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An Inexpensive Sidereal Drive Unit for 1 m Class Astronomical Telescopes

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Abstract

We describe here the details of the concept, the construction and the performance of an accurate and inexpensive sidereal tracking drive unit (SDU) using a frequency synthesizer with the basic crystal oscillator for the 1 metre or larger class of astronomical telescopes. The SDU is tunable and has a very highly stable and undistorted sinusoidal wave shape. The SDU consists mainly of a stable variable frequency generator and a distortion-free, low-cost power amplifier. Tracking accuracies of less than a couple of arc seconds in sky have been achieved. The unit can also be used in negative feed back mode to correct any errors in the tracking system. The accuracies in frequency stability obtainable with the SDU and the feasibility of operation in negative feed-back mode for correcting tracking errors are not possible in the commercially available battery back-up un-interrupted power supply (UPS) units.

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1 Introduction

An astronomical telescope is expected to track a star by keeping pace accurately with its apparent sidereal motion caused by the rotation of the earth. This demands a precise rate of rotation of 15 seconds of arc per second of the telescope about its axis aligned exactly with the celestial north pole. The atmospheric refraction, however, modifies this rate especially for smaller elevation angles or larger zenith angles. In the case of commercially available telescopes the sidereal tracking may be achieved usually by utilising a highly stable crystal oscillator with its frequency scaled down to match the required rate. However, the wear and tear of gears or inherent inaccuracies in the tracking motors may hamper the performance of the telescope in which case a corrective mechanism becomes essential. This happens particularly with the old telescopes. As the optical components and the mechanical systems are of quite good quality, such telescopes may best be utilised to their fullest potential by improving the tracking accuracies by some innovative and inexpensive methods. Such accuracies become very important in the present day trends of the imaging astronomy requiring long integration times. McMath and Mohler (1960) described the original method for telescope tracking using variable frequency electronic oscillators which was later improved upon by others using solid state components.

In this paper we describe the construction of an inexpensive sidereal drive unit with high accuracies in tracking for the 1 metre or larger class of telescopes made with components indegenously available in India.

2 Outline of the Method

Let us suppose that the tracking rate of the telescope is R_t . Ideally this should be equal to the actual sidereal rate of rotation, R_s (=15 seconds of arc per second, after neglecting the atmospheric refraction effects). We suppose further that the sidereal drive unit input frequency is F_d . Then it is required that

$$R_t \propto F_d \tag{1}$$

If the uncertainty in R_t is δR_t and that in F_d is δF_d , then we can write

$$\frac{\delta R_t}{R_t} = \frac{\delta F_d}{F_d} \tag{2}$$

For $R_t = R_s = 15$ seconds of arc/second and $\delta R_t = 1$ second of arc/1 hour (i.e., a drift of 1 second of arc in 1 hour of tracking of a star), one finds that

$$\frac{\delta F_d}{F_d} = 2 \times 10^{-5} \tag{3}$$

Or, for $F_d = 50 Hz$, $\delta F_d = 10^{-3} Hz$.

Therefore, our aim is to develop a drive unit which can give F_d within an uncertainty of about $(\delta F_d)_{min} = 10^{-3} Hz$ (at $F_d = 50 Hz$), so that any deviations in the frequency, either periodic or aperiodic, greater than $(\delta F_d)_{min}$ should be compensated suitably (see also, Ashok, Chandrasekhar and Manian, 1987). Furthermore, the shape of the wave pattern should be sinusoidal with minimum of distortions.

In order to achieve this, we have designed a sidereal drive unit which essentially consists of (i) a frequency synthesizer using crystal oscillator followed by a band-pass filter which generates a pure, drift-free sinusoidal wave pattern of a required frequency and (ii) a power amplifier which amplifies the sinusoidal wave without any distortion at required power. Thus these two circuits together function as a power oscillator whose output is fed to the telescope track-drive motor. The important features of these parts with their design considerations and their performance are described below in detail.

3 Frequency Synthesizer as drive rate generator

The schematic diagram of the system is shown in fig.1. The basic drive generator which is a frequency synthesizer employs a crystal oscillator of 1 MHz with long and short term stability of better than 30 parts per million. These osillations are scaled down and a monoshot is triggered whose width is adjustable and is added with the scaled down frequency. This output is then divided by two to give equal on/off square wave.

In order to get a final tunable frequency in the range of 50 Hz ± 0.5 Hz, a scaling factor of 9900 is set. The output of this scaler, triggers the monoshot and a further scaling is done by a factor of 2 (for square wave output) making an effective scaling factor of 19,800. This alongwith the variable monoshot width from 0 to 201 micro seconds gives the final required output of (50 Hz ± 0.5 Hz.)49.5 Hz to 50.5 Hz.

