A POWER ANGLE AND ROTOR SPEED MEASUREMENT DEVICE FOR SYNCHRONOUS MACHINES STABILITY STUDIES

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ABSTRACT

A device for measurement of power angle and rotor speed of a synchronous generator has been designed and realized. The device is supplying a signal proportional to the phase angle between the terminal voltage and generated e.m.f. phases of the synchronous machine. A second signal proportional to the rotor speed is also generated. These output signals can be used for both measurement and control purposes. The device under consideration can also be used in conjunction with digital systems through an analog to digital converter (A/D) to perform on-line computation and control.

The design and realization of the device depend on high speed digital and linear integrated circuits. The time delays introduced by the device components are negligible compared to the machine time constant , therefore the device is most suitable for applications in both transient and dynamic conditions in synchronous machines .

The device is capable of monitoring the variations in the power angle and the rotor speed for both measuring and control purposes. Further, this device can be used as a part of a digital control system to provide stabilizing signals to digital automatic voltage regulator of synchronous machines .

The test and calibration results obtained show the capability of the device to monitor the power angle and rotor speed in both steady state and transient conditions .

INTRODUCTION

In power system stability studies it is accepted that the internal e.m.f. of a synchronous machine is in phase coincidence with the quadrature axes of the rotor [1,2]. The power angle is defined as the phase angle between the terminal voltage and induced e.m.f. of the machine. The value of the power angle and the way by which it changes in both steady state and transient conditions are most important merits of stable operation of synchronous machines.

Actual measurements of power angle and speed error are necessary for both control and measurement purposes. The stroboscopic method of power angle measurement is quite successful at steady state conditions. This method is simple, accurate, and inexpensive. On the other hand it is not suitable for voltage regulators and speed governing systems.

Tachogenerator is usually used as a sensor to a produce voltage signal

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proportional to rotor speed , Since their mechanical assembly requires certain arrangement ,optical transducers are preferred for rotor position detection [3] .

The object of this research is to design and realize a device for measurement of the power angle and the rotor speed of a synchronous generator. In this device the rotor position is sensed by using an infrared optical transducer which is not affected by ambient light . It transmits an infrared beam to the rotor axis and then the reflected pulses are used to determine the rotor position . The power angle measuring device detects the phase difference between the reflected pulses (which represent the rotor position) and the signal which represents the infinite bus voltage . The phase difference is then converted to a dc voltage level proportional to the magnitude of the power angle . Also, this paper presents a rotor speed measuring device which counts the reflected pulses from the rotor axis and converts this count to dc voltage level proportional to the rotor speed .

The designed and realized device is so simple that it is constructed using only three low cost 14 pin dual in package (d.i.p.) integrated circuits . The tests and calibration results show that the device is accurate and simple and it can be used for both measuring and control purposes . In the following paragraphs the detailed procedures will be given to construct the measuring device .

OPTICAL TRANSDUCERS

Mechanical Assembly

The optical transducer is used to convert the revolutions of the machine into train of pulses whose rising edges are coincides with the quadrature axis of the field winding, added with it some error . The repetition rate of this pulses represents the rotor speed .

A schematic diagram of this optical transducer is shown in Fig. 1. It is composed of an infrared transmitter ,infrared receiver and shaping circuit. These components are assembled together on a 2.5X6 cm printed circuit board and inserted into a cylindrical probe with 2.5 cm diameter and 7 cm long. The probe was fixed to the machine by a holder at a right angle to the rotor axis. A five centimeter length of the rotor axis in front of the optical transducer probe is painted with white color (reflecting surface), and a thin black strip (absorbing surface) with one centimeter wide is fixed on the white surface of the rotor axis .

When the machine runs, the white and black areas are exposed alternatively to the transmitted infrared beam . The number of black strips on the rotor are equal to the number of pole pairs of the synchronous machine under consideration . In this work the number of pole pairs is one ,so only one black strip will be fixed on the rotor .

