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High-Accuracy Speed Controller Using Pulse Counting Methods

By

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Summary. This paper reports a digital controller for accurate speed control of electric motors. The speed is measured by counting the number of pulses from the pickup for a precisely determined period. The comparison of the measured speed with the reference is performed by a preset counter through a relatively simple method. An analog integrator is used to convert the digital error signal into a voltage signal. This voltage is fed into a power amplifier and controls the motor. The main part of this controller is multiplexed by time-division so that it can control two motors at a time. A new pulse frequency multiplier, which is useful for the digital speed control, is also developed. The principles and circuits of those devices as well as some test results are described in this paper.

1. INTRODUCTION

During the past few years there has been an increasing requirement for highly accurate speed control of electric motors. To meet the requirement several controllers using digital techniques were developed and some of them have been put in practical use in several scientific and industrial fields. One of these application fields is the aerodynamic wind tunnel in which the speed of the driving motor must be controlled precisely according to the various conditions of the experiments. Another application of the digital speed regulation is the control of calender machines in paper industry or the control of multistand rolling mills in steel industry.

These digital controllers employ magnetic or photo-electric pickups as their primary means, which convert the rotation of output shafts of the controlled motors to the electric pulses having frequencies proportional to the speed. F. T. Thompson [*1*] reported a controller in which signals from the pickup and a reference oscillator are converted into analog voltage signals by two identical precise frequency-to-voltage converters. The difference of these two analog signals serves as the actuating error. J. Inagaki and others [*2*] used the beat frequency between the outputs of the pickups as a measure of relative speed of the two motors, while W. C. Schmidt and R. R. Potts [*3*] described a method which utilizes a reversible counter as the controlling means.

W. Fritzsche [*4*] adopted a more straightforward method, that is, the speed of controlled motor is measured precisely by counting the number of the pulses from the pickup for a predetermined period. The heart of his device is a special counter which subtracts the preset number corresponding to the reference speed from the counted number. The difference is converted by a digital-to-analog converter into a voltage signal which, after amplified, controls the motor.

The speed controller described in this paper is also the pulse counting type. It compares the counted number with the reference through a rather simple method. It has a special feature that the digital error signal so generated is converted into voltage by an analog integrator, instead of being converted by a digital-to-analog converter. The digital part of this controller is multiplexed by time-division so that it can control two motors at a time. In order to achieve a high control accuracy without sacrificing the response speed of the control system, a pulse frequency multiplier using successive rectification of the input signal is provided as an optional equipment of the controller. The principles and circuits of those devices as well as some test results of the control system are described in this paper. A possibility of controlling relative speed of two motors with this controller is also mentioned therein.

