Center, Denver, Colo.
Ed:WFA/BDM

16. ABSTRACT
The correct modeling of power system loads for computerized stability studies is of great importance. Because of the diverse nature of loads and because of multiple feeds to most actual loads, very little modeling has been based on field measurements. This report is a description of a project to monitor loads and develop more accurate models.

17. KEY WORDS AND DOCUMENT ANALYSIS
a. DESCRIPTORS-- *power system operations/ power grids/ electric networks/ *system stability/ stability studies (electrical)/ *power loads/ *computer studies/ computer models/ *field data

b. IDENTIFIERS-- Longmont, Colo., substations

c. COSATI Field/Group 09C   *COWRR:* 0903   *SRIM:*

18. DISTRIBUTION STATEMENT

19. SECURITY CLASS (THIS REPORT)
UNCLASSIFIED

20. SECURITY CLASS (THIS PAGE)
UNCLASSIFIED

21. NO. OF PAGES
32

22. PRICE

GR-82-2

DYNAMICS OF LOADS ON POWER SYSTEMS USING FIELD MEASUREMENTS

by
J. R. Schurz
T. R. Whittemore

Power and Instrumentation Branch
Division of Research and Laboratory Services
Engineering and Research Center
Denver, Colorado
May 1984

SI METRIC

UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

CONTENTS

FIGURES

INTRODUCTION

The magnitude and time response of load deviations resulting from variations in system voltage and frequency need to be accurately represented for stability studies. Such characteristics influence dynamic performance of power systems, yet the only data heretofore available to be used in system studies have been calculated or estimated [1, 2, 3, 4][1]. System load stability programs currently use an exponential load model of the form $P = KV^m$, or a quadratic representation of the form $P = K + K_1V^1 + K_2V^2$. Using this exponential model, loads are represented as constant power ($P = K$), constant current ($P = KV^1$), or constant impedance ($P = KV^2$). The intent of this research was to use the general form of the exponential model ($P = KV^m$) and identify the value of the exponent m through actual system measurements. The exponential model was also expanded to include the effects of frequency on power. The general form then becomes $P = Kf^nV^m$, and the intent of the research is to identify the exponents n and m through actual system measurements and to develop instrumentation to perform the measurement.

CONCLUSIONS

An instrumentation package was developed and installed at various locations in northeastern Colorado. A total of 17 different sites were monitored, 9 of which produced a number of good data records. The remaining eight sites had very noisy power records from which it was nearly impossible to obtain reliable data on the power deviations.

Two system loads for which complete data were available were the Longmont NE and NW substations. Therefore, models of these two substations were developed. Both loads were primarily residential, with some light commercial, having 115-kV radial taps and about 7 MW and +2 MVar loads. These two installations were monitored, at separate times, using Δf and $\Delta V + K\Delta P$ as the input to the disturbance sensor. These records were reduced to provide $\frac{\Delta V}{V_0}$ and $\frac{\Delta P}{P_0}$ for those records where Δf equaled zero,

[1]Numbers in brackets refer to entries in the bibliography.

and $\frac{\Delta V}{V_o}$, $\frac{\Delta f}{f_o}$, and $\frac{\Delta P}{P_o}$ for those records where all three quantities were nonzero. The values for K, N, and m were determined, and the resulting exponential power equations are $P = 0.076\,f^{\circ}\,V^{1.4}$ for the Longmont NE substation and $P = 0.076\,f^{\circ}\,V^{1.5}$ for the Longmont NW substation. Neither load had frequency dependency for the small frequency deviations recorded.

This research showed the feasibility of field measuring the dynamic characteristics of system loads. More data recording and data reduction for more situations and more loads should be accomplished in the future. This study also clearly shows the need for a means of automatic data reduction.

EQUATION DEVELOPMENT

To develop a method by which the exponents n and m can be determined, we start with the general form of the exponential power equation:

$$P = Kf^{n}V^{m} \tag{1}$$

where P = real power,
K = constant,
f = frequency,
n = exponent of system frequency,
V = voltage, and
m = exponent of system voltage.

The derivative of equation (1) is:

$$dP = Knf^{n-1}V^{m}df + Kf^{n}mV^{m-1}dV \tag{2}$$

Divide (2) by (1)

$$\frac{dP}{P} = \frac{Knf^{n-1}V^{m-1}Vdf + Kf^{n-1}fmV^{m-1}dV}{Kf^{n-1}fV^{m-1}V}$$

$$= \frac{nVdf + fmdV}{fV}$$

For all n and m:

$$\frac{dP}{P} = n\frac{df}{f} + m\frac{dV}{V} \tag{3}$$

Derive equation (3) in finite form:

where $P = P_o + \Delta P$

$f = f_o + \Delta f$

$V = V_o + \Delta V$

where P_o = steady state power

f_o = steady state frequency

V_o = steady state voltage

ΔP = incremental change in power

Δf = incremental change in frequency

ΔV = incremental change in voltage

Then

$$P = P_o + \Delta P = K(f_o + \Delta f)^n\,(V_o + \Delta V)^m$$

or

$$P = P_o\left(1 + \frac{\Delta P}{P_o}\right) = Kf_o^{\,n}V_o^{\,m}\left(1 + \frac{\Delta f}{f_o}\right)^n\left(1 + \frac{\Delta V}{V_o}\right)^m$$

Dividing by $P_o = Kf_o^{\,n}V_o^{\,m}$

$$\frac{P}{P_o} = 1 + \frac{\Delta P}{P_o} = \left(1 + \frac{\Delta f}{f_o}\right)^n\left(1 + \frac{\Delta V}{V_o}\right)^m$$

Using the binomial series

$$1 + \frac{\Delta P}{P_o} = \left(1 + n\,\frac{\Delta f}{f_o} + \frac{n(n-1)}{2!}\left(\frac{\Delta f}{f_o}\right)^2 + \ldots\right)\left(1 + m\,\frac{\Delta V}{V_o} + \frac{m(m-1)}{2!}\left(\frac{\Delta V}{V_o}\right)^2 + \ldots\right)$$

and multiplying:

$$1 + \frac{\Delta P}{P_o} = 1 + n\,\frac{\Delta f}{f_o} + \frac{n(n-1)}{2!}\left(\frac{\Delta f}{f_o}\right)^2 + \ldots + m\frac{\Delta V}{V_o} + mn\frac{\Delta f}{f_o}\frac{\Delta V}{V_o} + m\,\frac{n(n-1)}{2!}\left(\frac{\Delta f}{f_o}\right)^2\frac{\Delta V}{V_o} + \ldots$$

$$+\frac{m(m-1)}{2!}\left(\frac{\Delta V}{V_o}\right)^2 + n\,\frac{m(m-1)}{2!}\,\frac{\Delta f}{f_o}\left(\frac{\Delta V}{V_o}\right)^2 + \ldots$$

Retaining only the first order terms:

$$\frac{\Delta P}{P_o} = n\frac{\Delta f}{f_o} + m\frac{\Delta V}{V_o} \tag{4}$$

The instrumentation package measures the three quantities $\frac{\Delta P}{P_o}, \frac{\Delta f}{f_o}$, and $\frac{\Delta V}{V_o}$ during a system disturbance. From a disturbance when Δf is zero, m can be determined from:

$$m = \frac{\Delta P}{P_o}\left(\frac{V_o}{\Delta V}\right) \Bigg|_{\frac{\Delta f}{f_o} = 0} \tag{5}$$

followed by the determination of n when all three quantities change from the equation:

$$n = \left(\frac{\Delta P}{P_o} - m\frac{\Delta V}{V_o}\right) \frac{f_o}{\Delta f}$$

The instrumentation package provides a selection of Δf (frequency deviation) or $\Delta V + K\Delta P$ (voltage and power deviation) as the quantity used to initiate recording of a disturbance. The use of $\Delta V + K\Delta P$ allows records to be stored in which Δf is zero. A value for m from equation (4) can then be determined.

The output of the disturbance sensor Z will be:

$$Z = \Delta V + K\Delta P$$

The use of the factor $K\Delta P$ as a modifier on ΔV provides a means of differentiating between a disturbance within the load monitored and one external. Within the monitored load when a device is turned on, the power will increase and the voltage will decrease; thus ΔV and ΔP are out of phase. Therefore, K is selected to be equal to $-\frac{\Delta V}{\Delta P}$ for an internal load change on the load being monitored. Thus, for an internal load change:

$$Z = \Delta V + K\Delta P = \Delta V - \left(\frac{\Delta V}{\Delta P}\right)\Delta P = 0$$

A typical value for K would be about -0.1 due to the reactance of the system. For a voltage disturbance external to the load being monitored, voltage and power will be in phase and the output of the disturbance sensor will be:

$$Z = \Delta V + K\Delta P > 0 \tag{6}$$

The use of Δf for the disturbance sensor allows records to be stored in which all three quantities, ΔV, Δf, and ΔP, are nonzero. The value of n can then be determined from equation (6) along with the previously determined value of m (equation 5).

INSTRUMENTATION

The dynamic load instrumentation system (fig. 1) has been designed to monitor and record power system disturbances with a frequency range of 0.1 to 1.0 Hz. The quantities monitored are voltage, frequency, real and reactive power. A system disturbance initiates a magnetic tape recorder to record the monitored quantities for later analysis. A transducer connected to the station PT's and CT's provides voltage, real power, reactive power, and a 60-Hz frequency signal to the signal conditioning and recording package. A signal conditioning and recording unit filters and converts the four quantities of each power system being monitored. There are four channels of analog delay of about 1 second each to allow the tape recorder to attain the proper speed after initiation by an event, prior to recording the disturbance. There are four channels of FM (frequency modulation) record and playback, which also record the DOY (day of year), hour and minute of the event.

Transducer Unit

The transducer unit (fig. 2) contains two Hall-effect watt transducers, one connected to measure watts and the other to measure vars. Each transducer provides a low level d-c signal to the signal conditioning circuits proportional to the watts or vars measured. There are also three step-down isolation transformers connected wye-delta, and a three-phase bridge rectifier providing a minus 18-V d-c signal for a 115-V a-c three-phase input. One other transformer winding provides a 24-V rms, 60-Hz signal to the frequency transducer. The transducer unit is connected to the three-phase power system with three current plugs, three potential clips, and one neutral clip. It is also connected to the signal conditioning and recorder unit with two multiwire shielded cables.

Signal Conditioning and Recording Unit

A Telex Model 230 four-channel, two-speed, magnetic tape recorder is included which has remote control start and stop features allowing it to be controlled by the signal conditioning section. There are 16 printed-circuit cards in the signal conditioning and recording unit.

Cards one through four each provide for one channel of FM record and playback (figs. 3 and 4). Recording at 95 mm/s (3.75 in/s) is on a center frequency of 6.75 kHz and is automatically switched to 13.47 kHz for a speed of 190 mm/s (7.5 in/s). The input sensitivity to the record channel is ±0.54 V equals ±40 percent modulation. The output of the playback channel is approximately (uncalibrated) ±5 V equals ±40 percent modulation.

Cards 6 and 7 are each two channels of analog delay lines. Together they provide a 1-second delay for each of the four channels in order to allow the tape recorder to attain the proper speed prior to recording the disturbance (fig. 5). The operating range of the input signal to the delay line is about ±0.8 V. The output of the delay line is the input signal superimposed on approximately a 3-V d-c level.

Card 5 provides an interface between the delay lines and the record channels; blocks the d-c component of the delay line output; and provides a gain adjustment for each channel for calibration purposes, such that a ±0.5 V signal into the delay line results in ±40 percent modulation (fig. 6)

Card 13 provides signal conditioning for ΔV (figs. 7 and 8). The three-phase rectified voltage signal are filtered with four poles at approximately 21 Hz. To prevent slow changes in system voltage from biasing ΔV, a high-pass filter at 0.005 Hz is provided. Gain adjust allows the base of ΔV to be varied from 20 to 50 V/unit. Thus, for a ±40 percent modulation on the tape recorder, a ΔV of ±1.0 to ±2.5 percent peak could be recorded.

Cards 11 and 12, the frequency transducer, measure frequency deviation (figs. 9 and 10). Card 11 is the frequency transducer, providing an output signal proportional to the deviation of frequency from 60 Hz. Card 12 provides some input filtering for the frequency transducer and an output gain adjust and offset blocking function (0.005 Hz) to prevent slow frequency changes from biasing Δf. The frequency transducer output base is 2 V/Hz deviation from 60 Hz. The gain adjust provides a range of 0.0 to 2 V/Hz. With the maximum sensitivity (2 V/Hz), the largest deviation that can be recorded is ±0.25 Hz, which provides a ±40 percent modulation.