When the black strip is under the probe, it interrupts the reflected infrared beam ,and the electronic circuit in the probe generates a pulse ,the leading edge of which is synchronized with the leading edge of the

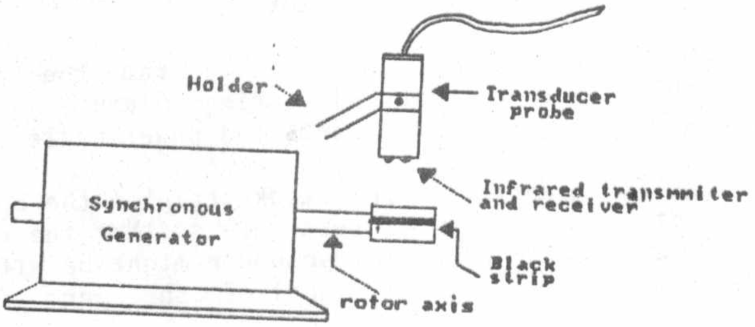


FIG. 1 Optical transducer probe and rotor axis arrangement .

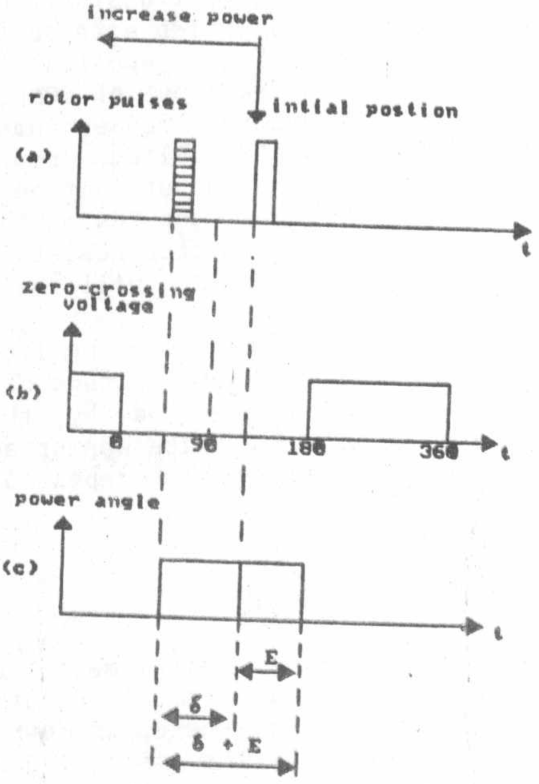


Fig. 2 Pulse waveform for generating the power angle.

black strip. The duration of this pulse,depends on the width of the black strip as well as the speed of the rotor .

Fig. 2 a,b shows the waveform generated from the optical transducer together with that of the zero detecting circuit . The phase shift between these two waveforms represents the power angle .

During the initial mounting of the black strip on the reflecting white area of the rotor axis , we must take care so that the rising edge of the pulse generated from the optical transducer might be within the 90 degree to 180 degree past of the output signal of the zero detecting circuit (see Fig. 2b).

Circuit Diagram of the Optical Transducer

The circuit diagram of the optical transducer is shown in Fig. 3 . Infrared diode D_1 is used to generate a beam of continuous wave of the infrared band towards the shaft of the rotor . If reflecting surface (white area) is in front of the probe (during the rotation) ,the reflected wave will illuminate the photo transistor TR_1 .This transistor is sensitive to the infrared wave band and will conduct to pass small amount of current . This is amplified by transistor TR_2 . The amplified current is passed through resistor R_3 which acts as emitter load for TR_2 [4,5] . The voltage generated across R_3 is applied to inverted input of the comparator $COMP_1$ .The non-inverted input of $COMP_1$ is biased to some positive voltage ,which can be adjusted by potentiometer VR_1 .In normal operation VR_1 is adjusted such that the voltage drop across R_3 is larger than that across VR_1 . Therefore ,the output voltage of the comparator in this case is near zero voltage . Transistor TR_3 in this case is turned off and a zero voltage appear across emitter resistor R_6. The L.E.D., which is connected to the collector of TR_3 will be in off state .