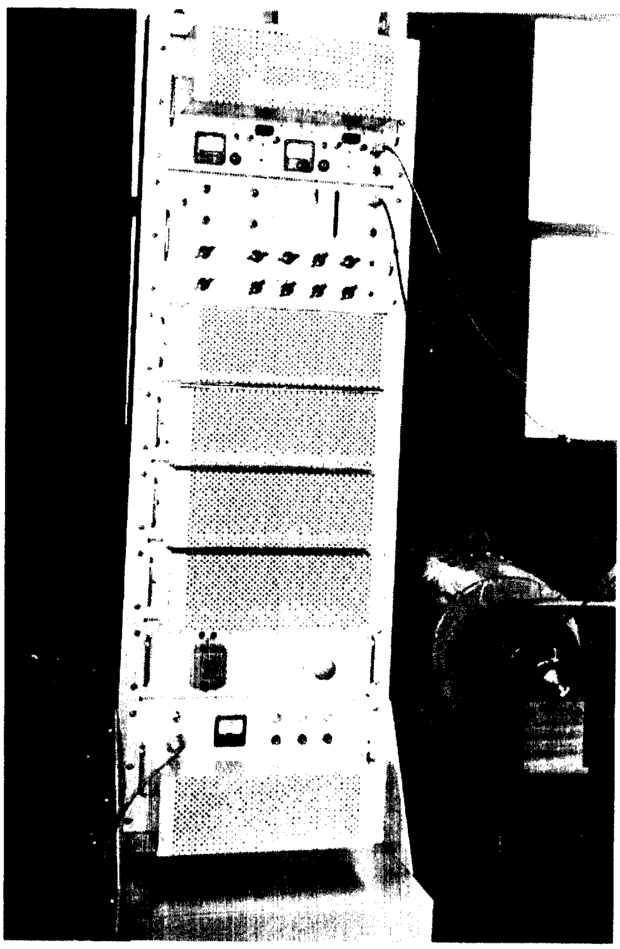

PHOTO. 1. Front view of the digital controller

2. Basic System

Fig. 1 shows the block diagram of the whole control system. The input signals of the digital controller are obtained from the self-contained magnetic pickups whose shafts are connected directly to the shafts of the controlled motors. Assuming that the selectors of multiplexers are on "A" side, the output pulses of pick-up(A) are conducted to the input gate and counted for a precisely determined period, giving a number proportional to the speed of motor(A). At the end of this period the counter compares its digital content with the preset number corresponding to the reference speed and generates the error pulses, the number of which is equal to the difference of the counted and preset numbers. In this instance the electric polarity of the error pulses is determined according to the algebraic sign of the difference.

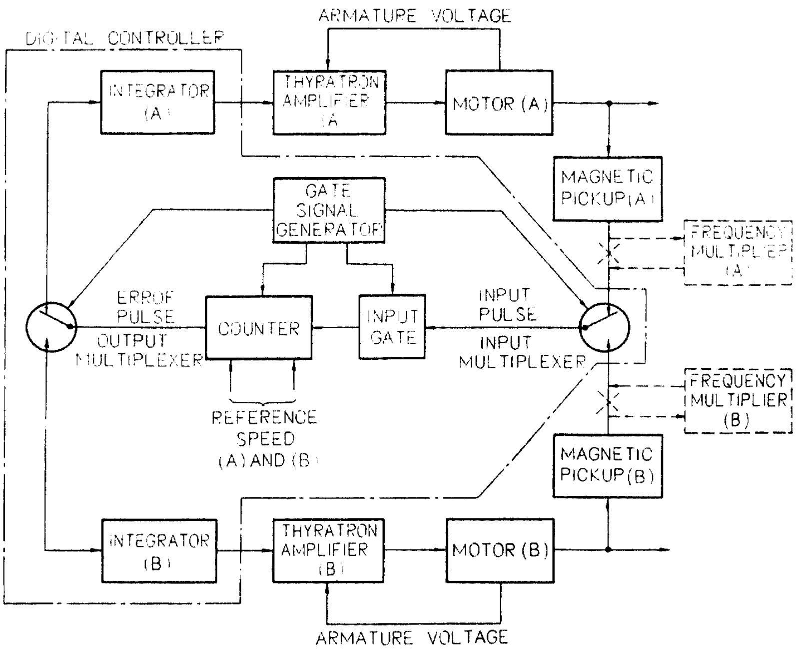

FIG. 1. Block diagram of the whole control system

Integrator(A) accepts these pulses as an analog input and integrates their voltage waveforms. The output voltage of the integrator controls the thyratron power amplifier so as to maintain the motor speed at the given speed. After the sequence of these control actions is completed, the multiplexers are switched to "B" side and, this time, motor(B) is controlled in the same manner. Thus, the digital part of the controller is multiplexed so that it controls two motors alternatively. The gate signal generator has a crystal-controlled oscillator as its time reference and delivers the gate signals and other timing signals of the controller.

The thyratron amplifier has an analog feedback loop of its own and constitutes a control system by itself. The output of the integrator is nothing but the reference voltage to this analog control system. Therefore, there are two kinds of control loops; one is the analog loop attached to each motor, which is mainly responsible to the dynamic characteristics of the whole control system, and the other is the main digital loop, which monitors the analog control systems at a regular interval. The steady-state accuracy of the whole control system is determined by this digital, sampled-data control loop. The off-set of the controlled speed can not exist because the integrators are contained in the forward path of the main loop.

3. Detailed Description of the Controller

3.1 *Magnetic Pickup*

The pickup consists of a gear, a permanent magnet, a coil and other parts. When the shaft of pickup is driven, the gear teeth modulate the magnetic reluctance and produce a sinusoidal voltage at the output terminals of the coil. The pickup used delivers 150 cycles of the sinusoidal voltage in one revolution of its shaft (that is, the frequency of 2500 cps is obtained at the speed of 1000 rpm).

3.2 *Multiplexer*

The multiplexers are merely the assemblies of several electronic logic gates which are controlled by the signals from the gate signal generator. The input multiplexer contains also the pulse shapers which convert the sinusoidal signals from the pick-ups into narrow pulses.