Fig.2 shows the frequency synthesizer circuit where the output frequency is as follows:

$$F_{out} = \{2NT_{cp} + [Int(T_{ms}/T_{cp}) + 1]T_{cp}\}^{-1} Hz \tag{4}$$

where N is the scaling factor $N = (N_1 + 10 \times N_2) \times N_3$(see fig.3), T_{cp} , the crystal oscillator pulse width in seconds, $Int(T_{ms}/T_{cp})$ is the integer part of T_{ms}/T_{cp}, and T_{ms}, the Monoshot pulse width in seconds.

Thus it can be seen that the output frequency can be varied by changing the values of N, T_{cp} and T_{ms}. In order to achieve a wide range of variation in the output frequency, for example, ± 10%, the factor N can be controlled by a correcting voltage through an analog-to-digital converter. The variation of T_{ms} gives finer corrections. In the present case, we have kept N and T_{cp} constant and only T_{ms} is varied to achieve the required output frequency within ± 1%. Here the scaling factor is a steady value and does not change the frequency once the value is fixed. T_{cp} depends upon the crystal oscillator stability. The T_{ms} controlled by the monoshot should have jitter less than one half of the crystal osicllator pulse-width, so that the monoshot trailing edge can be accommodated within the crystal pulse and after gating, this jitter is effectively bypassed (Refer fig. 3 for timing details).

The output frequency can be varied in discrete steps with the resolution of one clock pulse i.e. the crystal frequency of oscillation as can be seen from eqn.(4). The final square pulse thus obtained after the division-by-two counter is fed to an active bandpass filter to achieve a pure sine wave for further power amplification.

The crystal oscillator circuitry is housed in a separate, grounded aluminium box for shielding from electro-static and electro-magnetic pick-ups.

The power amplifier was built around the available discrete components. The amplifier is capable of delivering 120 watt (r.m.s) with a low distortion and has a built-in short circuit protection(Sanjay, 1990).

4 Circuit description

The crystal oscillator, shown in fig.2, is built with a 1 MHz crystal and with two TTL $NAND$ gates U_6 .

This output is again $NAND$-gated with the $\bar{Q}_1$ output of U_5 the Monoshot $74LS123$ and is fed to U_3 the dual decade counter $74LS390$ to get a scaled down factor of 100. This is followed by two up/down counters $74LS192$'s, U_1 and U_2 , with the preset down count value of 99. Thus the overall N value is set at 9900 in this case.

The scaled down output from the U_2 the final 74192 up/down counter is fed to a dual mono-shot 74123 as well as to a D flip-flop U_4 , using $74LS74$, connected in toggle-mode (division by two counter) to get a square pulse. Thus, ultimately a scaling factor of 19800 is used to bring down the frequency from 1 MHz to give an output of 50.5 Hz.

The dual monoshot 74123 has its first monoshot width Q_1 which is variable by a ten-turn precision-graduated potentiometer. The potentiometer can be set to an accuracy of 0.05% of the full scale value. The $\bar{Q}_1$ of this monoshot is used as a gating pulse to the crystal oscillator output fed to the $divide - by - N$ counter chain as mentioned earlier. This $\bar{Q}_1$ inhibits the clock pulse to the counters and thus extends the time of each pulse at the output. Thus the output pulse from the counters would be 9900 clock pulses (crystal oscillations) plus the monoshot pulse width Q_1 as shown in the timing diagram of fig.3. The trailing edge of this pulse triggers the second monoshot.

The complementary outputs of the second monoshot Q_2 and $\bar{Q}_2$ whose pulse width is set at 100 nanosec are used to preset the 74192 counters i.e. to load the preset scaling factor value N and setting the dual decade counter 74390 to its initial value of zero. (This is to make sure that all the counters are properly initialized in every cycle). The monoshot outputs have less than 10 nanosec jitter.

The square pulse of frequency F_{out} thus obtained is

$$F_{out} = \{2 \times 9900 \times 10^{-6} + [Int(T_{ms}/T_{cp}) + 1]T_{cp}\}^{-1} Hz \qquad (5)$$

where $T_{cp} = 10^{-6}$ sec.

We can see that F_{out} is 50.505 Hz for $T_{ms} = O$ sec and 49.5 Hz for 201.0 microsec.