When the probe is in front of the black strip, no light will be reflected on photo-transistor TR_1. And therefore the voltage drop across R_3 is zero voltage ,and hence a pulse will be generated by the comparator $COMP_1$ .Transistor TR_3 will be turned on and a pulse appear across R_6 In this case the L.E.D. will be lighted. This sequence is repeated during the rotation of the rotor .

POWER ANGLE MEASURING DEVICE

The block diagram for the power angle measurement device is shown in Fig.4 . This device is fed by two signals,the first is obtained from phase voltage of the infinite bus. It is stepped down and converted to square wave of the same frequency by the zero crossing detector. The second signal is generated from the rotor optical transducer .The pulse width obtained is 2.5 ms when a black strip of one centimeter wide is used and at rotor speed of 3000 r.p.m. .

The output signal from zero crossing detector block and the output of optical transducer are fed to the phase detector circuit which works as a bistable multivibrator . The output of this stage is a train of pulses whose frequency is the supply frequency and with a pulse width equals to the phase difference between the infinite bus voltage and the pulsed

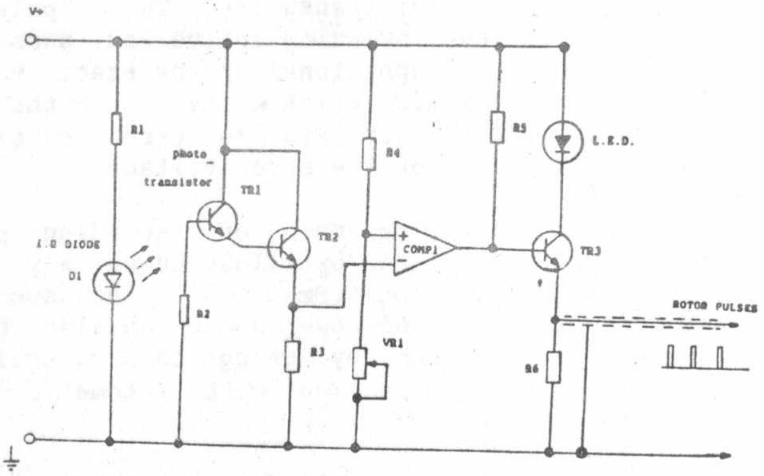


FIG. 3 Circuit diagram of the optical transducer .

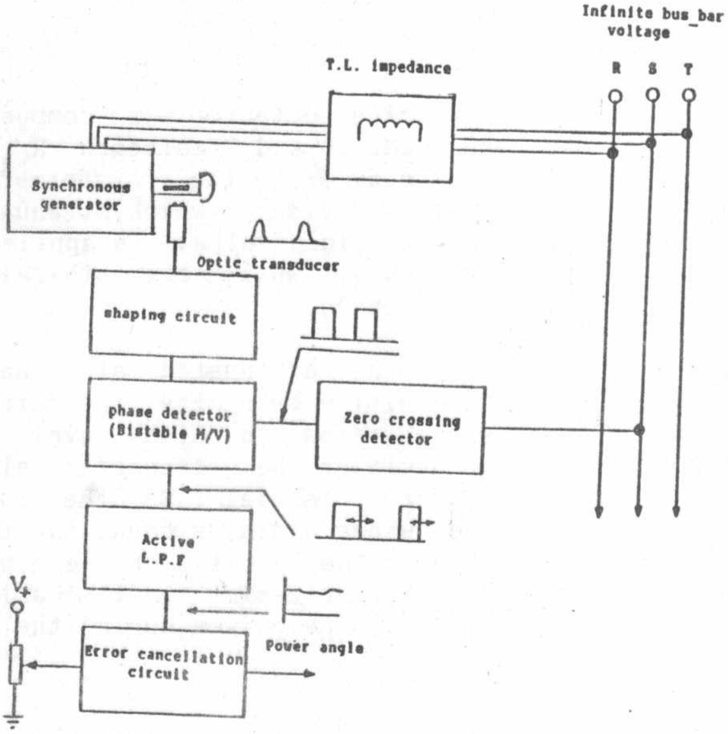


Fig. 4 Block diagram for forming the power angle.