3.3 *Input Gate and Counter*

Fig. 2 is the detailed block diagram of the input gate and the counter. The timing relationship among the gate signals and other controlling pulses is shown in **Fig. 3**.

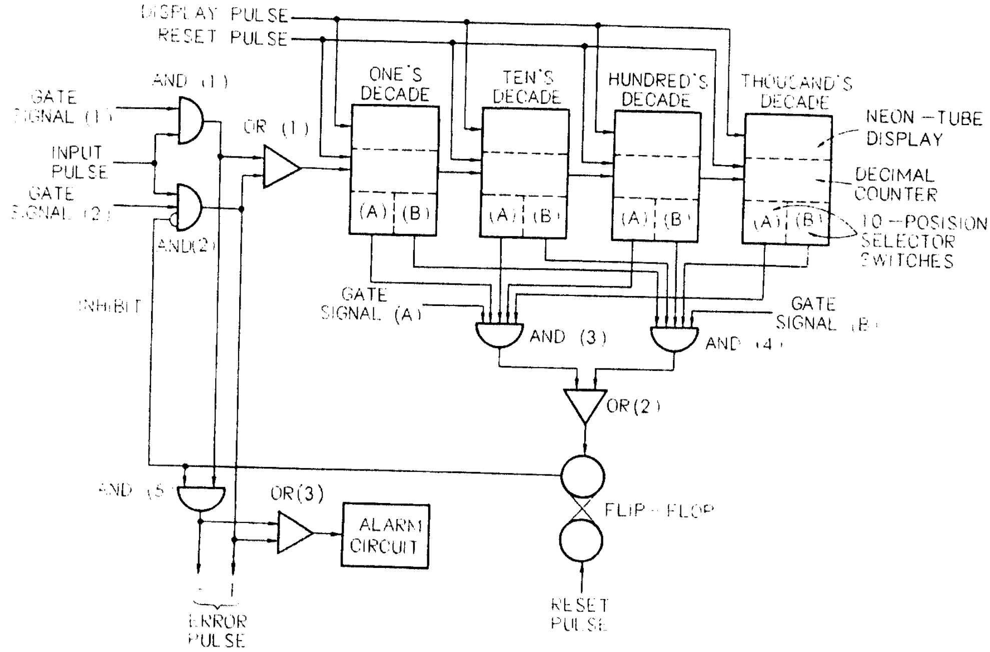

FIG. 2. Block diagram of the counter and the input gate

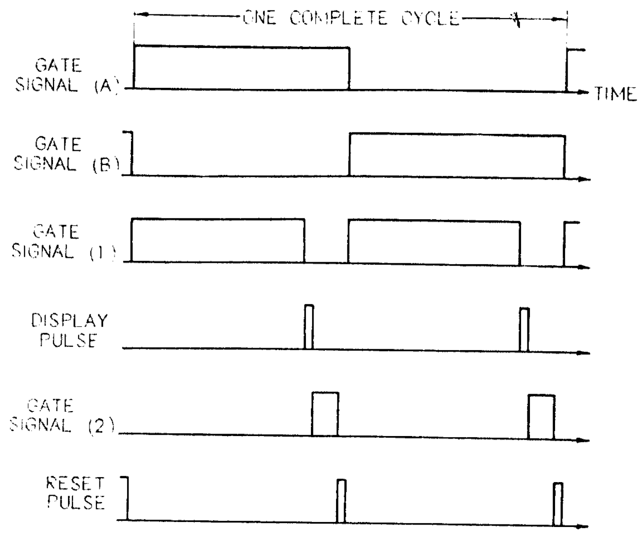

FIG. 3. Timing relationship among gate signals and controlling pulses

"AND" gate(1) and (2) together with "OR" gate(1) constitute the input gate which accepts the pulses from the input multiplexer. The counter consists of four decade units, each having ten outputs corresponding to the numbers from 0 to 9. One of those ten outputs is arbitrarily selected by a 10-position selector switch. To each decade two selector switches are attached, so that the preset numbers corresponding to the reference speeds of motor(A) and (B) are given to the counter as a pair of the decimal numbers of four figures.

The method of comparison of the measured speed with the reference must be considered in two different periods. In the first period, which is determined by gate signal(1), the input pulses pass through "AND" gate(1) and reach the counter, where they are counted giving the number proportional to the speed of the motor which is just being connected to the controller by the multiplexers.