The presettable up/down counters which are used in down count mode can be loaded with any N value and will be effective in the following counting. This is done by loading the counters with the preset value of N (in our case 99 using two 74192's with a preset value of 9 each) with each cycle, by the second monoshot output. The second monshot width is set at 100 nano second so that the loading of the 74192's and the resetting of the dual decade counter 74390 are assured. The width of this second monoshot is only one tenth of each clock pulse and would not affect the timings of the oscillator circuit as a whole.

The square pulse thus obtained is finally passed through an active Butterworth bandpass filter. This circuit is built around the op-amp $\mu A741$. This circuit has a Q of about 10 and a midband gain of around 7. The output of this stage is 28 V (± 14 V) peak-to-peak pure sinewave. The preset-potentiometer R_{v3} is used to tune the centre frequency of the bandpass filter and has a range 49.5 to 50.5 Hz. The output is taken through a 10 KΩ potentiometer R_{v4} for feeding variable input signal to the power amplifier for further amplification.

The power amplifier circuit selected is modified for the present purpose and is shown in fig. 4 (Sanjay, 1990). The first stage is a differential cascode amplifier consisting of T_1 to T_4 to which the input signal as well as negative feed back signal from the output stage via a $R - C$ $(R_{11}, R_9, C_5, C_6 \& C_{12})$ network are given. The $R - C$ network sets the gain and the bandwidth of the amplifier. The value of the $R - C$ network is set to give a overall bandwidth of 20 Hz to 5 KHz and a voltage gain of around 20. The output power can be varied by varying the input to the amplifier by R_{v4}.

This cascade stage output is then fed through an emitter-follower T_5 to a class A amplifier T_6. This amplifier T_6 with T_7 (the V_{BE} multiplier) gives the split-phase output required for driving the following complementary emitter-follower stages. T_{10} , T_{11} and T_{12} amplify the positive half-cycles and T_{13} , T_{14} and T_{15} amplify the negative half-cycles. The V_{BE} multiplier T_7 ensures the d.c. stability at the output close to zero volts and minimizes the zero cross-over distortion in the output and also compensates for temperature variations.

The transistors T_{11} , T_{12} , T_{14} and T_{15} are mounted on a heat sink with sufficient capacity to dissipate and remove the heat in the free-air cooling conditions. The heat transfer through the heat sink was better than $0.5°C/Watt$.

The short circuit protection is done by the transistors T_{16} and T_{17} along with the associated components for both the positive half-cycles and the negative half-cycles respectively at the output.

The power amplifier supply is ± 35 V d.c. with maximum current of 6 amps. An undistorted 65 V peak-to-peak or 22.75 r.m.s at 6 amps can be derived. Thus this amplifier is set to give a maximum of 120 watts with 1 V rms input or 2.8 V peak-to-peak input. The amplifier output is taken through an output step-up transformer with 1:6 ratio. The output transformer is of 150 watts capacity and has a flat frequency response from 45 Hz to 55 Hz. The required output power is realised by adjusting the amplifier input potentiometer R_{v4} and is adjusted to give 100 watts output.

5 Performance

This unit has been tested with an inductive load (a pedestal fan) of 125 watts for 8 Hrs a day. The temperature of the chassis has been maintained within 60°C with the ambient varying between 25°C to 30°C by using a 30 cm x 18 cm heat sink (Type 204, AFCO make) with cooling fins. The total harmonic distortion (T.H.D) at 50 Hz is around 5% at 125 watts output (output voltage 110 V a.c.) and at 100 watts output the T.H.D is less than 0.5%.

The frequency stability is also monitored and found to be better than one milli Hertz. The frequency was varied between 49.5 to 50.5 Hz for testing and the performance remained the same.

The drive system housed in a chassis unit measuring 43.5 x 17.7 x 30.5 cm^3, is thoroughly tested in the laboratory, and found to be rugged in performance. The stability of frequency as well as the power output remained constant for the long time testing. The temperature of the system as a whole is well within 60°C even at 30°C ambient with free-air cooling.

This amplifier has been in use as a sidereal drive amplifier for the last two years to drive the 1.2 metre telescope at Japal-Rangapur Observatory (JRO) near Hyderabad, India. The unit, in its final form, is quite handy and portable having dimensions of 43.5 x 17.7 x 30.5 cm^3. The sidereal drive of the telescope has a synchronous-motor operated at 110 volts a.c. and consumes around 100 watts. The amplifier is working without any failure and without any degradation in performance. The drive frequency was set at 50.12 Hz for minimum drift operation.