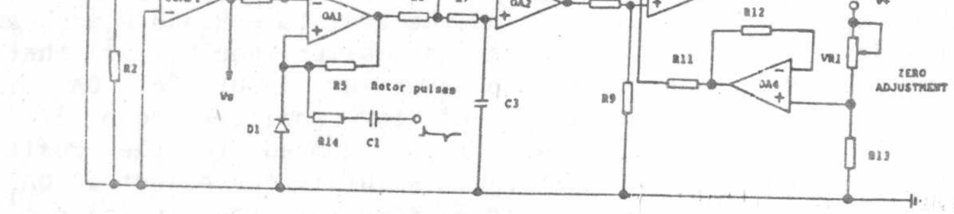


FIG. 5 Circuit diagram of the power angle device .

waveform generated from the rotor optical transducer. These pulses are then converted into a dc voltage level by using active low pass filter (L.P.F) .The resulting dc voltage is proportional to the exact value of the power angle,with some error signal (E),which arising from the random attachment of the black strip on the rotor axis. An error cancellation circuit is used to eliminate the value of the error voltage .

The obtained dc voltage can be used for measuring or recording purposes by connecting this signal for example to an oscilloscope or x-y plotter to monitor the steady state and dynamic performance of the synchronous machines. The dc voltage representing the power angle can also be used for control purposes .This can be done by using this signal as a stabilizing signal to be used in conjunction with automatic voltage regulators or speed governing systems [2] .

The complete circuit diagram of the power angle device is shown in Fig.5 .The circuit diagram of each block in the figure will be explained in the following sections .

Zero Crossing Detector Circuit

The circuit diagram of the zero crossing detector is composed of,a step-down transformer T_1,a comparator $COMP_1$ and resistors R_1 and R_2 .Infinite bus voltage is stepped-down to $6V_{rms}$ by the transformer T_1.The resistors R_1 and R_2 are used as a potential divider , which attenuates the stepped sine wave voltage to about 1 V_{rms} .This voltage is applied to the non-inverting input of the comparator $COMP_1$,while the other input of the comparator (inverting-input) is grounded .

During the positive half cycle of the attenuated sine wave the non-inverting input of $COMP_1$ is more positive than the inverting input ,so the output of the comparator is saturated to high level positive direction . During the negative half cycle of the attenuated sine wave the output of the comparator will be zero potential . So the output of the comparator is a square wave pulses whose width is equal to the half wave length (10 ms for 50 Hz operations). The function of the comparator in this circuit is to detect the instant of crossing the time axis by the attenuated sine wave and converts it to square pulses during the positive half cycles .

Phase Detector Circuit

The circuit diagram of the phase detector (bistable multivibrator) is composed of an operational amplifier OA_1 ,resistors R_3 , R_4 , R_5 ,R_{14}, condenser C_1 and diode D_1.The rotor pulses from optical transducer are differentiated by the series circuit R_{14} and C_1 . The differentiated positive pulses are applied to the non-inverting input of the OA_1 ,while the negative differentiated pulses are limited by the voltage drop of the diode D_1. During the negative half cycle of the infinite bus voltage the output of the comparator $COMP_1$ is low ,and the resistors R_3 and R_4 work as a potential divider . The resistor R_3 is chosen smaller than R_4, so that a small positive voltage is applied to the inverting input of OA_1 .This voltage is less than the amplitude of the positive edge of the differentiated pulse ,so the output of OA_1 is jumped to the positive saturation level .The feedback resistor R_5 maintain the output of OA_1 in saturation condition . When the trailings edge of the infinite bus voltage signal is applied to the non-inverting input of $COMP_1$, its output will jump to positive saturation . This voltage is applied to the non-inverting input of OA_1, so its output falls to the zero potential. Hence a positive pulse is obtained from the output of the OA_1 , whose leading edge coincides with the positive edge of the rotor pulse ,and it,s trailing edge coincides with the positive edge of the infinite bus voltage (see fig.2) . The pulse width obtained from OA_1 represents the phase difference between rotor pulse and infinite bus voltage ,which it is the power angle.