If the motor speed is higher than the reference, the input count reaches the preset number at some instant in the first counting period. This instant is detected by takinig the coincidence of the signals from a set of the selector switches by an "AND" gate. Gate signal(A) and (B) determine which of the two preset numbers is used. The coincidence output sets the flip-flop which, in turn, opens "AND" gate(5) permitting the input pulses to go to the output multiplexer during the rest of the first counting period. These pulses serve as the actuating error that corresponds to the negative difference. In the case where the motor speed is just equal to the reference, no error pulse is generated because the counter is triggered by the trailing edge of the input pulse.

If the motor speed is lower than the reference, the input count does not reach yet the preset number even after the first counting is completed. In this instance, the second counting of the input pulses adds counts until the content of counter becomes equal to the preset number. This process is controlled by gate signal(2) and the output of the flip-flop which inhibits "AND" gate(2) when the input count reaches the preset number. The number of the pulses counted in this period is nothing but the actuating error that corresponds to the positive difference. These pulses also are transmitted to the output multiplexer. In the former case where the motor speed is higher than the reference, "AND" gate(2) has been inhibited at the beginning of second period so that any counting is not made further. The comparison processes which have been mentioned above are illustrated in **Fig.** 4.

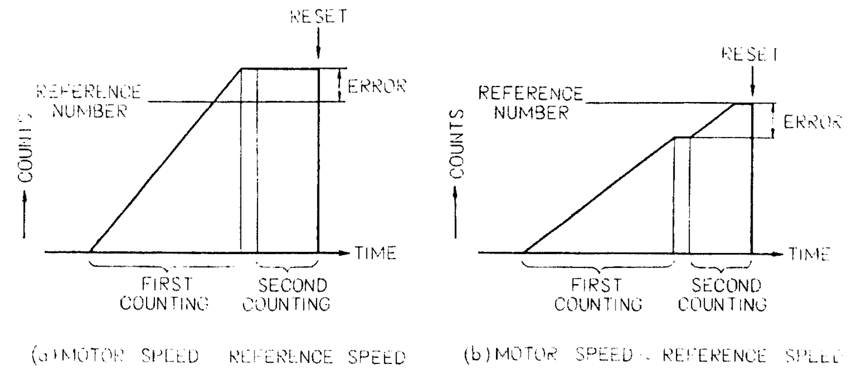

FIG. 4. Comparison process of the measured speed with the reference

The two counting periods are separated by an interval for displaying the measured value of the motor speed. This interval is represented by the display pulse in Fig. 3. It connects momentarily the counter with the neon-tube display units. The digital content of the counter at that time is transfered to the display units. Thus the display readout is renewed at every measurement. The storage function which keeps the readout during the interval between the measurements uses the fact that the neon-tubes which have a common current-limiting resistor can not fire except one tube.

In the controller, an alarm circuit is provided to inform the occurrence of unusual large deviations of the controlled variables. It examines the number of error pulses and actuates a buzzer when the number exceeds the limit which is also preset by a selector switch.

The input gate and the counter as well as the gate signal generator are constructed from transistor logic elements. Germanium alloyed-junction transistors for high speed switching are used throughout the digital part of the controller.

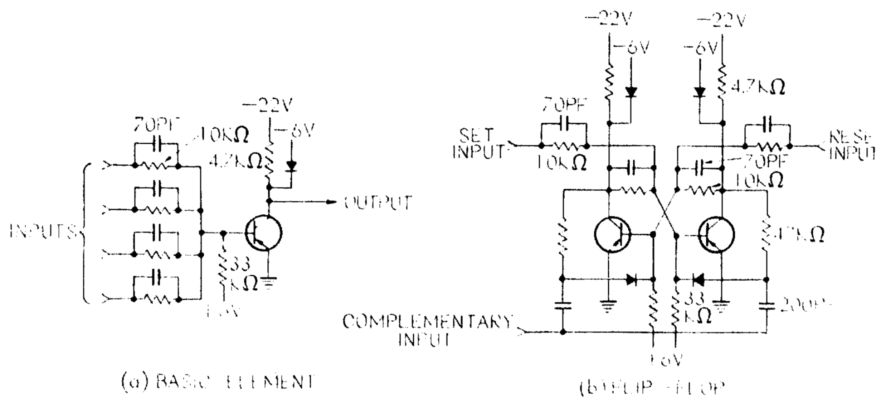

FIG. 5. Circuit diagram of basic logic element

Fig. 5(a) is the basic form of the logic element while (b) shows how a flip-flop is composed of the basic elements. Other fundamental circuits such as one-shot multivibrators are also composed of the basic elements with slight modification.