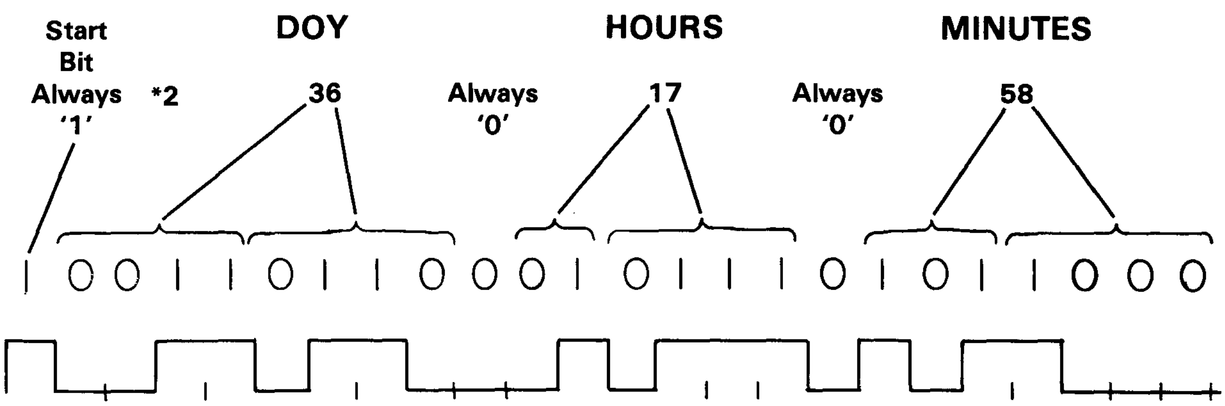
Card 10 contains the real power conditioning circuits to derive $\Delta P/P_o$ (figs. 11 and 12), where ΔP is the deviation in power and P_o is the steady-state power at the time of the deviation. The circuits provide a low pass filter cutoff frequency at 0.005 Hz from which P_o is derived, and low pass filtering with four poles at 23 Hz from which ΔP is obtained. These two quantities are then applied to an analog signal divider, providing an output of $\Delta P/P_o$. A gain adjust is provided to vary the output base from 10 to 40 V/unit. With this output base range, the maximum deviation in $\Delta P/P_o$ that can be recorded (±40 percent modulation) is between 1.25 and 5 percent. The gain adjust potentiometers for the real and reactive power conditioning circuits were calibrated (fig. 13) for these values.

Cards 8 and 9, the reactive power conditioning circuits (figs. 11, 14 and 15) derive $\Delta Q/Q_o$; provide a flag to indicate capacitive vars; and provide an absolute value circuit, required by the analog divider. Card 9 contains the absolute value cirucit which provides a negative output to card 8 regardless of the polarity of the reactive power, and provides a flag circuit which generates a pulse every 5 seconds if the polarity of the reactive power is capacitive. This pulse is summed with ΔQ on card 8, providing a flag to indicate reactive power polarity. Card 8 derives $\Delta Q/Q_o$. The circuits provide a high pass filter cutoff frequency at 0.005 Hz from which Q_o is derived, and low pass filtering with four poles at 23 Hz from which ΔQ is obtained. These two quantities are then applied to an analog signal divider providing an output of $\Delta Q/Q_o$. A gain adjust was provided to vary the output base from 2.5 to 10 V/unit. With this output base range, the maximum deviation in $\Delta Q/Q_o$ that can be recorded (±40 percent modulation) is between 5 and 20 percent.

Card 14, the event sensor (fig. 16), initiates the recording of an event and shuts the recorder off after a variable time interval. A switch on the card selects either a deviation in frequency or a deviation in voltage (fig. 17) as the event to start the recording. This gain versus frequency characteristic prevents very slow changes and very fast changes in the selected signal from initiating a recording. The recording time is adjustable from 5 to 80 seconds by a potentiometer on the card.

Cards A and B (figs. 18 and 19) provide DOY and time information, which is recorded in BCD (binary coded decimal) on the frequency channel during the last one-third of the record.

Information is recorded as follows:



*This digit is not recorded, as it is assumed the operator will know what quarter of the year the recordings were made.

The clock is synchronized to the 60-Hz line frequency as long as the transducer package is connected to the recorder and the PT connections are made. During loss of PT voltage or power to the recorder package, the clock will continue to run on battery backup at approximately 60 Hz. A switch is provided to stop the clock in order to set the proper DOY and time. Three pushbuttons are used to set the clock, one each for DOY, hours, and minutes. Pressing the button will advance that quantity at a 1-Hz rate. The DOY and time can be observed on a series of LED's which are enabled by a switch. Reading the LED's is the same as described above. The LED's must be turned off for normal clock operation as the battery is not of sufficient capacity to power the LED's but for a short period of time. Whenever the system is not being used, the battery clip should be removed.

RESULTS

Beginning with the set of records from Longmont NE with Δf equal to zero, 53 events were reduced to $\frac{\Delta V}{V_o}$ and $\frac{\Delta P}{P_o}$ (fig. 20) and where Δf was nonzero (fig. 21). The value of m was then determined to range from 0.85 to 2.33, but eliminating the extreme values, m ranged from 0.98 to 1.96. A scatter plot of these values of m (fig. 22) produced an average of 1.43, with a standard deviation of 0.25. A slight tendency toward a normal distribution was evident. The swing on the frequency trace (fig. 21) was about 0.35 Hz, which was different than that on the power and voltage traces (about 0.66 Hz). On the power swing there was no evidence of influence from the frequency swing. Evidence of influence would be in the form of a mix of the two swing frequencies; thus, the value of n must have been nearly zero for this record. The value of $\frac{\Delta P}{\Delta V}$ for this record was 1.25, which was reasonably close to the 1.43 average value determined previously. The 16 good records from this set evaluated for $\frac{\Delta P}{\Delta V}$ averaged 1.37, with a standard deviation of 0.29. These values were very close to those determined from the previous set, further strengthening the fact that n was nearly zero for this load; that is, this load is nearly independent of the small frequency swings recorded (less than 0.1 percent of 0.06 Hz peak).

Reducing the set of records of 31 events from Longmont NW with Δf equal to zero revealed a much broader range of m values. The value m was then determined to range from 0.1 to 5.87; but eliminating the extreme values, m ranged from 0.17 to 3.45, with an average of 1.50, and a standard deviation of 0.69.

On the set of records where Δf was not equal to zero, there was no discernible evidence that the frequency swing affected the power swing. Taking $\frac{\Delta P}{\Delta V}$ for these records produced an average m value of 1.39 and a standard deviation of 0.44, which was very close to the first set of records. This load also has negligible frequency dependency for small swings in frequency.

BIBLIOGRAPHY

[1] "Dynamic Modelling of Loads in Stability Studies," PAS–88, No. 5, Southern California Edison, pp. 756-763, May 1969.

[2] Akhtar, M.Y., "Frequency-Dependent Power-System Static-Load Characteristics," *Proceedings of IEEE*, vol. 115, No. 9, pp. 1307-1314, September 1968.

[3] Dandeno, P.L., "System Load Dynamics — Simulation Effects and Determination of Load Constants," A talk prepared for presentation at the symposium "Adequacy and Philosophy of Modeling: System Dynamic Performance," in connection with IEEE Power Engineering Society Summer Meeting, July 9-12, 1972, San Francisco, California, July 12, 1972.

[4] Akhtar, M.Y., "Frequency-Dependent Dynamic Representation of Induction-Motor Loads," *Proceedings of IEEE*, vol. 115, No. 6, pp. 802-812, June 1968.

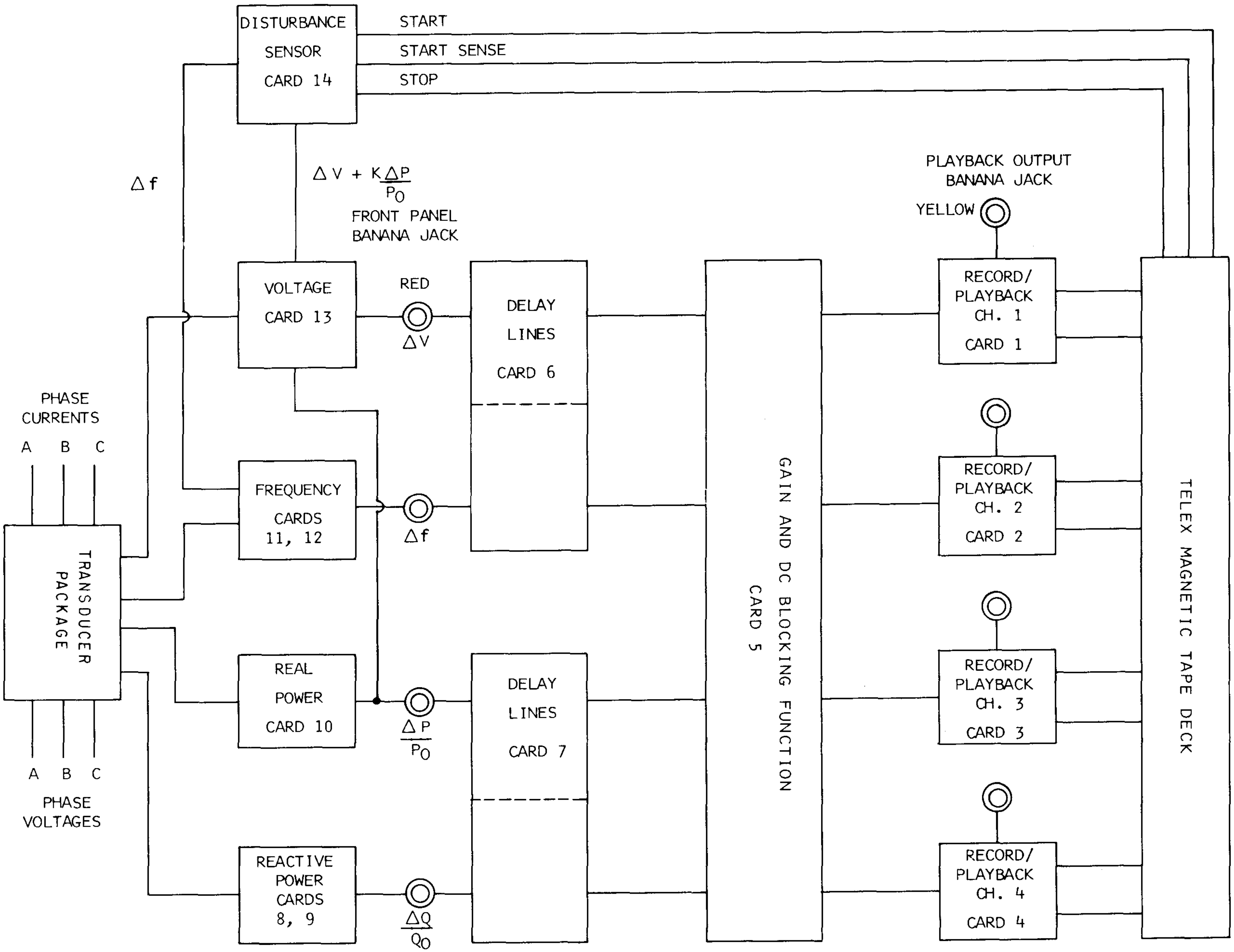


Figure 1. — Instrumentation system block diagram.

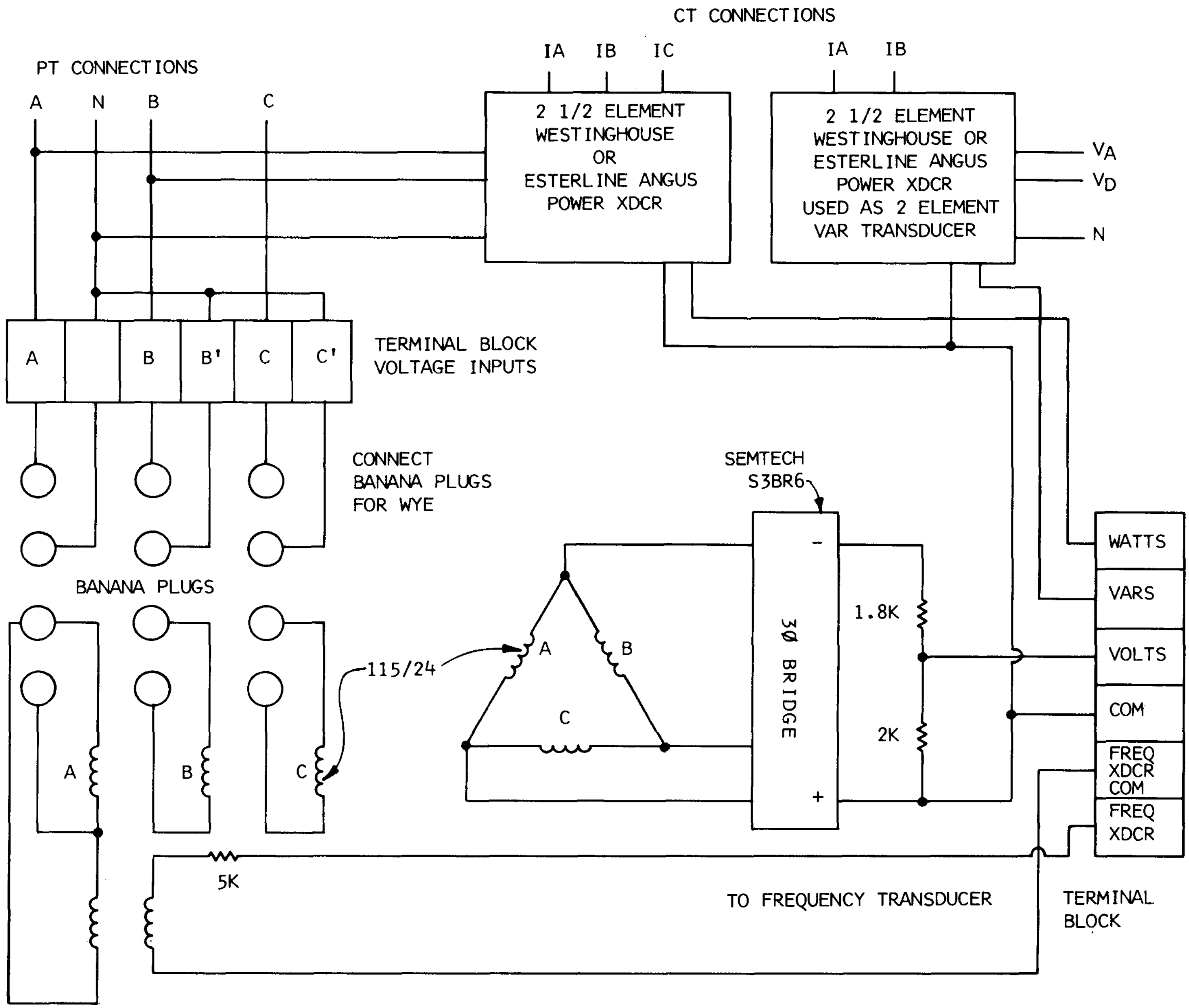


Figure 2. — Transducer unit block diagram.