The output pulse from the phase detecting circuit is fed to an active low pass filter,which consists of OA_2, R_6, R_7, C_2 and C_3 .The output signal is a dc voltage level which is proportional to the input pulse width .

Error Cancellation Circuit

Its well known that the power angle of a synchronous generator is equal to zero at no load condition . Due to the random fixation of the black strip on the rotor axis , there would be some error voltage (see fig. 2c). This error voltage is canceled by the error cancellation circuit .

The circuit diagram of the error cancellation circuit is consists of OA_3, OA_4 ,resistors R_8, R_9, R_{10}, R_{11}, R_{12}, R_{13} and variable potentiometer VR_1 .The dc voltages representing the power angle with some error voltage are applied to the non - inverting input of the OA_3 which works as a difference amplifier with a gain equal to 10. The other input of OA_3 is a dc voltage representing an error voltage (E) which is subtracted from the composite signal representing power angle and the error(E). The result of the subtraction is a voltage the magnitude of which represents the power angle only .

The dc voltage representing the error is obtained from the potential divider consists of VR_1 and R_{13} . This error voltage can be adjusted by VR_1 to match the error voltage (E), this error signal is applied to the non-inverting input of OA_3 through the a buffer stage OA_4 .

EXPERIMENTAL SET-UP AND TEST RESULTS

The experimental set-up for testing the power angle and rotor speed device is schematically shown in Fig. 6 .The device was operated and tested in the laboratory of Military Technical College, Cairo ,Egypt with a three phase cylindrical rotor synchronous machines . This alternator is connected in parallel with the infinite bus via a short transmission line .The following disturbance are considered :
[1] Step increase in mechanical torque by suddenly changing the motor field resistance .
[2] Changing the tie-line impedance.

Fig. 7 shows the waveforms of the pulses obtained from the rotor optical transducer with the output of the zero detecting circuit at both no load operation (Fig. 7a)and with 75 % full load (Fig. 7b), .Fig. 8 shows the output of the phase detector circuit , which represents the power angle and the equivalent dc output voltage obtained from the low pass filter with 40% loading (Fig. 8a) and with 75 %loading (Fig. 8b) .We note from the figure that when the machine is loaded ,the pulse width and the dc