The drift in tracking for 1 hour is less than a couple of arc seconds as judged visually from observations. It shows that the amplifier driver is working excellently both in drift-free drive rate and distortion-free output at the rated wattage.

Further, it should be noted that (i) owing to the use of an accurate crystal oscillator, the frequency stability in the SDU is far better than that may be achieved in battery back-up uninterrupted power supply (UPS) units (controlled by solid-state inverters) by a factor of more than hundred; (ii) the UPS units cannot be corrected for any errors caused by frequency drift through negative feed-back method which is possible in the SDU (see Appendix).

The overall cost of the SDU works out to be approximately US Dollars 200/- currently and all the components are indegenously available in India. The time required for building and testing of the unit was about one man-month.

Finally, the simplicity of the design of the unit makes it easy to tune, operate and service in the field where laboratory facilities are usually unavailable. Further improvement on the oscillator section using negative feed back is on the anvil. This is disucssed in the appendix.

6 Conclusions

The important conclusions are already listed in the abstract of the paper. Though this oscillator was developed for tracking the telescope, this can be used in any application where the stability, as well as tunability of the frequency is required. The unit was reliable, easily serviceable, rugged and be capable for continuous operation of more than 8 hrs per day.

Acknowledgements

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Appendix: Negative feed-back loop for Auto-correction

In what follows, we suggest a negative feed-back loop procedure for auto-correction in the set frequency-error of the oscillator.

As mentioned in the text, the frequency division value N of the presettable up/down counter 74192's can be made variable for more than ± 10% of the set frequency. This can be achieved by using an analog to digital converter (ADC) in the negative feed-back loop for shaft encoder with analog output as shown in Fig.5. For shaft-encoder with digital output the ADC be replaced by a suitable binary counter, also shown in the Fig.5.

The shaft encoder analog output used as output monitoring signal voltage and can be compared with the set speed control voltage and the error derived can be fed to the A.D.C. To avoid discrete ($1LSB$) jumping the residual ($1LSB$ value) can be suitably amplified, limited, and then fed to a voltage controlled M.S. for monoshot pulse width variation. The circuit operation remains the same.

The ADC can be triggered for conversion with the $\div N$ counter output. Thus the N value from the ADC gets loaded in the following cycle of counting, i.e., the frequency variation in the output is effected in the next half-cycle. This response is quick enough for correction.

The above example is given for the present application of driving the telescope side-real drive tracking motor. But same principle can be incorporated in other suitable application of similar requirements.

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Figure Captions

Fig. 1 : Sidereal Drive Unit(SDU) - Functional Block Diagram

Fig. 2 : Circuit Diagram for the Oscillator

Fig. 3 : Timing Diagram of different signals in the SDU

Fig. 4 : Circuit Diagram for the 120 W Power Supply Unit

Fig. 5 : Circuit Diagram for the negative feed-back loop for auto-correction.