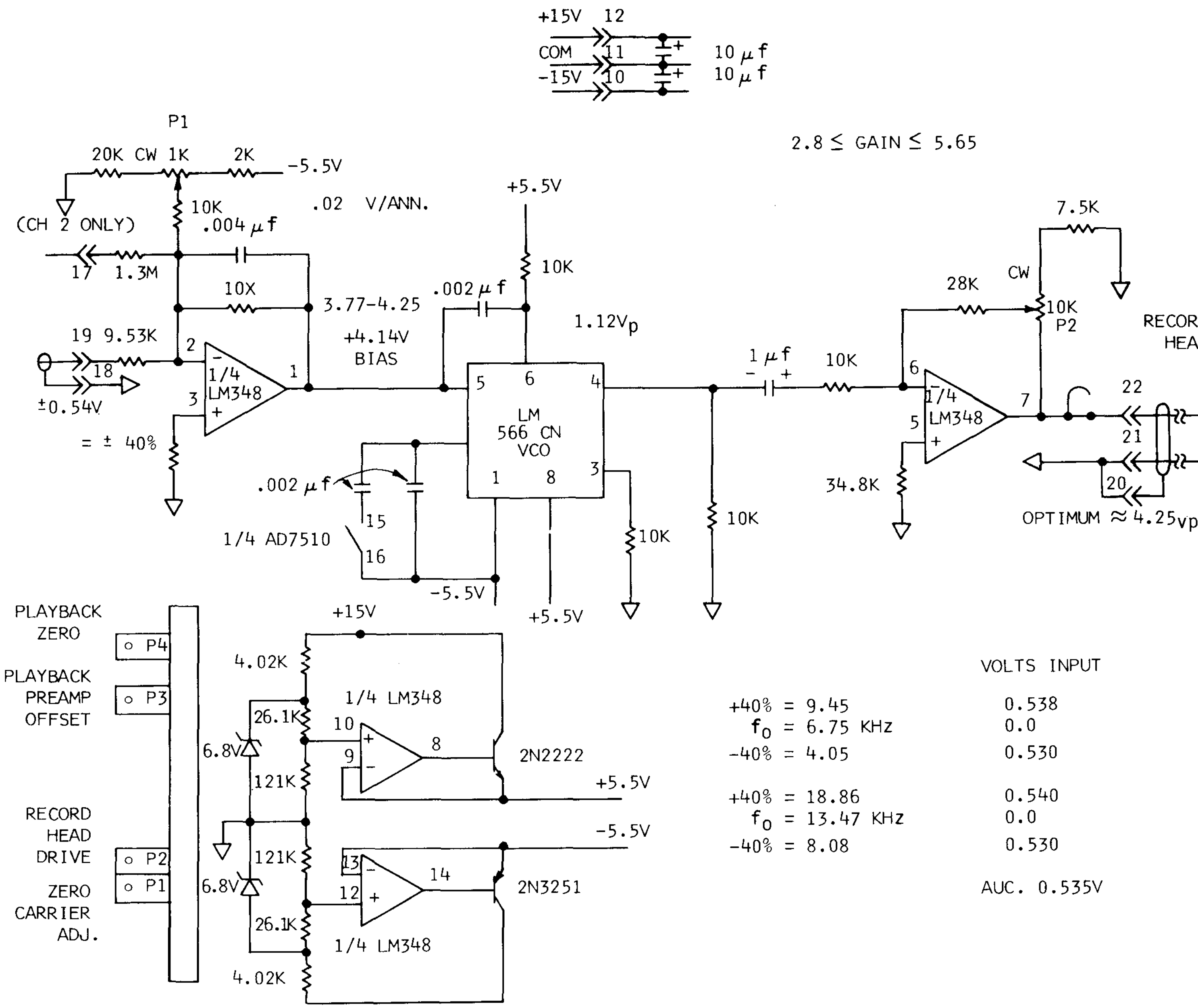


Figure 3. — Record schematic for the signal conditioning unit (cards 1-4).

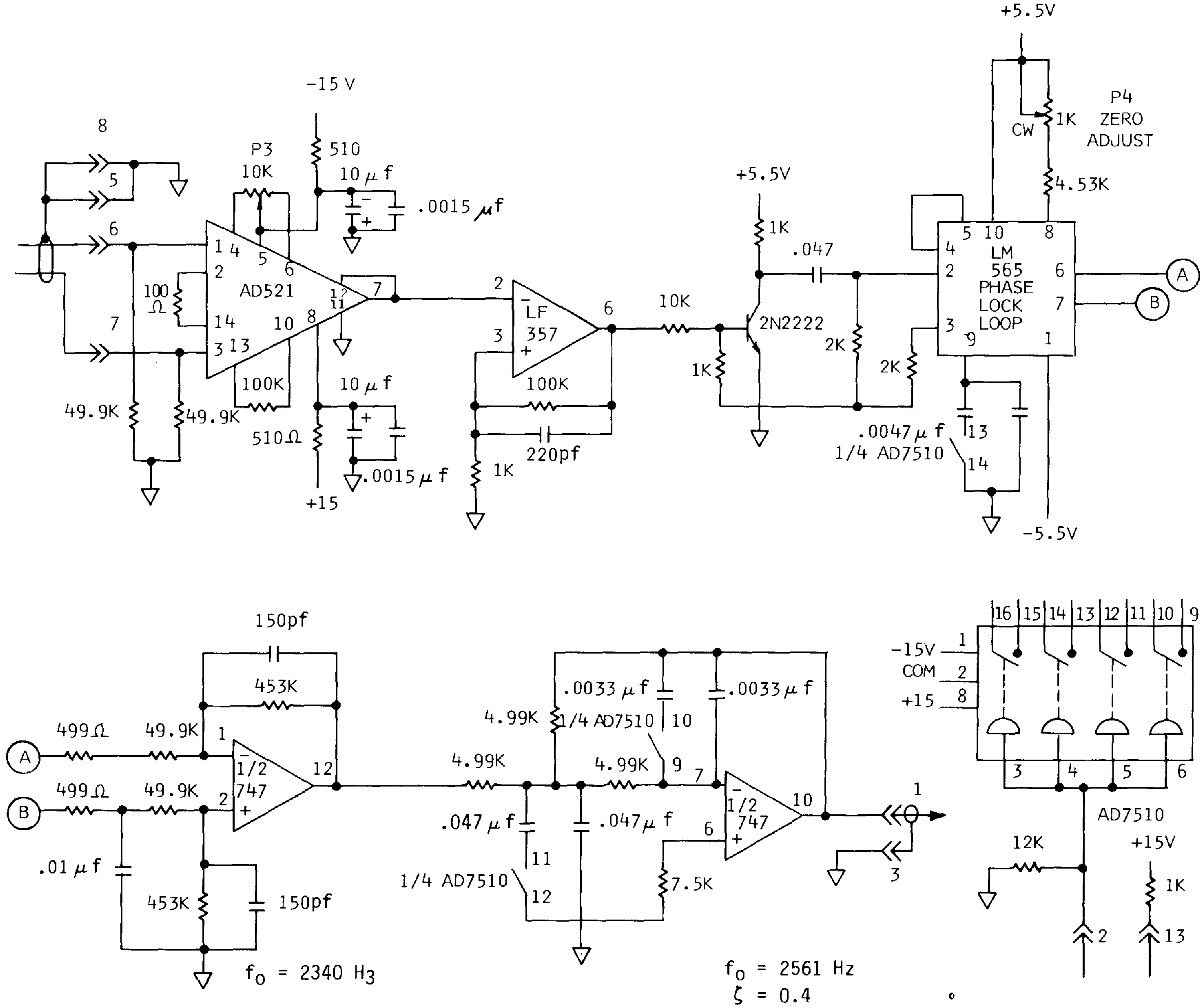


Figure 4. — Playback schematic for the signal conditioning unit (cards 1-4).

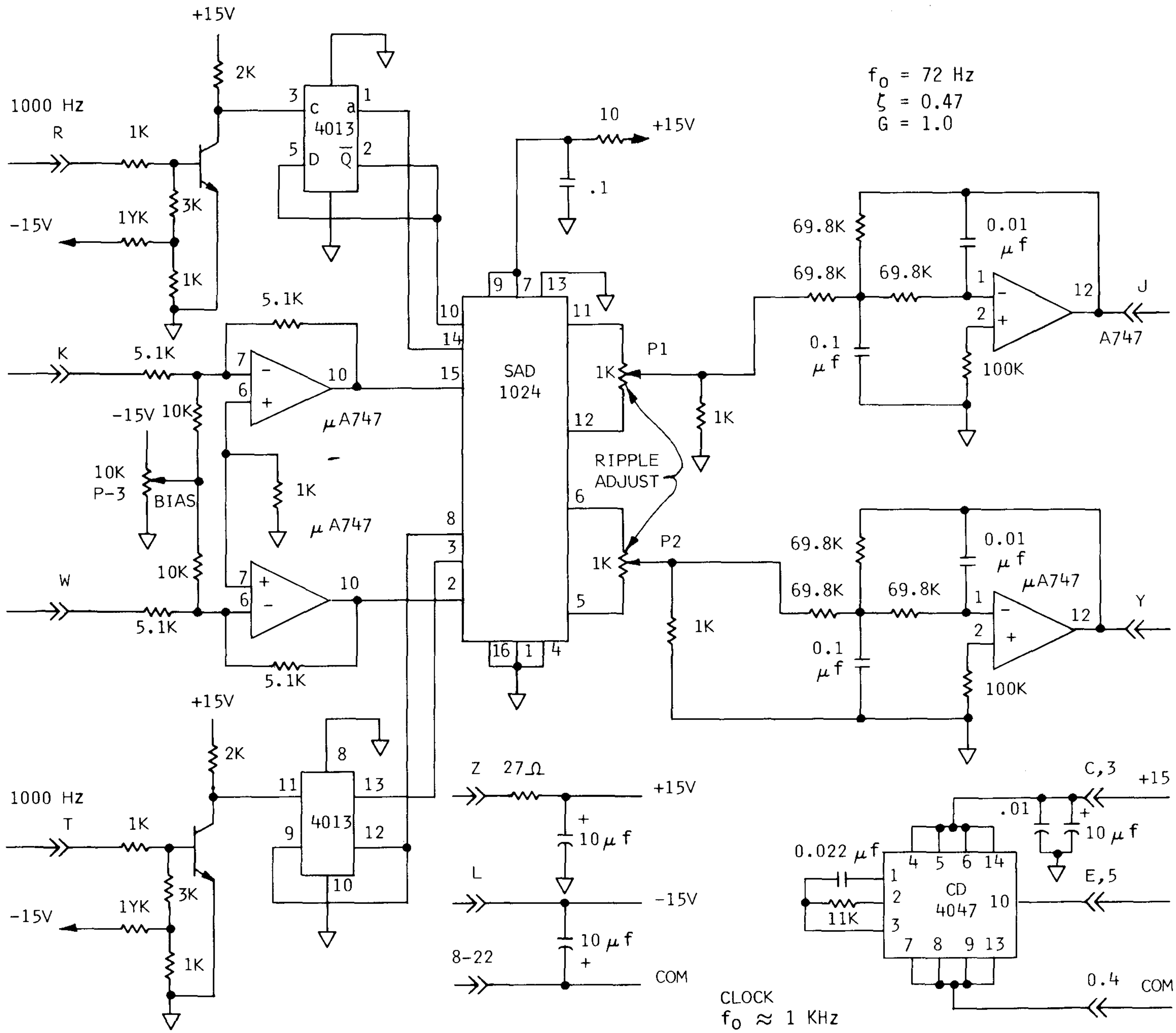


Figure 5. — Analog delay schematic (cards 6 & 7).