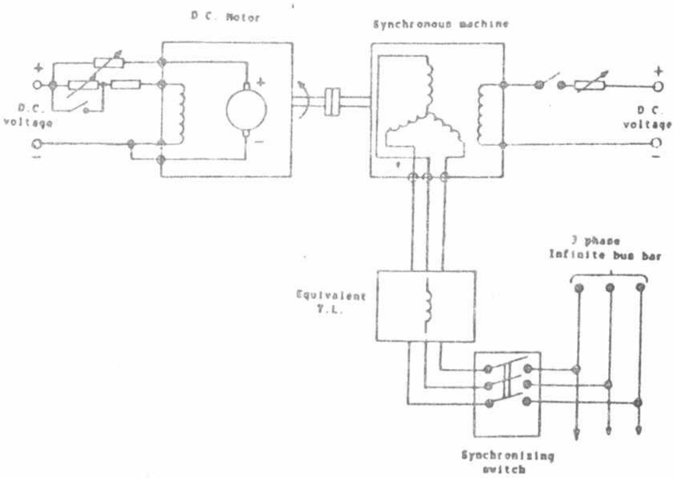
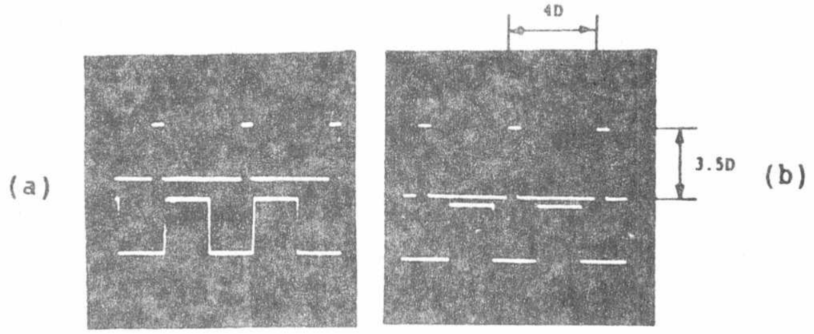
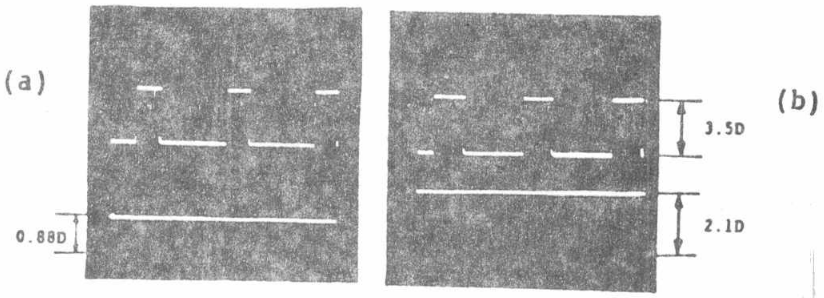


FIG. 6 The experimental set-up for testing the power angle and rotor speed measuring device .



Vert. :2 V/D Horiz. :5 ms/D

FIG. 7 Rotor pulses with the output of the zero detecting circuit for (a) zero power loading. (b) 75% loading .



Vert. :2 V/D Horiz. :5 ms/D

FIG. 8 Power angle pulses with the output from the transducer for (a) 40% loading .(b) 75% loading .

voltage level increase proportionally . The power angle and the transducer output curve is illustrated in Fig. 9. It can be noticed that the linearity is evident from this figure. Fig. 10 shows the dynamic behavior of the power angle device when a suddenly step change in mechanical torque is occurred. This is done by sudden addition of a series resistance in the field circuit of the dc motor (see Fig. 6).The obtained results shows the oscillatory nature of the response . Fig. 11 shows the behavior of the power angle when a change in tie-line impedance occurred .

The results obtained previously illustrate the steady state and dynamic performance of the power angle device . Therefore the device is capable of on-line detection of the power angle variations at any operating conditions of the synchronous machines .

ROTOR SPEED MEASURING DEVICE

As it have been mentioned previously the, the output pulses from the optical transducer probe is used for both power angle and the rotor speed. The rotor speed measuring device is based on counting of the optical transducer pulses. The device used for this purpose is based on a single 8 pin d.i.p integrated circuit type LM 2907 ,together with some external passive components . This device provides a dc output voltage level proportional to the input frequency, and gives a zero output voltage at zero input frequency .The circuit diagram for the rotor speed is shown in Fig. 12 . The integrated circuit used in this device contains in a single ship an input amplifier with built-in hysteresis , a charge pump frequency to voltage converter, and an operational amplifier with an output transistor [6].

Basic Design Steps

The input amplifier has a built in hysteresis at positive and negative 15 mV. This provides clean switching when noise is present on the input signal .Also it allows total rejection of noise below this amplitude when there is no input signal . The amplitude of the input pulses of the optical transducer are attenuated by a resistor divider consisting of R_3 and R_4. The dc output voltage is obtained from pin 4 (emitter follower of the output transistor).The dc output voltage obtained (V_{odc})is given by:

$$V_{odc} = K \cdot V_s \cdot F_{in} \cdot C_1 \cdot R_1 \qquad [1]$$

Where K is the gain constant (normally equal to 1) , V_s is the power supply voltage ,and F_{in} is the input frequency . The emitter output (pin 4) is connected to the inverting input of the operational amplifier(pin 7), so that the voltage of pin 4 will follow the voltage of pin 3 ,therefor the output impedance will be decrease and the voltage obtained will be proportional to the input frequency .The linearity of this voltage is typically better than 0.3 % of full scale .