3.4 *Gate Signal Generator*

The gate signals shown in Fig. 3 are obtained from a sequence control circuit. The time reference is the crystal-controlled oscillator unit whose output is a 100 cps square voltage signal. The reference oscillator unit is followed by a frequency divider consisting of four stages, each of which divides the frequency by the scale of two. Any output from these successive stages including the output of oscillator unit may be used as the clock pulse of the sequence control circuit.

One complete cycle of the controller is 50 cycles of the clock pulse and the duration of gate signal(1) is equal to 20 cycles of it. Therefore, if the frequency of clock pulse is, for instance, 25 cps, the gating period is 0.8 sec and the number of display readout is twice the speed in rpm, while the sampling period of the measurement is 2 sec.

It should be noted here that, if the reference oscillator unit is removed and the output of the pickup of some other motor is introduced as the reference signal, a digital draw controller would result. This change of arrangements may be done easily since the oscillator unit is pluged into a socket on the front pannel of the controller. In this draw control system, the speeds of two motors are controlled so as to maintain their speed ratios to the third reference motor at the given values.

3.5 *Integrator*

A simple vacuum-tube operational amplifier is used to integrate the difference signal generated by the counter. The input terminals of the integrator are connected to the output multiplexer by two separated lines, one for the plus difference and another for the minus difference. These lines convey the error pulses having the polarities opposite to each other. The correspondence between the polarity and the sign of difference is set by the internal connection of the output multiplexer. Of course, this correspondence should be set so that a negative feed-back would result.

After the amplification and clipping, the voltage waveforms of the error pulses are applied to the input resistors of the operational amplifier as shown in **Fig. 6**. A neon-tube is inserted between the pulse source and the input resistor. It fires

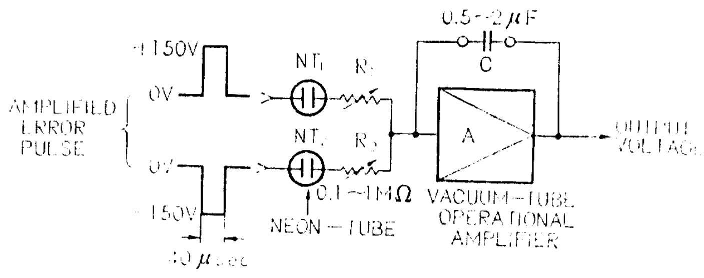

FIG. 6. Block diagram of the integrator

when the error pulse is applied but does not allow any current to flow through the input resistor during the absence of error pulse, thus preventing the drift of output voltage due to the change of DC level of the signal. If the neon-tubes were not used, the difference voltage between the zero level of the error pulse and the grid potential of first tube of the amplifier would have to be kept within ±1 mV. This necessitates the increase of complexity of the circuitry and the merit of using an analog integrator in place of a digital-to-analog converter would be lost.

The loop gain of the digital control system can readily be adjusted by the input resistors R_1 and R_2. R_1 determines the gain in the direction of the increasing speed, while R_2 determines the gain in the decreasing direction. Such an arrangement is necessary because the controlled system which follows the integrator exhibits an unsymmetrical step response in both directions.

3.6 *Power Amplifier and Motor*

A 7.5 KW DC shunt motor is used as the controlled machine for the test of this system. A thyratron speed regulator which is manufactured as a standard device for DC motor control is adopted as the power amplifier. It takes the armature voltage of the controlled motor as a measure of the speed and keeps this voltage equal to the reference given by the integrator. The speed regulation is done through the modulation of firing angle of the thyratrons. The speed range of the regulator covers from 0 to 2000 rpm.

It should be recognized that the power amplifier of the digital controller is not restricted to the thyratron regulator. Any device which regulates the speed according to an externally given voltage may be equally fit to this controller.

4. The One-Count Error Problem

It is well known that in the measurement of speed by pulse counting method, there is an inaccuracy so-called one-count error. This error is in part due to the quantization and in part due to the time incoherency between the gate signal and the pulses from the pickup. Statistically, the one-count error is equivalent to a white noise whose mean-square value is $q^2/6$, where q is the increment of speed corresponding to one count, or the magnitude of quantum.