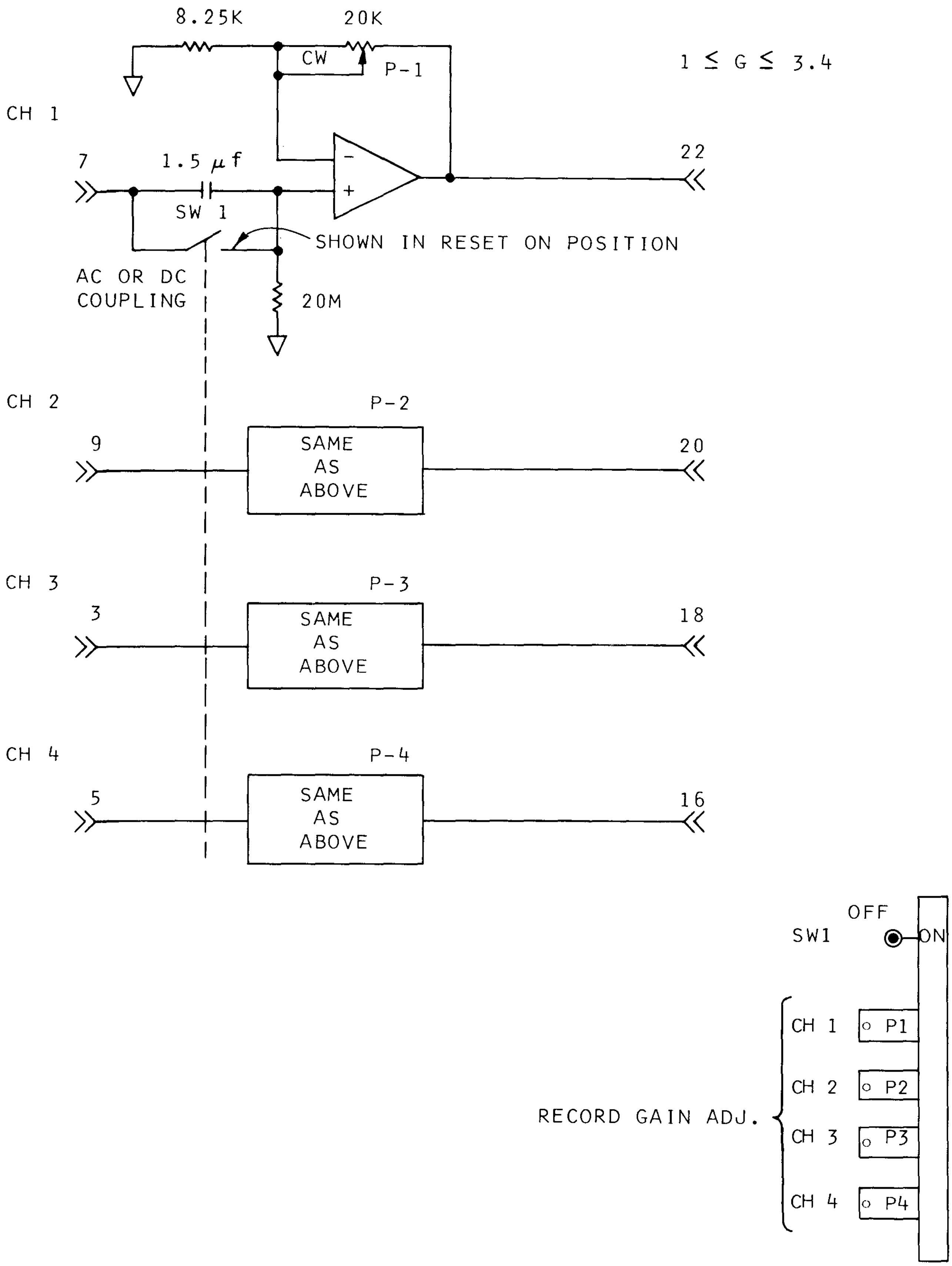


Figure 6. — Reset/gain schematic (card 5).

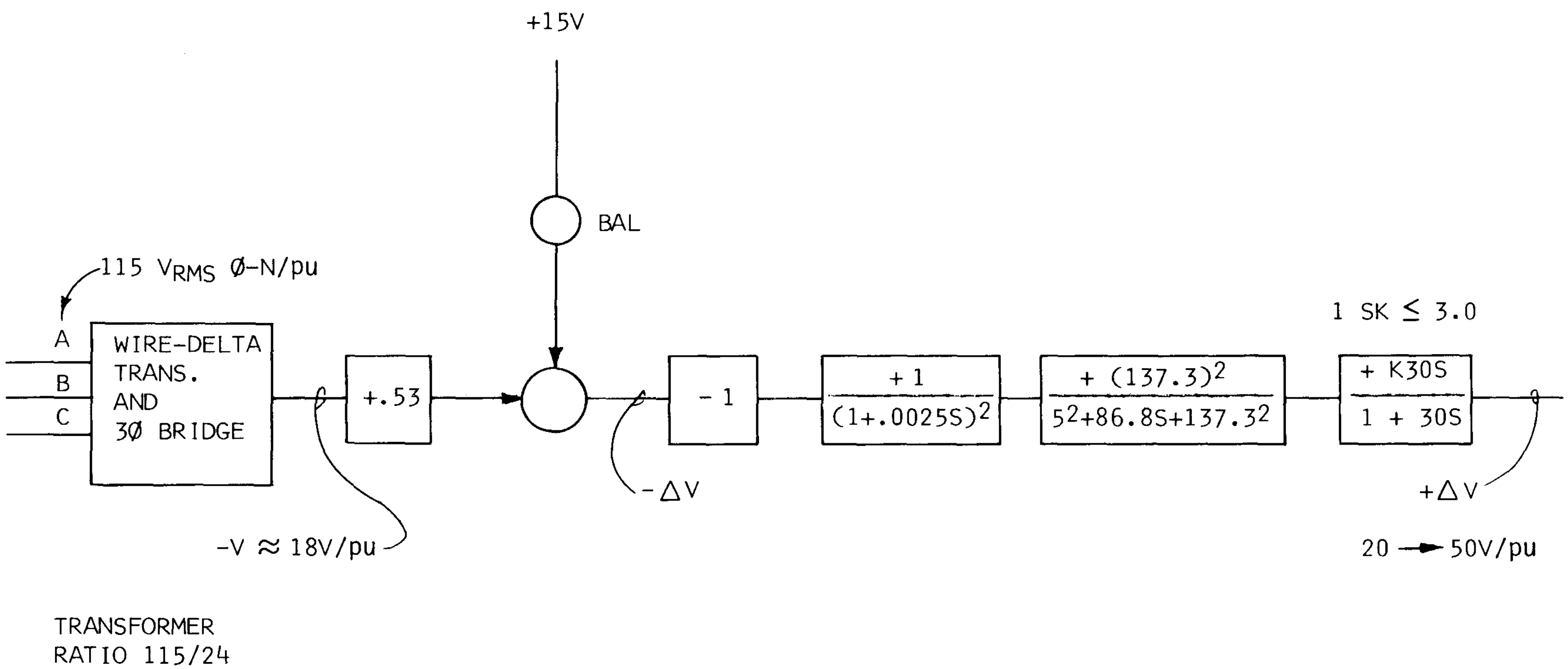


Figure 7. — Voltage transducer block diagram.

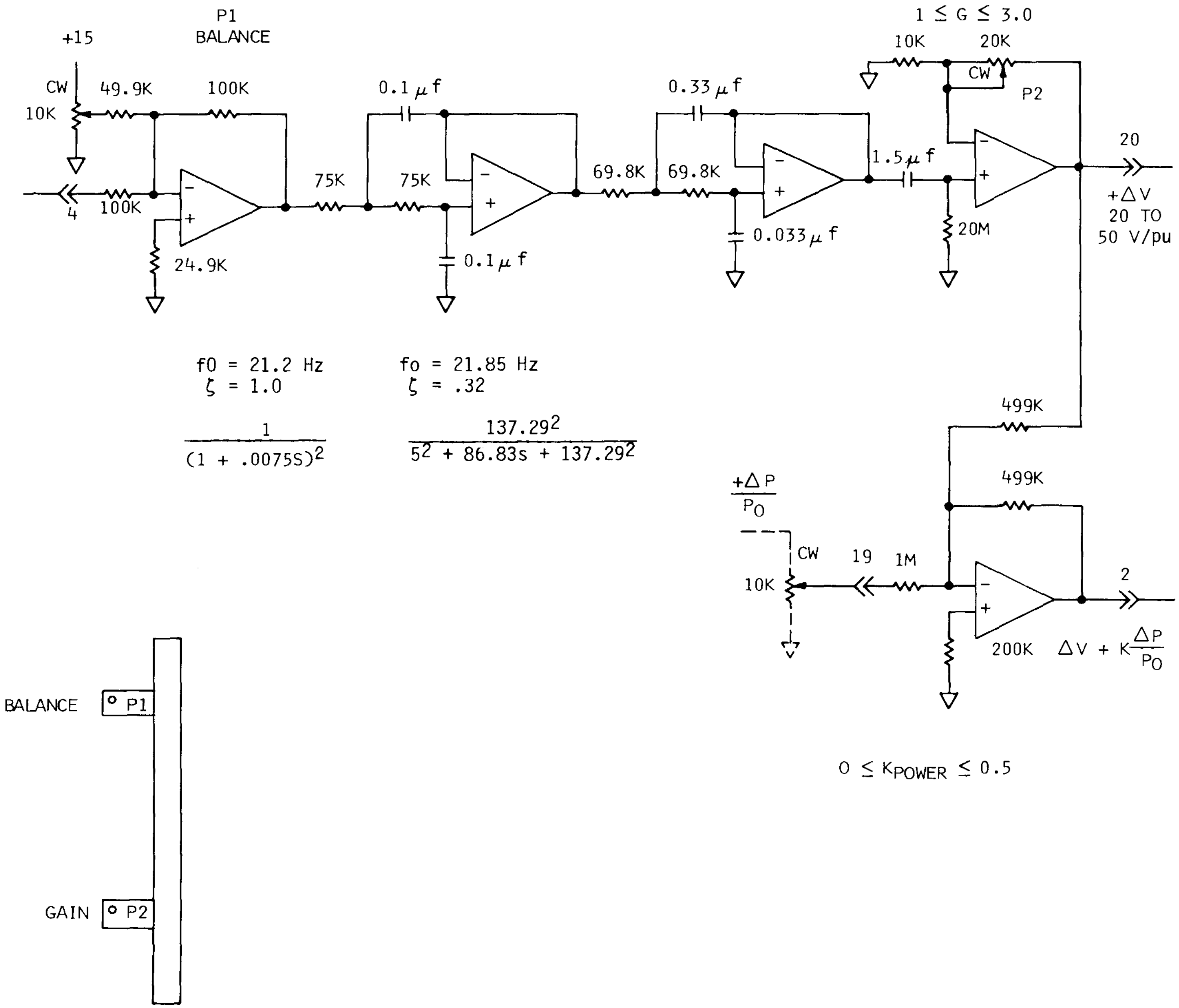


Figure 8. — Voltage transducer schematic (card 13).