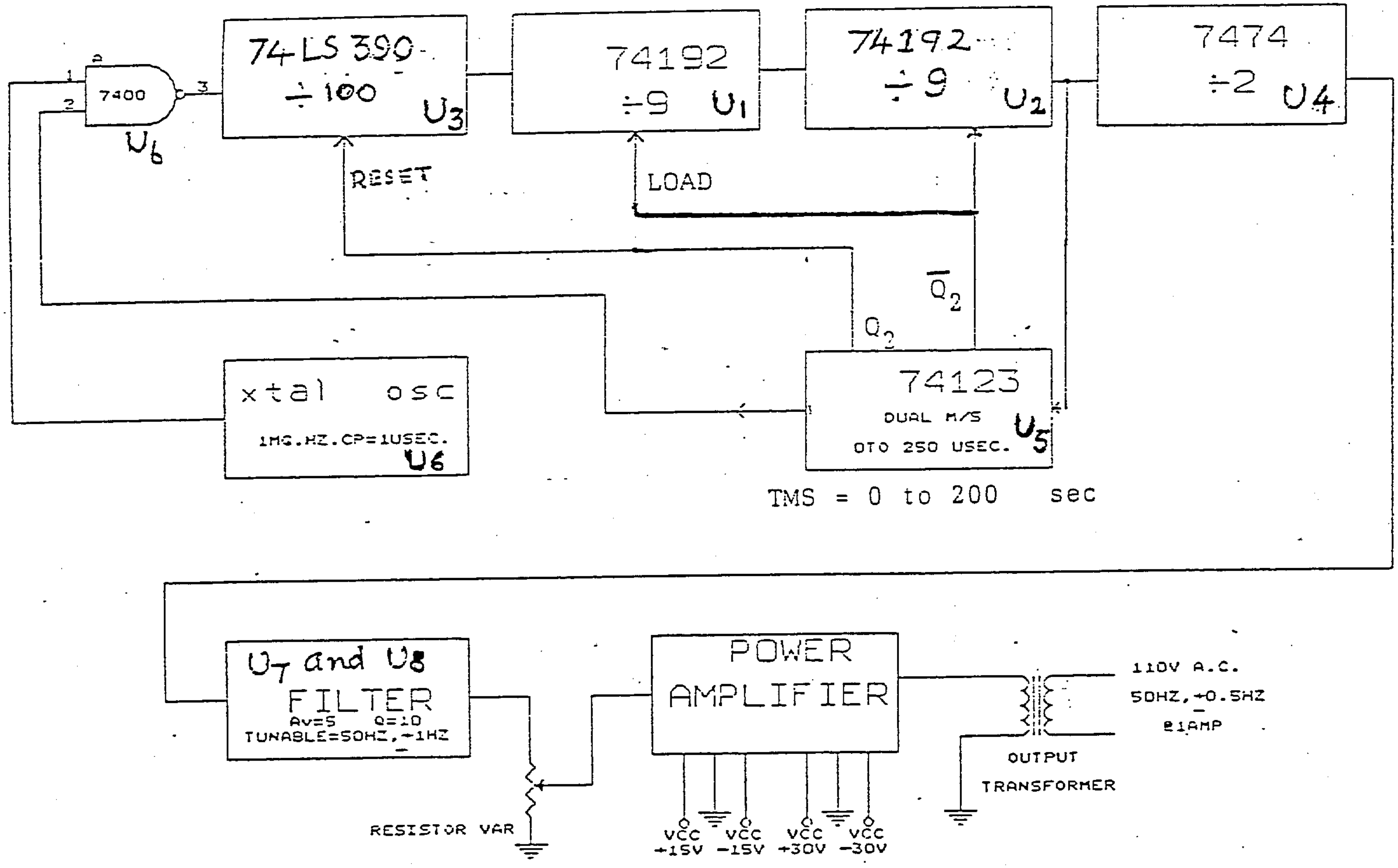

FIG 1 : SIDEREAL DRIVE UNIT

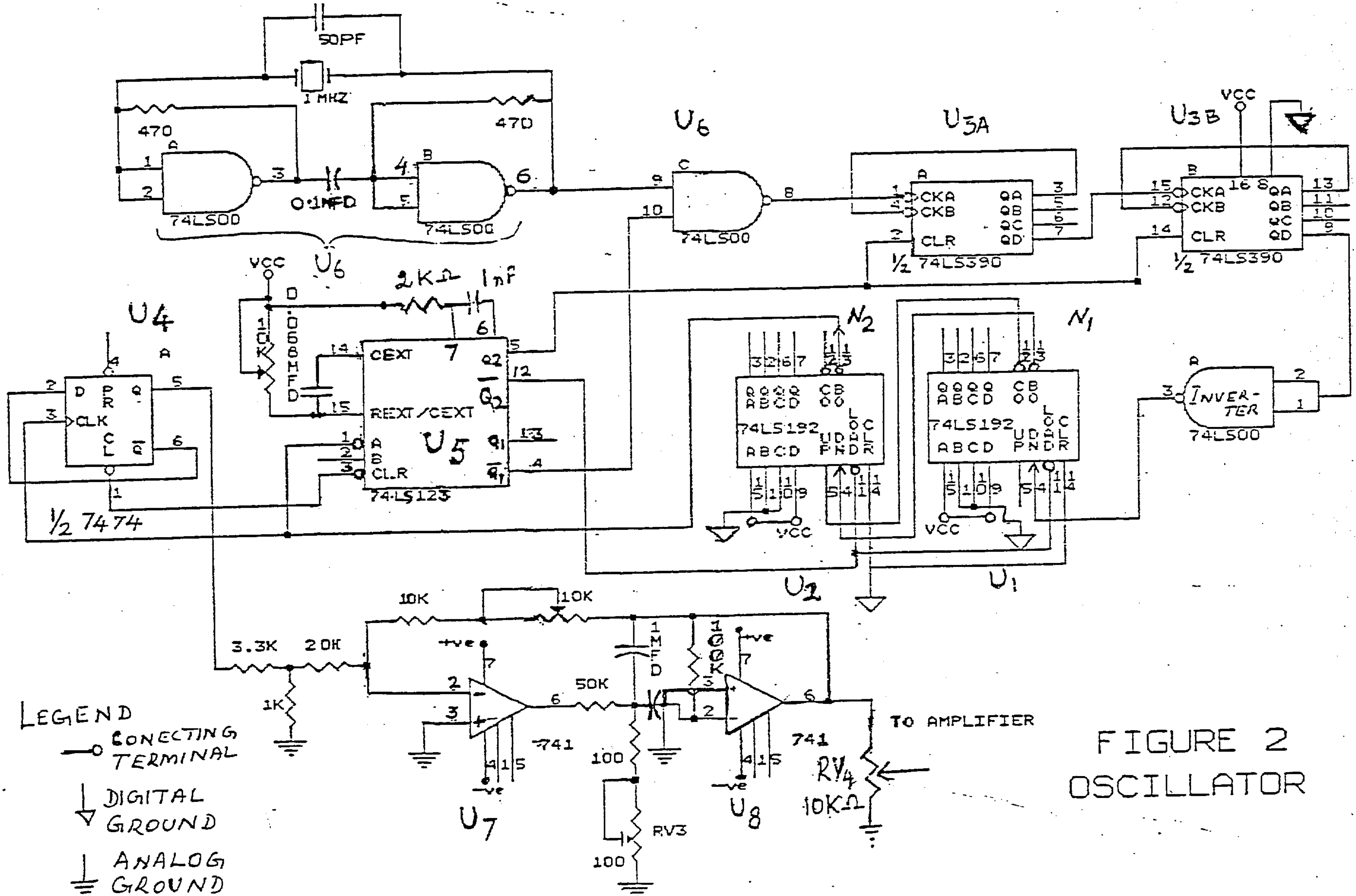