The magnitude of one-count error is independent of the number of the pulses which are counted in the gating period. Therefore, it is necessary to increase the number of counts to achieve a highly accurate speed control. The use of a long gating period is a conventional method to get large count. This method, however, is objectionable in control systems because an additional time delay is introduced in the control loop. An elaborate pickup which produces a large number of pulses in one revolution might be a solution to this problem, but it is not so preferable because of its cost and the need of maintenance.

To get a large count in a short gating period, an electronic frequency multiplier is provided as an optional equipment of the controller. It is inserted between the pickup and the input terminals of the controller as shown by the dotted lines in

Fig. 1. The principle of the frequency multiplication is based on the fact that the frequency of a signal is doubled by a full-wave rectification. In order to rectify the signal successively, the input signal is converted into triangular waveforms as shown in **Fig. 7**. This conversion is achieved by transforming the input into a square wave-form and then integrating it. To restore the amplitude of signal, each rectifier is followed by an amplifier having the gain of 2.

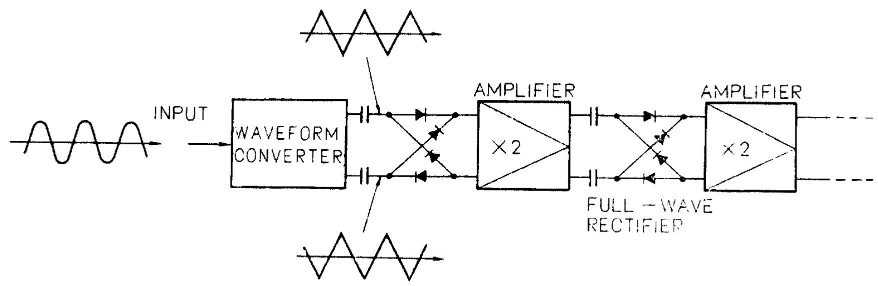

FIG. 7. Principles of frequency multiplication

Fig. 8 shows the circuit of a part of the multiplier. The transistors Q_2 and Q_4 constitute a Miller integrator. This integrator is preceded by a Schmitt circuit which supplies the square-wave voltage signal. The transistor Q_1 maintains the DC operating voltage of the integrator. Q_3 and Q_5 form an amplifier of the gain of -1. Thus, two triangular waveforms which are same in frequency and amplitude but different in phase by 180° appear at the points p and p'. These signals are rectitied iteratively through the succeeding stages.

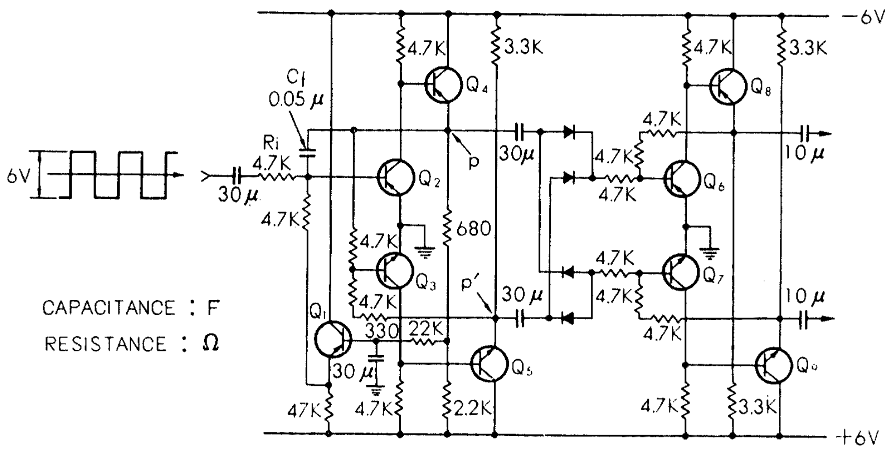

FIG. 8. Circuit diagram of a part of the frequency multiplier

The multiplication factor of 8 is easily obtained by this circuit, as shown in **Photo. 2**. The frequency multiplier would be specifically useful for controlling many motors with a digital controller by time multiplexing method.