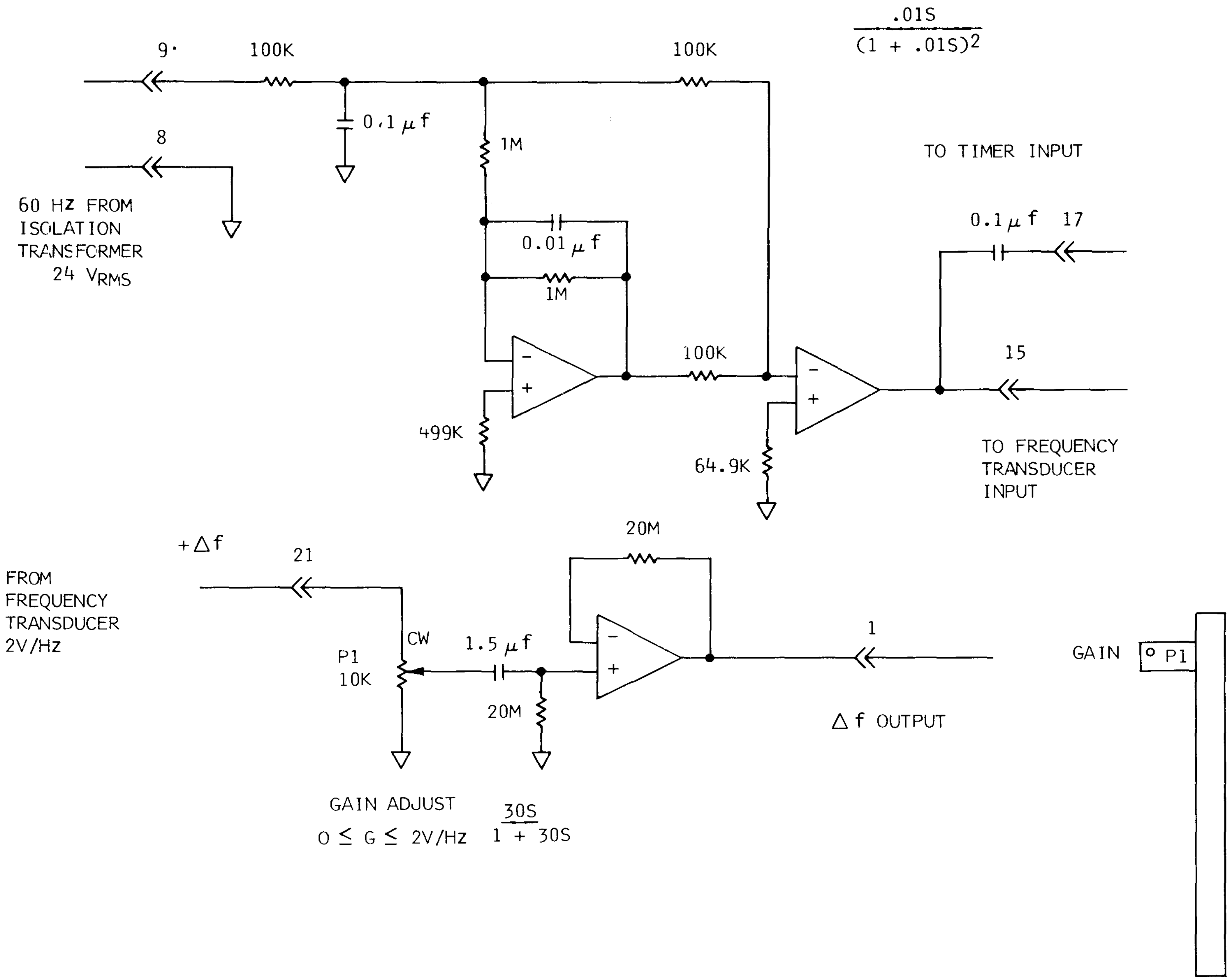


Figure 9. — Frequency transducer signal conditioning schematic (card 12).

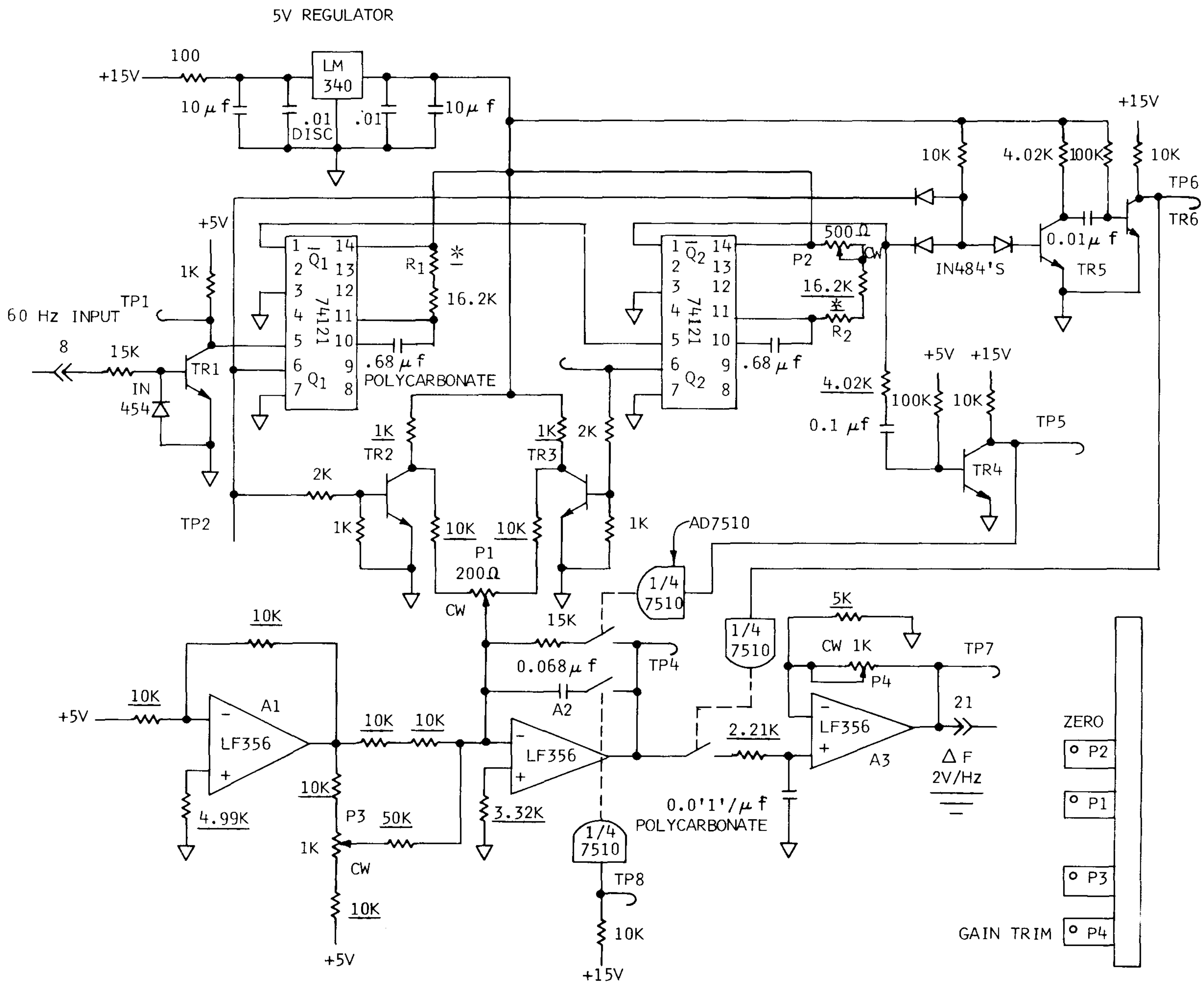


Figure 10. — Frequency transducer schematic (card 11).

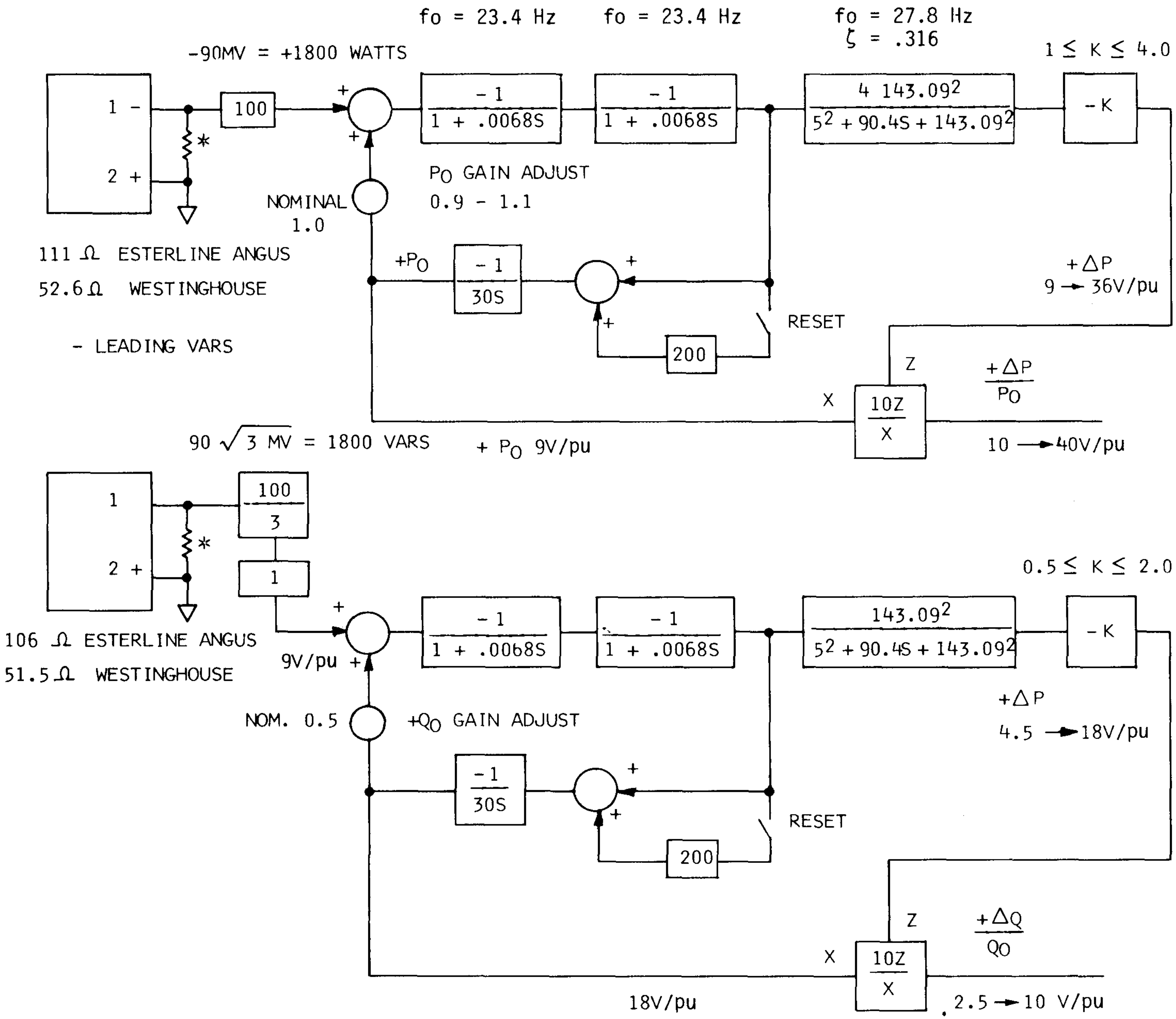


Figure 11. — Real and reactive power conditioning block diagram.

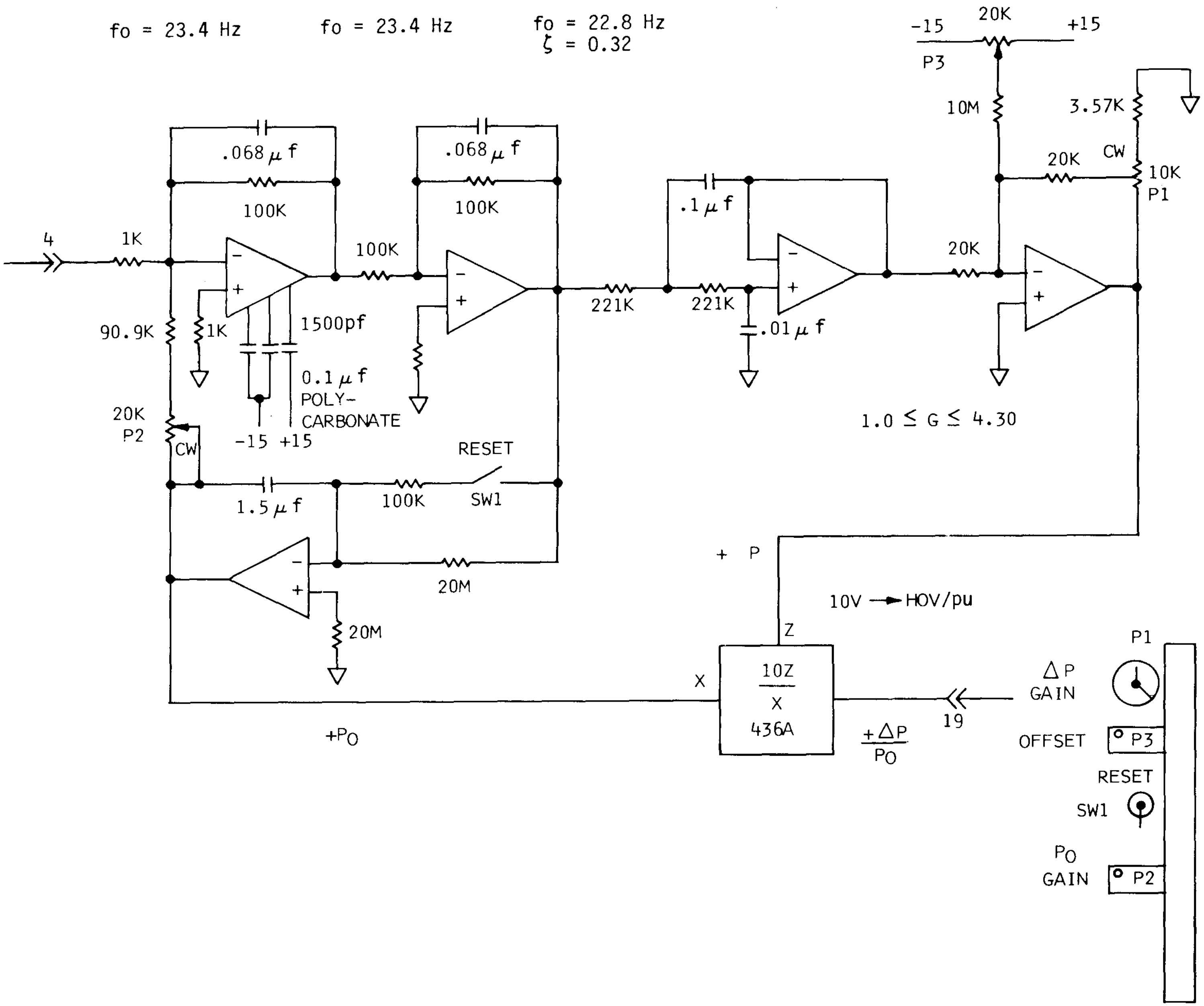


Figure 12. — Real power, $\Delta P/P_o$, calculation schematic (card 10).