FIGURE 2
OSCILLATOR

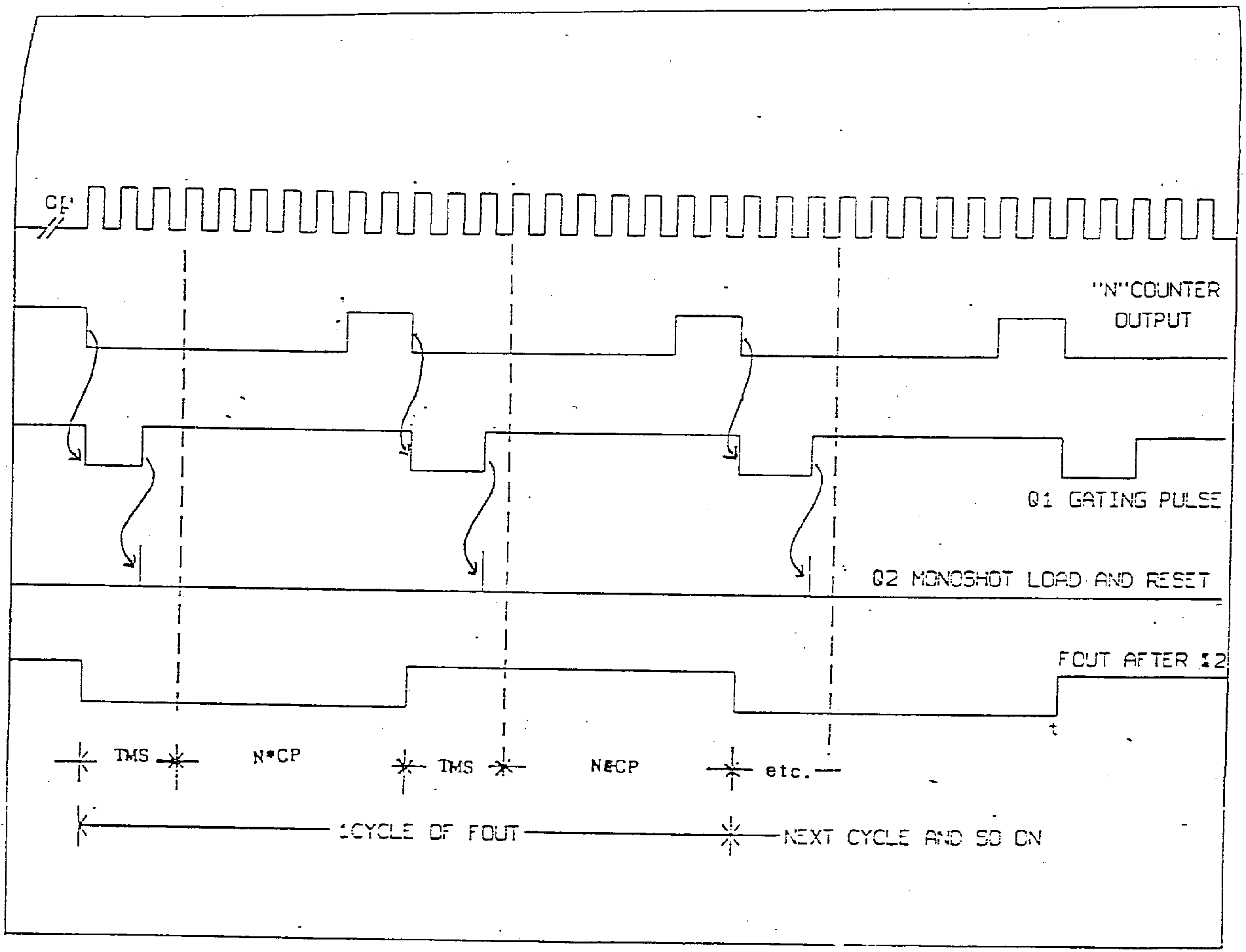

Fig. 3 : Timing Diagram of the Different Signals in the S.D.U.