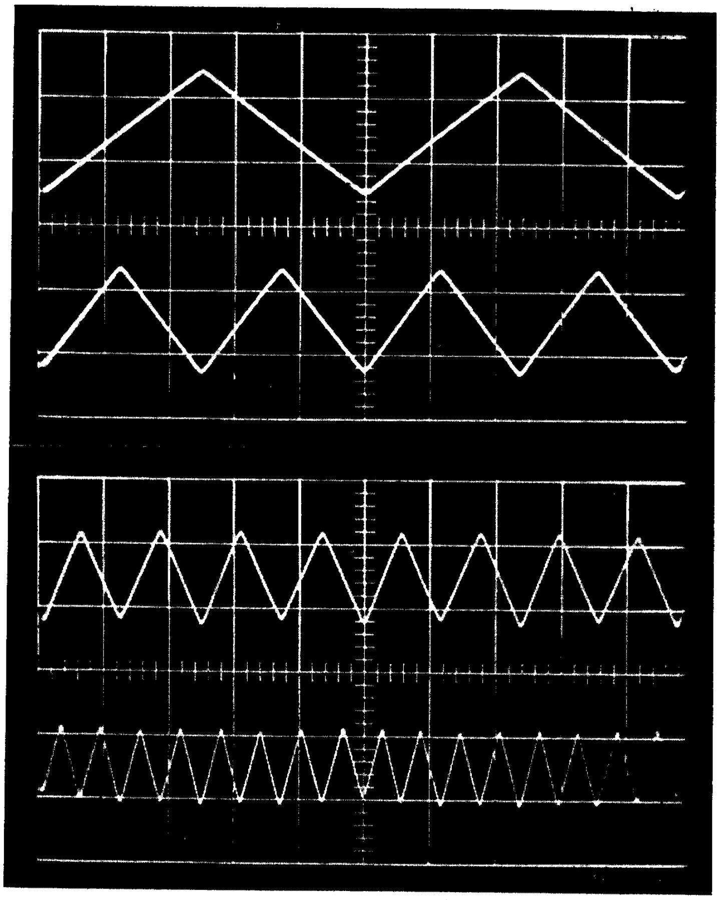

PHOTO. 2. Output waveforms from successive stages of the frequency multiplier
Horizontal: 200 μsec/div. Vertical: 2 V/div.

5. TEST RESULTS

The tests of the control system were made in the laboratory. Although the digital controller has the capability of controlling two motors, the test was made individually on each channel using one controlled motor. One of the two channels was idle during another was under the test. A DC generator was used as the load of the controlled motor.

The step response for a large change of the speed setting is shown in **Fig. 9**. The sampling period is 1 sec, as apparent from the record. A saturation is observed in the direction of the increasing speed. This comes from the fact that the maximum number of error pulses which are generated by the second counting is limited by the rather short period of gate signal(2).

The tests of fine speed control were made under several different conditions. A record of the tests is shown in **Fig. 10**. The load of the controlled motor was about 1 KW. The frequency multiplier was used, setting the multiplication factor to 8. The sampling period of the control system was 1 sec. Therefore, the gating period for the measurement of speed was 0.4 sec and the number of display readout was 8 times of the number of rpm. A slight change of the speed setting was made in the test. To give a disturbance to the control system, the load was increased to