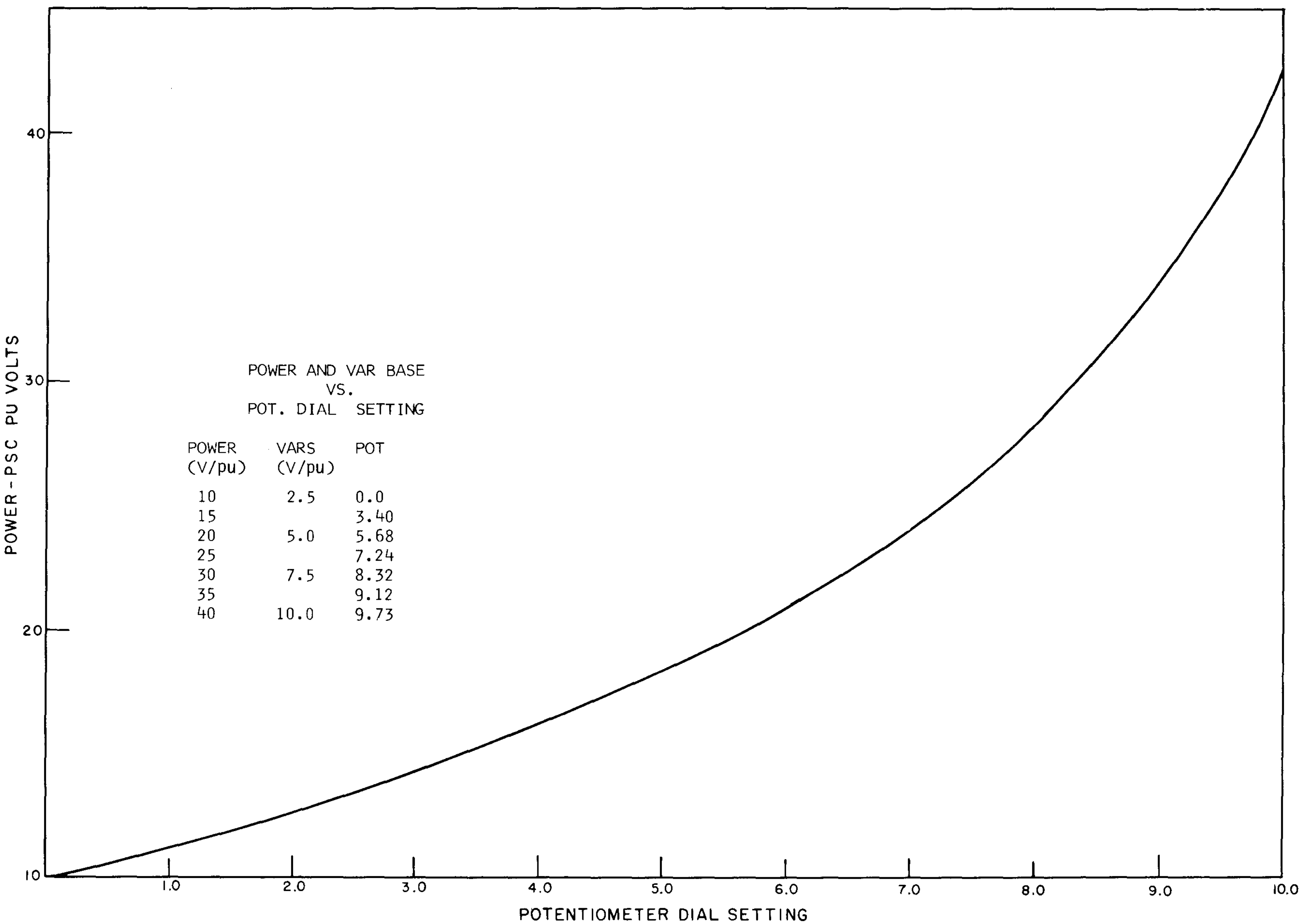


Figure 13. — Real and reactive power gain dial setting calibration.

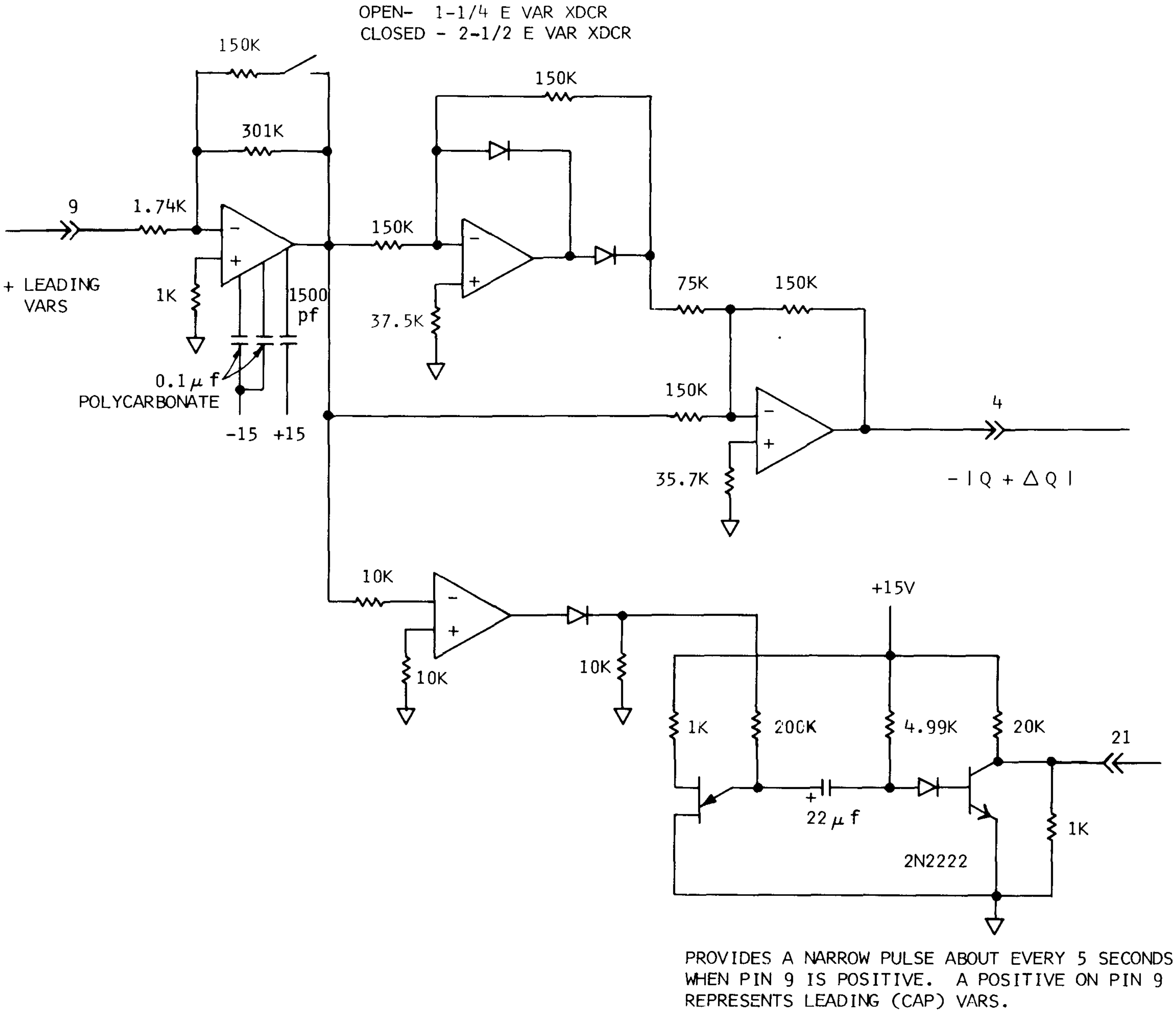


Figure 14. — Reactive power gain, absolute value, and flag pulse circuit (card 9).

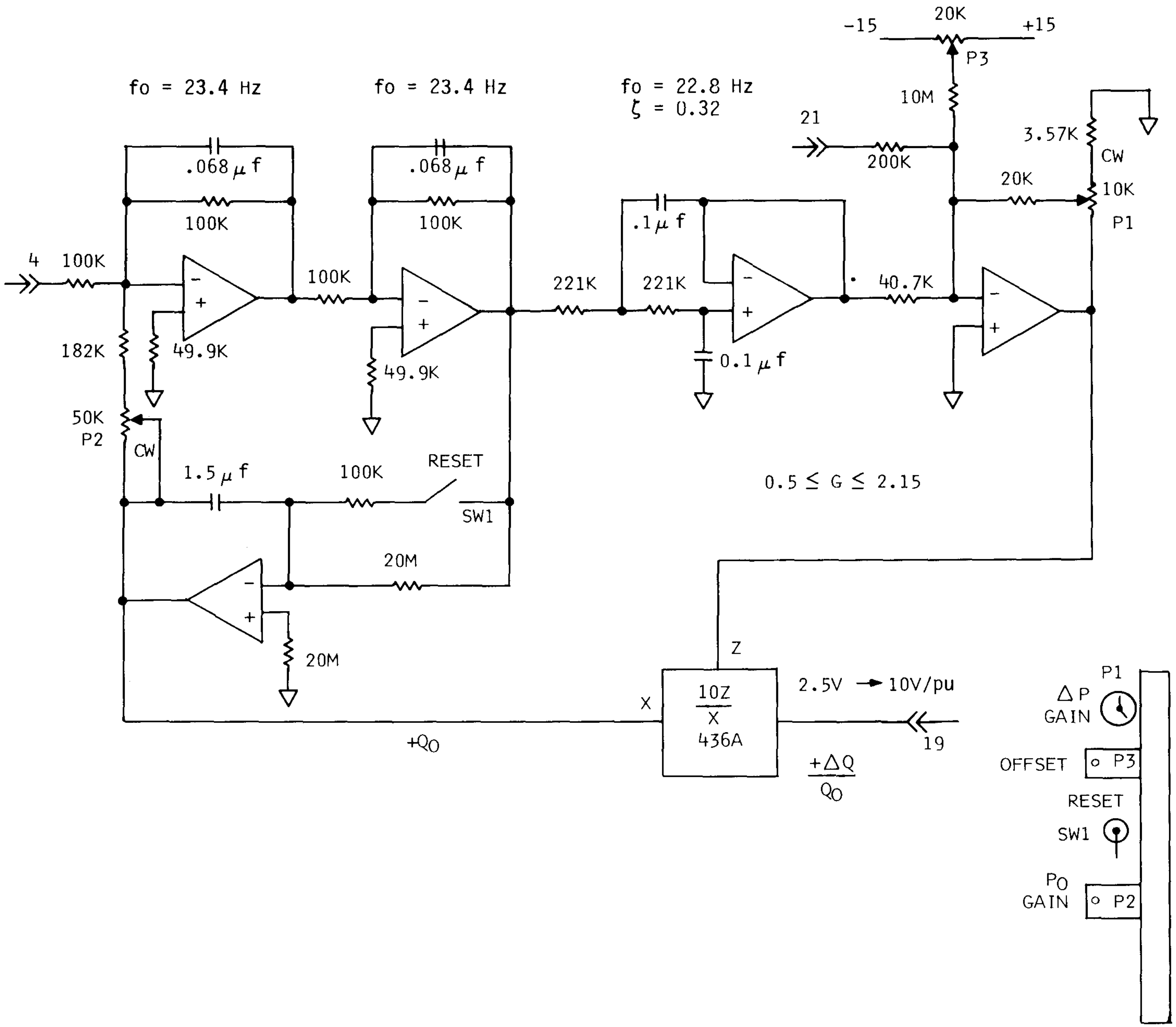


Figure 15. — Reactive power, $\Delta Q/Q_o$, calculation schematic (card 8).