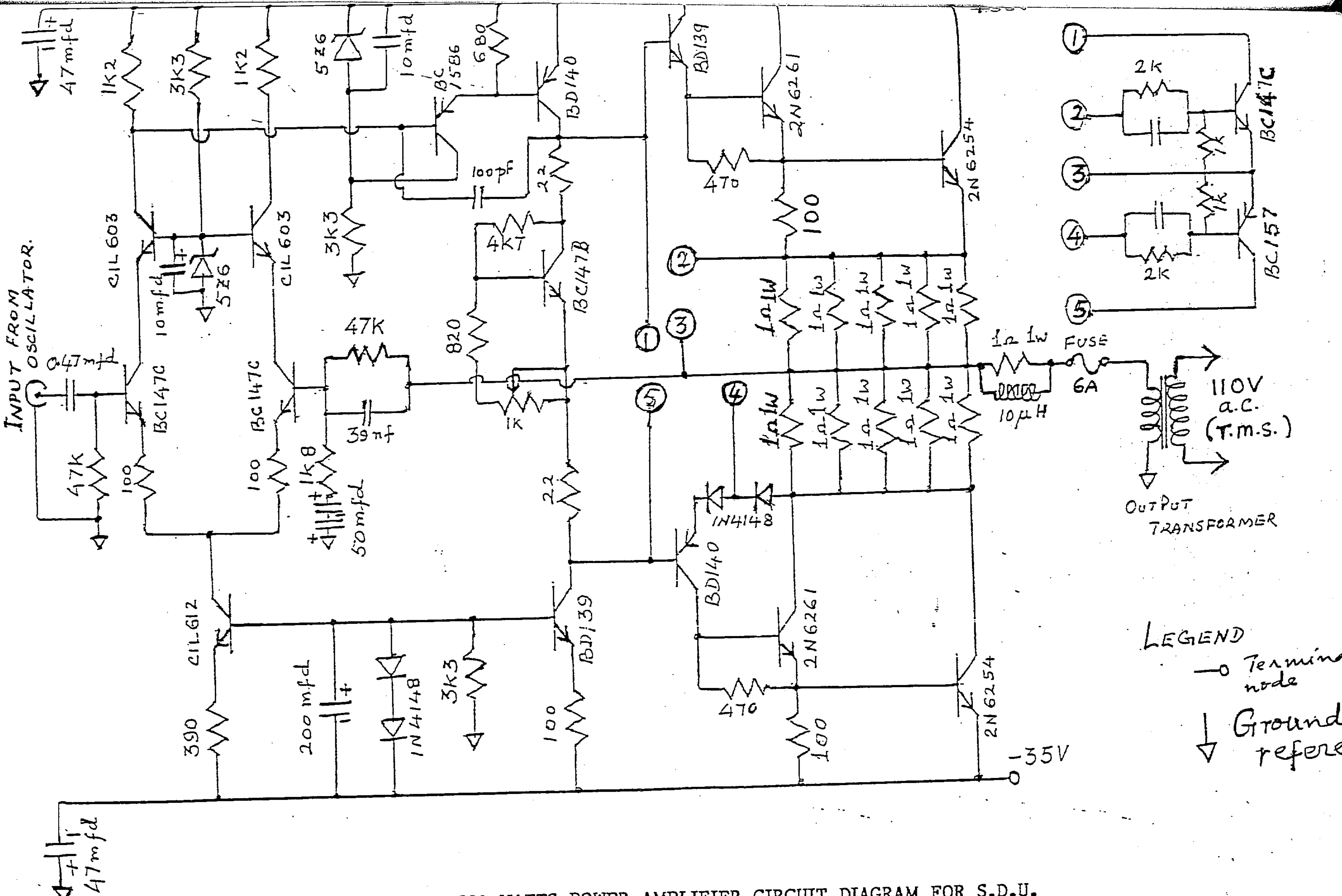

Fig. 4: 120 WATTS POWER AMPLIFIER CIRCUIT DIAGRAM FOR S.D.U.