It can be noticed from Eq.(1) that V_s , C_1 R_1 and K are all constants and therefore the output voltage (V_{odc}) is proportional to the input frequency only . There are some limitations in the selection of the

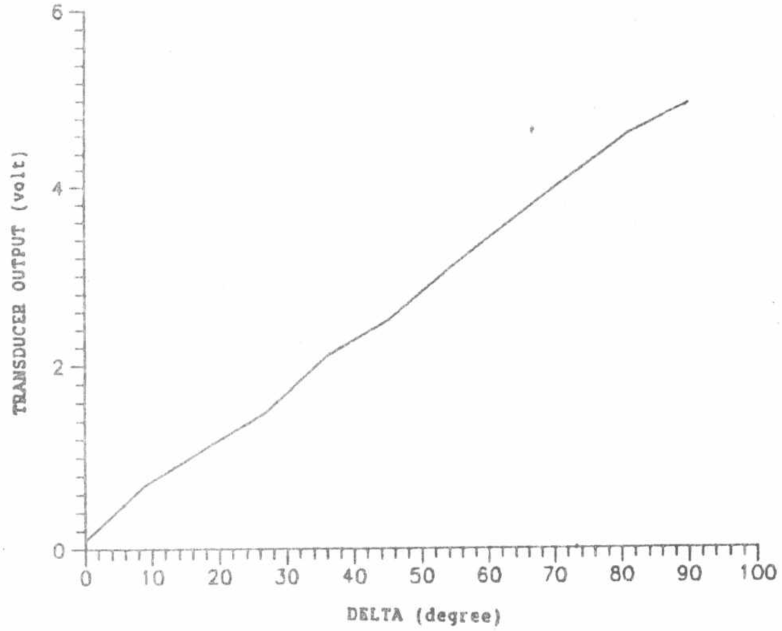
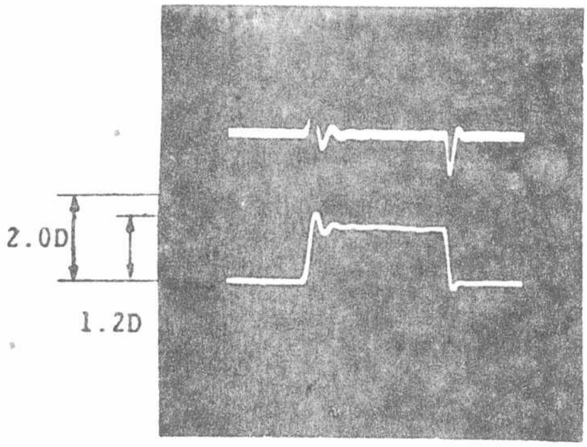
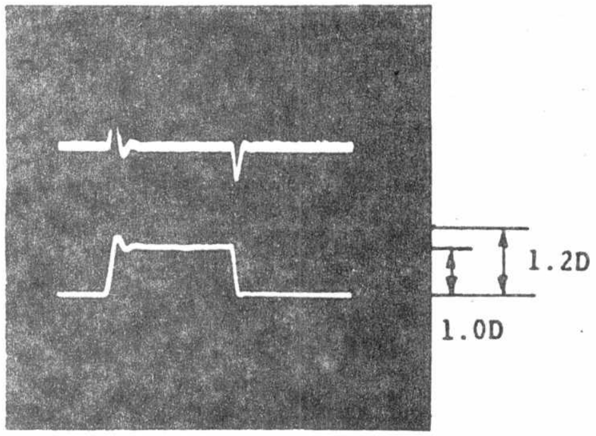


FIG. 9 Power angle - transducer output curve .





Transient. : 0.5VDC/ Time :1 s/D
Steady state :0.5VDC/D Time 1s/D

FIG. 10 Power angle variations following a step increase and decrease in the input torque .