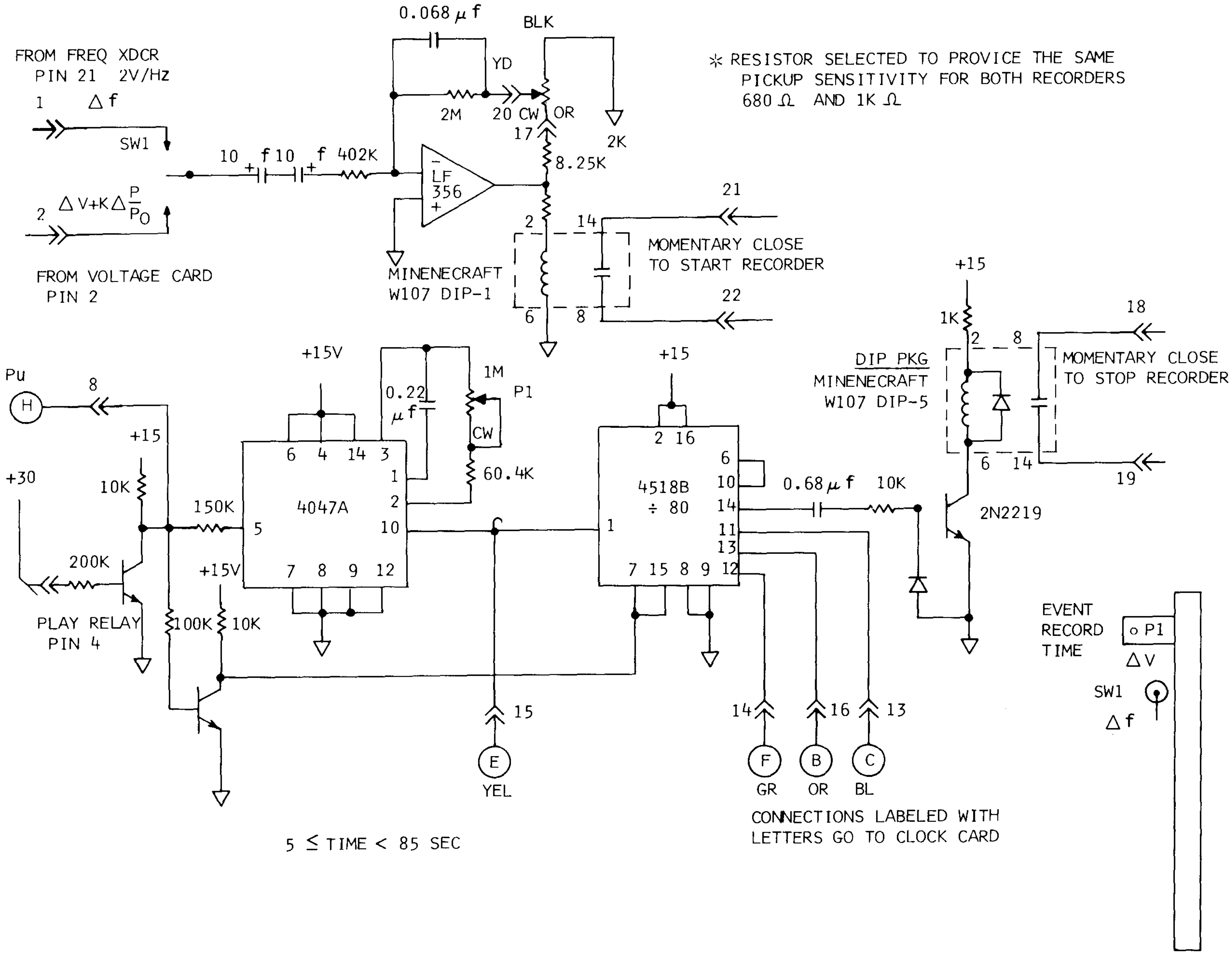


Figure 16. — Disturbance sensor and record start/stop circuit (card 14).

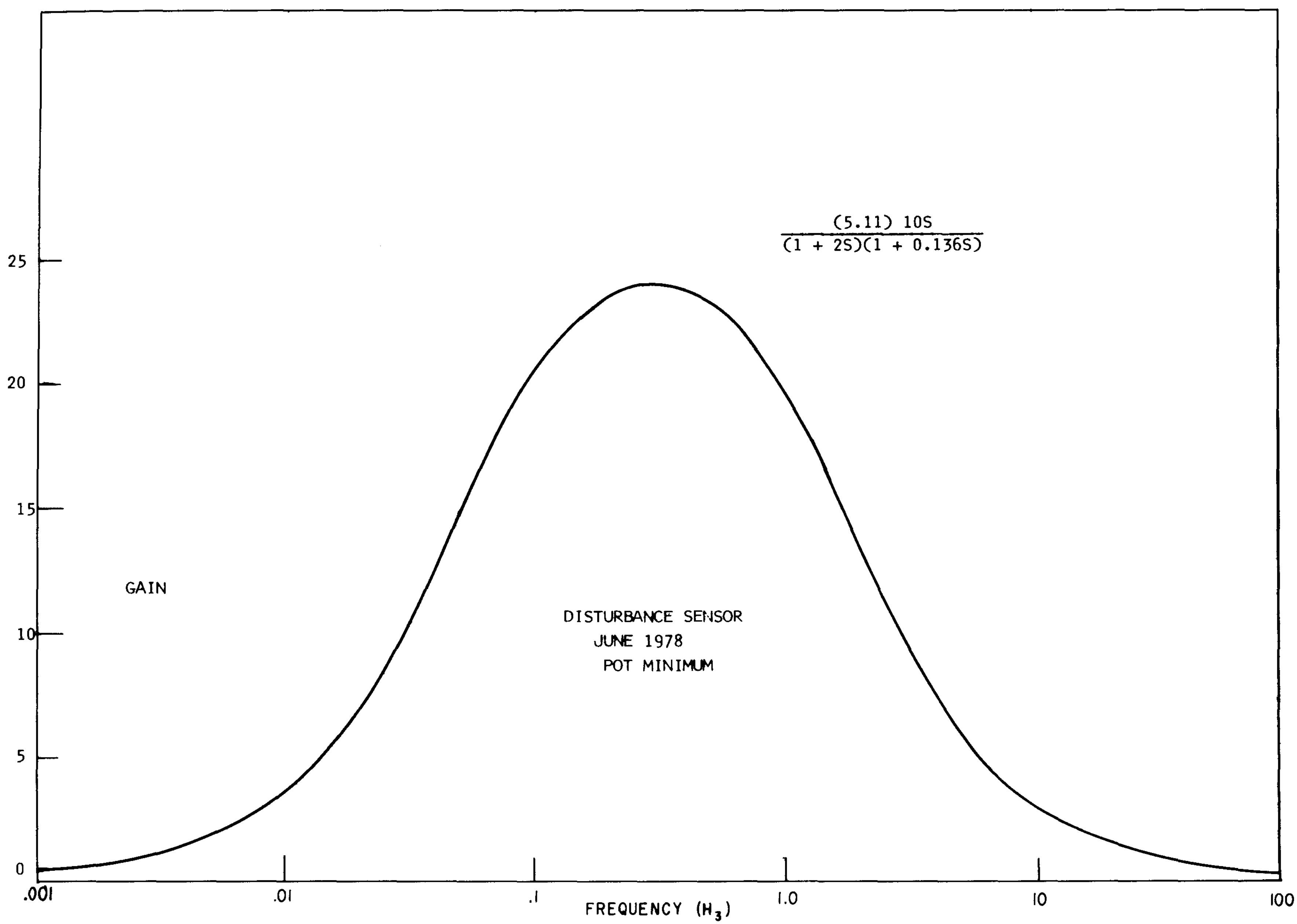


Figure 17. — Response curve of frequency disturbance sensor.

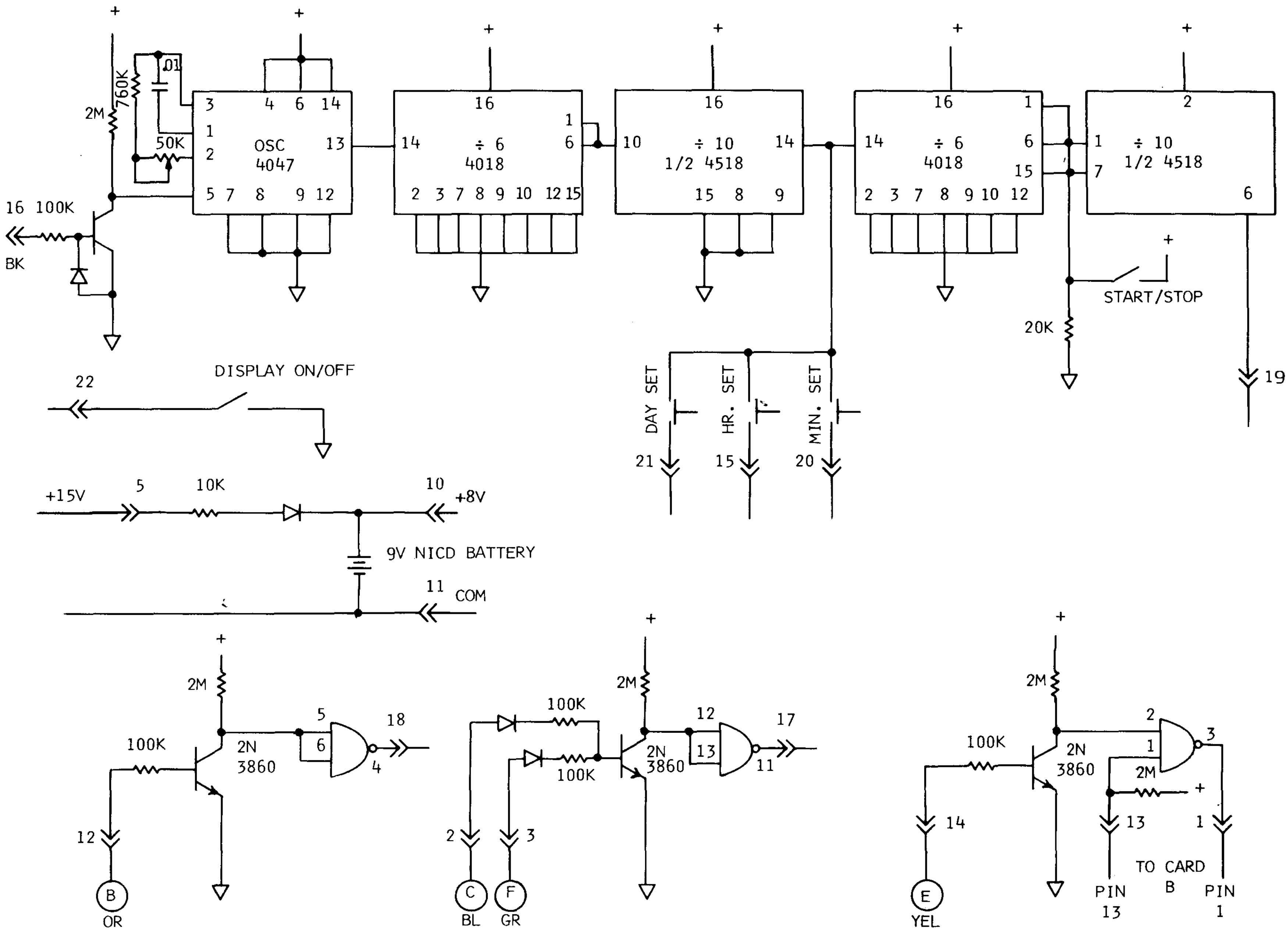


Figure 18. — DOY and time schematic — 1 of 2 (card A).