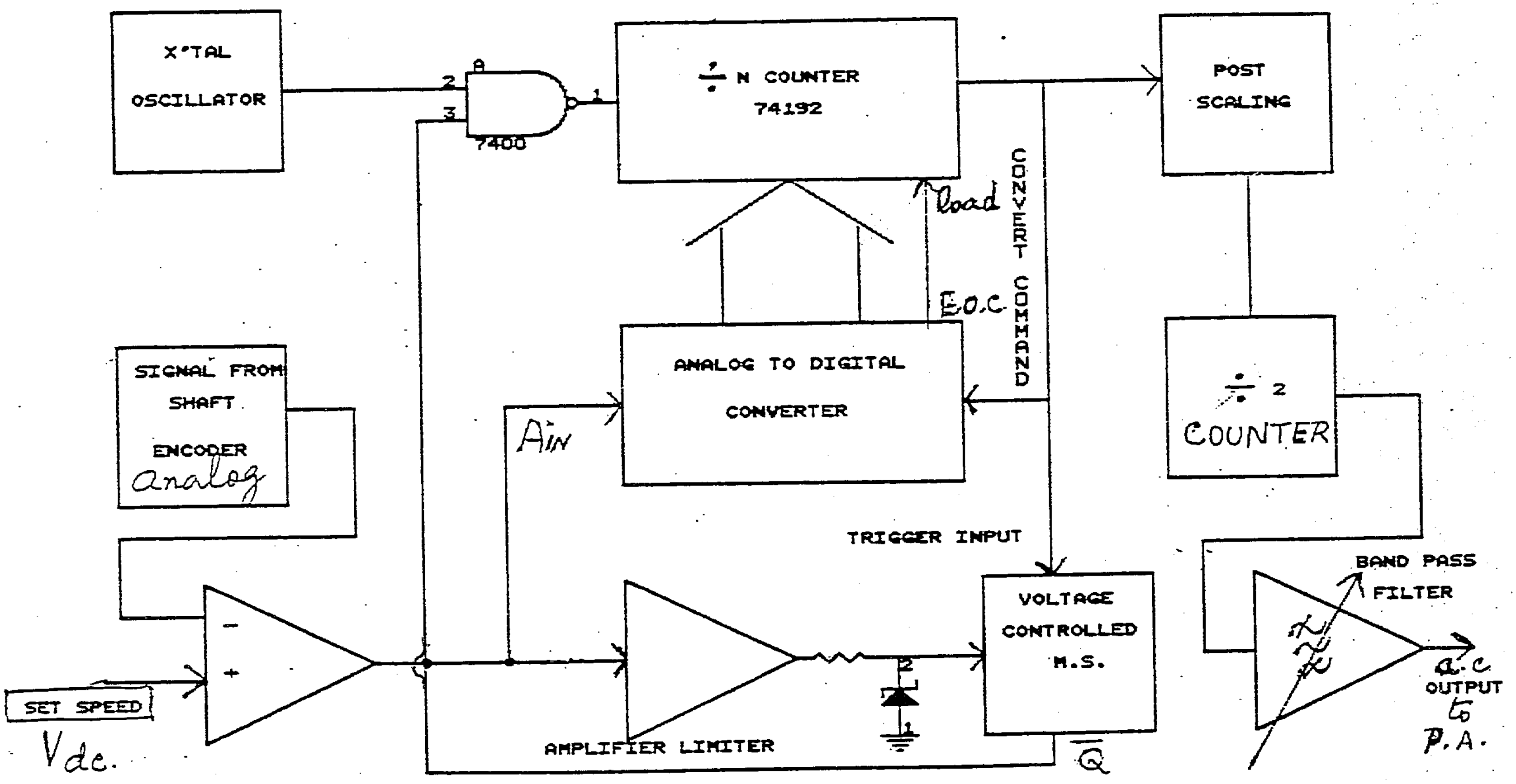

Fig.5. Corrected drive rate with feed back.

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