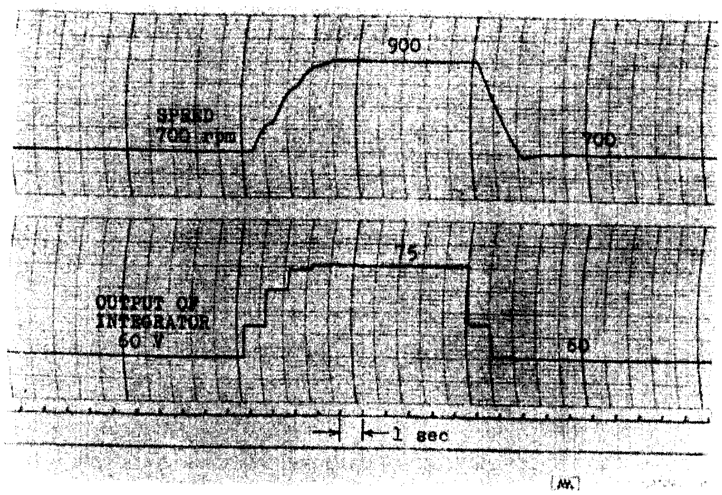

FIG. 9. A step response of the control system

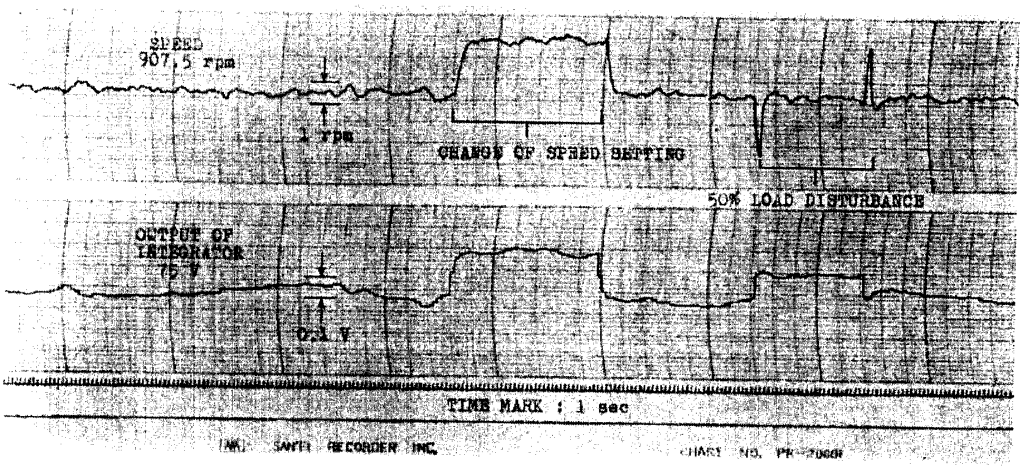

FIG. 10. A record of fine speed control test

1.5 KW for a short period. From the record, it is observed that the speed is maintained within $\pm(1/2)$ rpm of the reference value except the short transient periods, while the output of the integrator is continually compensating the off-set of the speed.

Fig. 11 is a record showing the stability of the digital control system. The output of the integrator exhibits a relatively large change for 30 minutes after the starting up the control system, which otherwise would cause a large drift of the speed.

6. CONCLUSION

A highly accurate speed controller using pulse counting method has been described. It consists of rather simple circuits and has no elaborate parts in it. A new frequency multiplier, which is useful for speed control by digital method, was also reported. In this paper the controlled variable of digital controller is confined to the rotational speed of electric motors, it may be equally well applicable to any other control of the quantities which can be converted into the frequencies.

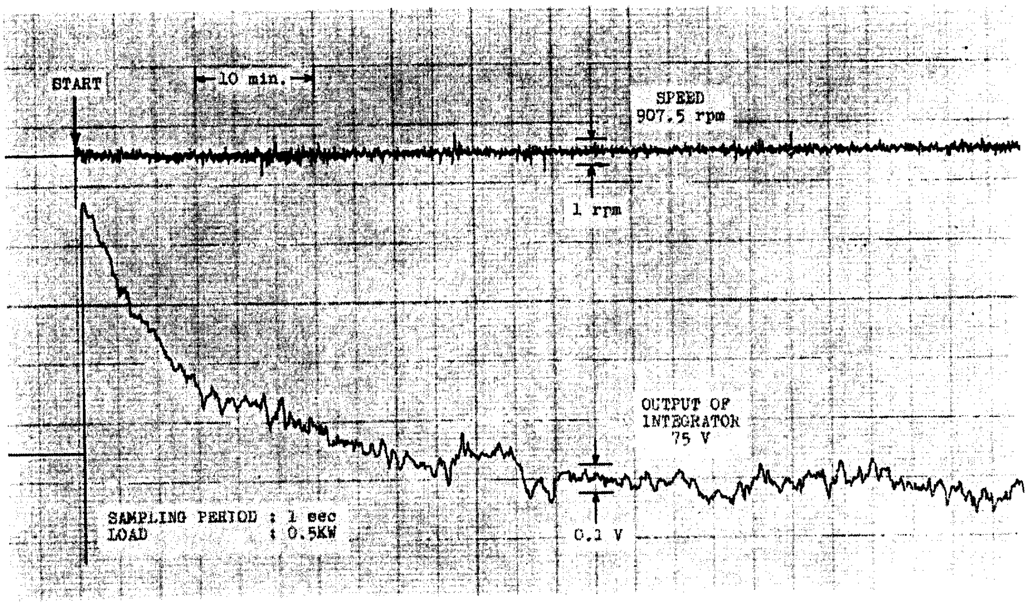

FIG. 11. A record of 1 hour after the starting up the control system

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