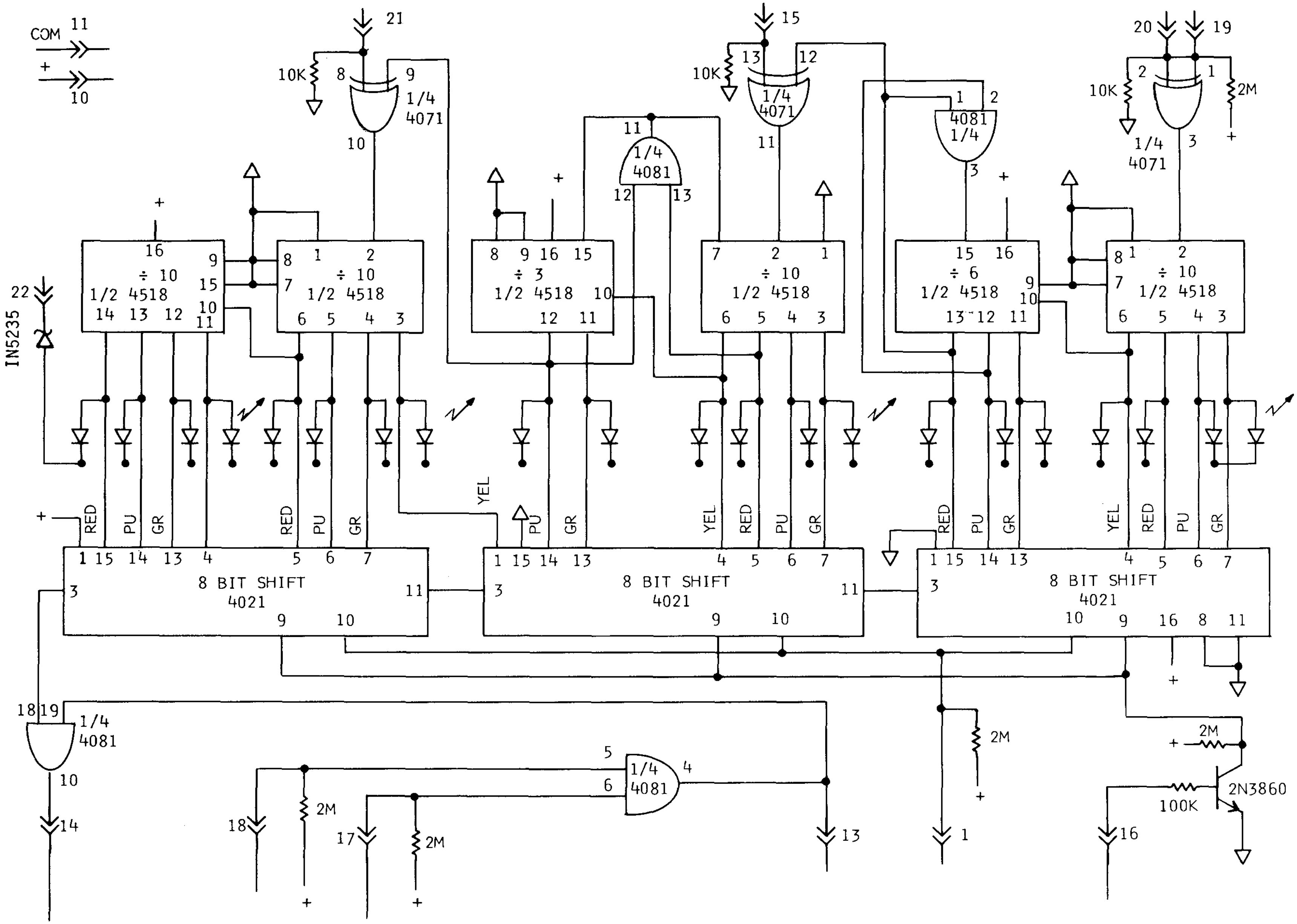


Figure 19. — DOY and time schematic — 2 of 2 (card B).

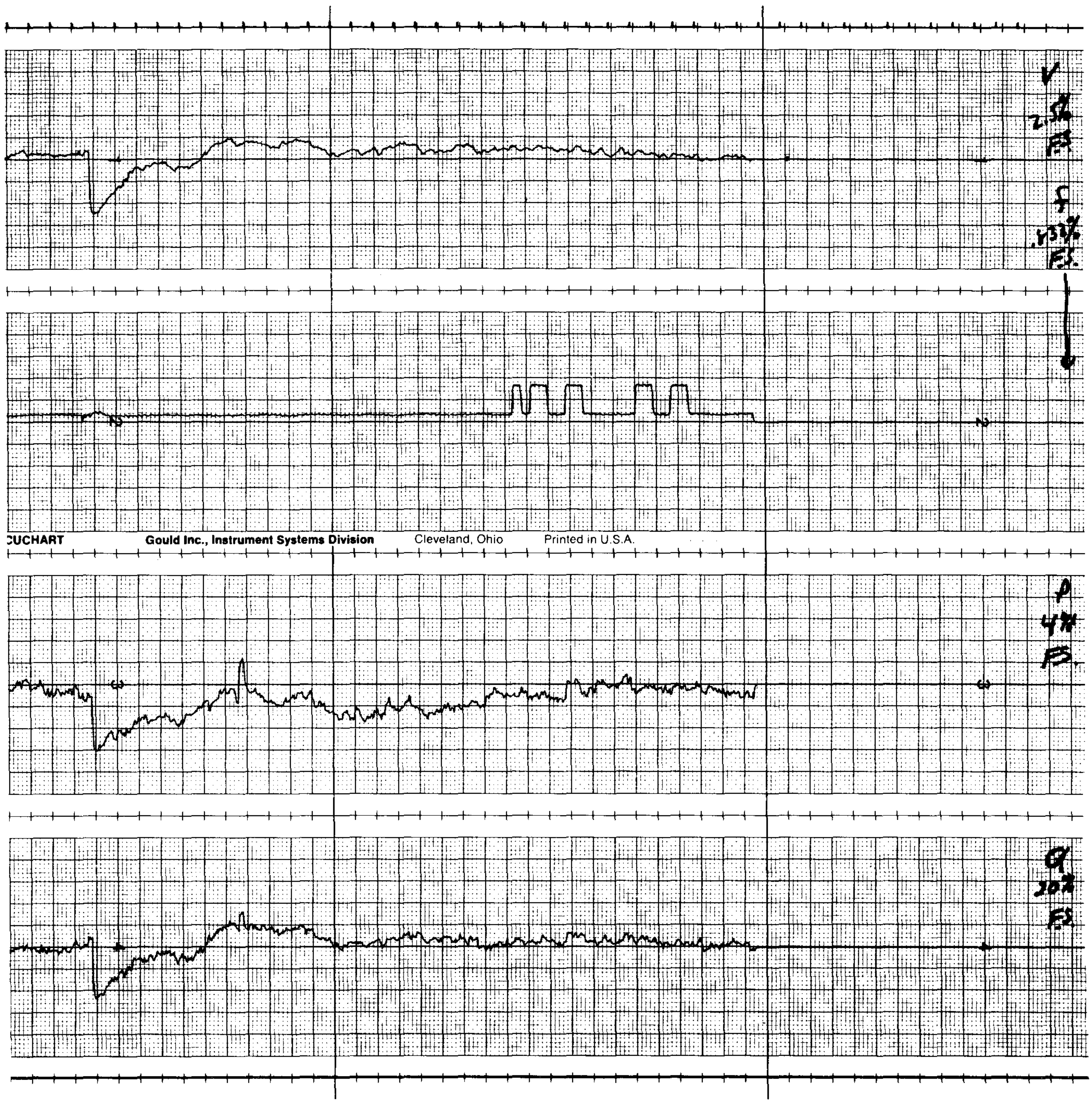


Figure 20. — Sample of data for $\Delta V/V_o$ and $\Delta P/P_o$ for $\Delta f = 0$.

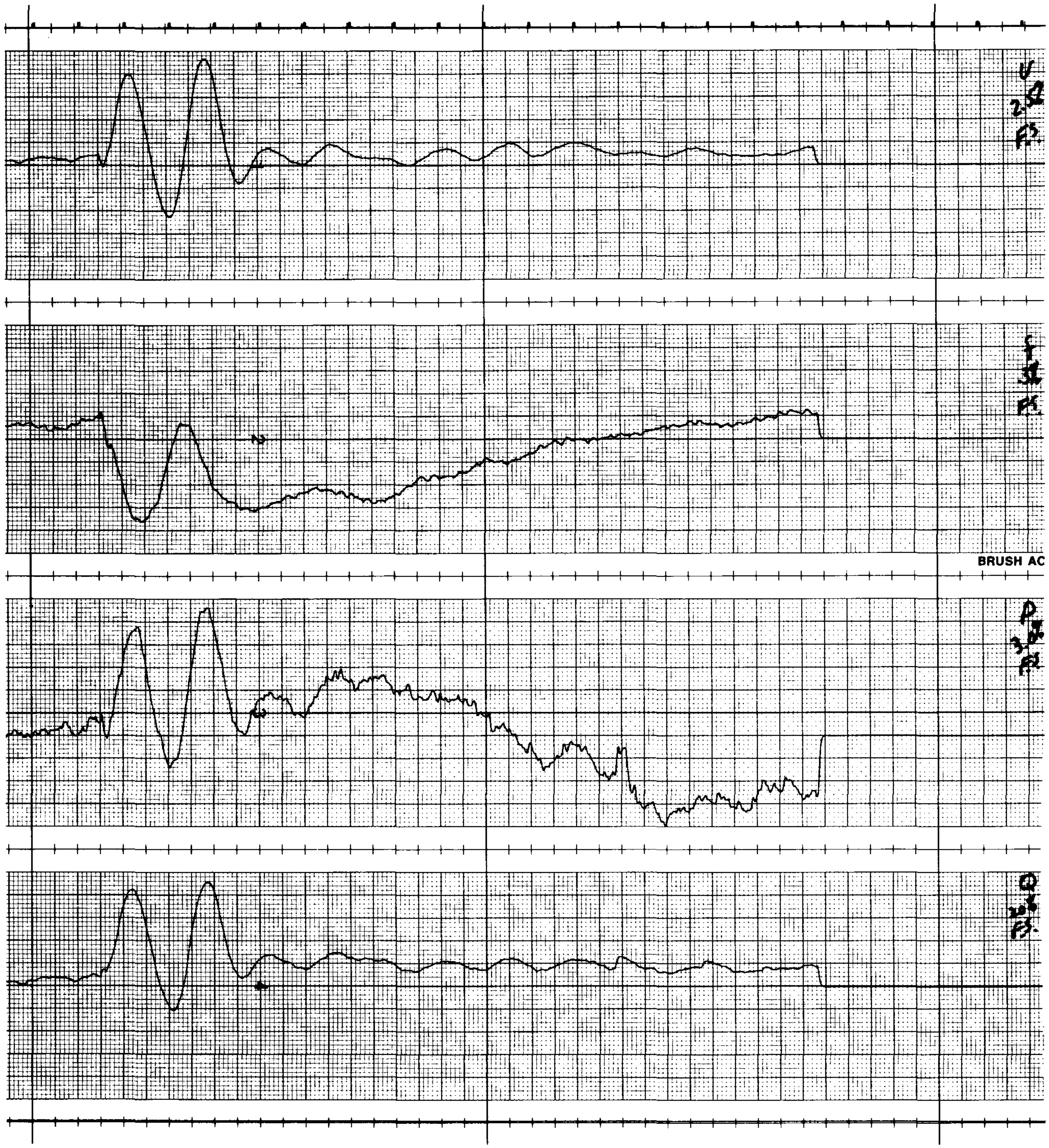


Figure 21. — Sample of data for $\Delta V/V_o$ and $\Delta P/P_o$ for $\Delta f \neq 0$.

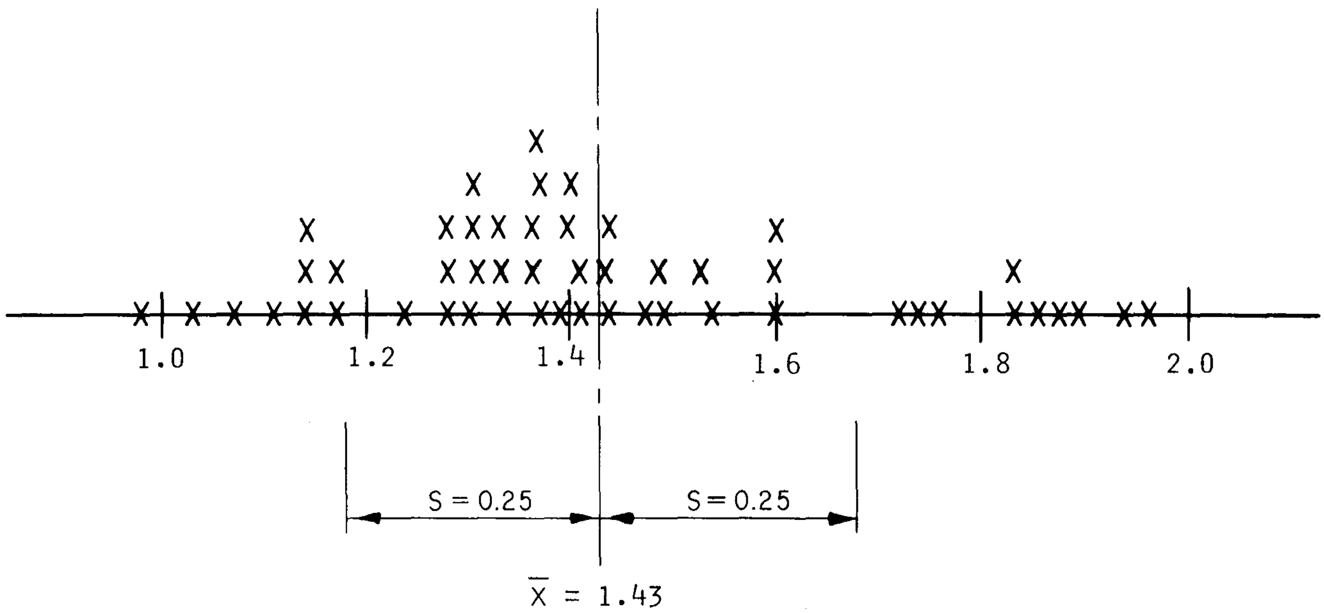


Figure 22. — Distribution of the values obtained for *m*.

Mission of the Bureau of Reclamation

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

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

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

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