Fig. 11 Power angle variations following a change in tie-line impedance .

values of R_1 , C_1 and C_2 for optimum performance [6] .The value of R_1 should be obtained from the inequality :

$$R_1 > V_{max} / I_{norm} \qquad [2]$$

Where V_{max} is the full scale output voltage required at pin 3 and I_{norm} is the normal current drained from pin 3 , it is determined from the data sheet (150 μA) . The value of C_1 is selected according to :

$$C_1 = V_{max} / (F_{max} . R_1 . V_s) \qquad [3]$$

Where F_{max} is the maximum input frequency . The value of C_2 is selected according to the following equation :

$$C_2 = (V_s / 2) . (C_1 / V_r) . (1 - V_{max} / 2) \qquad [4]$$

Where V_r is the maximum permissible ripple . In the realized device for measuring the rotor speed the value of R_1 is chosen to be variable to adjust V_{odc} to the desired value at the nominal input frequency .

Fig. 13 shows the relation between the input frequency and the obtained dc output voltage from the rotor transducer. The linearity is evident from this figure.

CONCLUSIONS

The power angle and rotor speed measuring device described in this paper has been designed and realized using minimum number of components to achieve economy in both space and cost. Also,it,s simple in construction, reliable in operation, and has high accuracy. The realization of the power angle and rotor speed measuring device is based on only three 14 pin(d.i.p.) integrated circuit operating from single polarity power supply. The operation of the circuit in conjunction with analog to digital converter makes it possible to use it for both measurement and control purposes in analog and digital systems. The output signals of this device can be used as stabilizing signals in automatic voltage regulators to perform sophisticated control strategies .The test results obtained show that the power angle and rotor speed measurement device is suitable for reflecting the behavior of the synchronous machines performance in both steady state and transient conditions .

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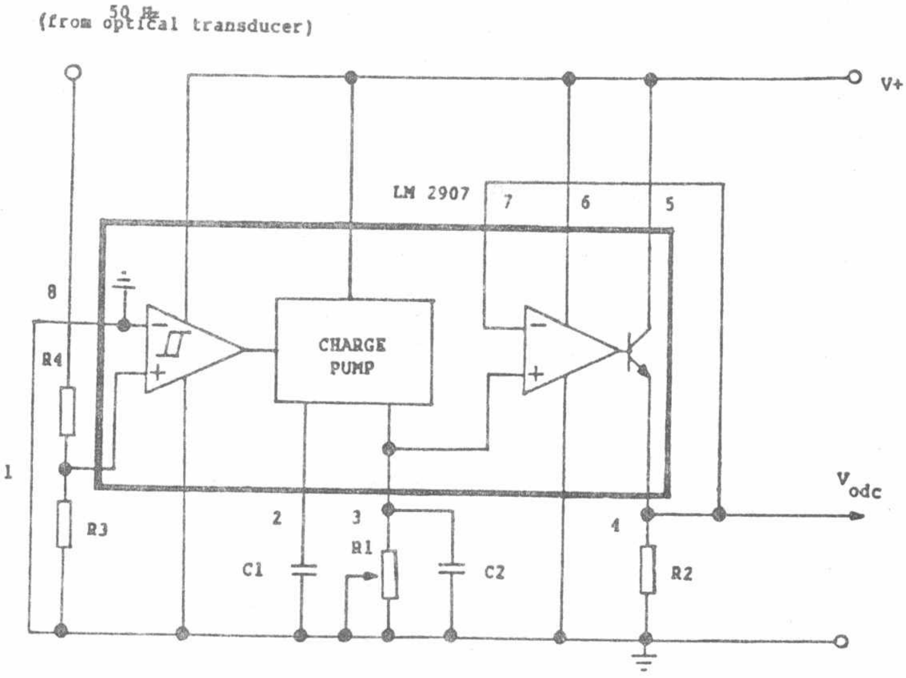

FIG. 12 Circuit diagram for the rotor speed measuring device .

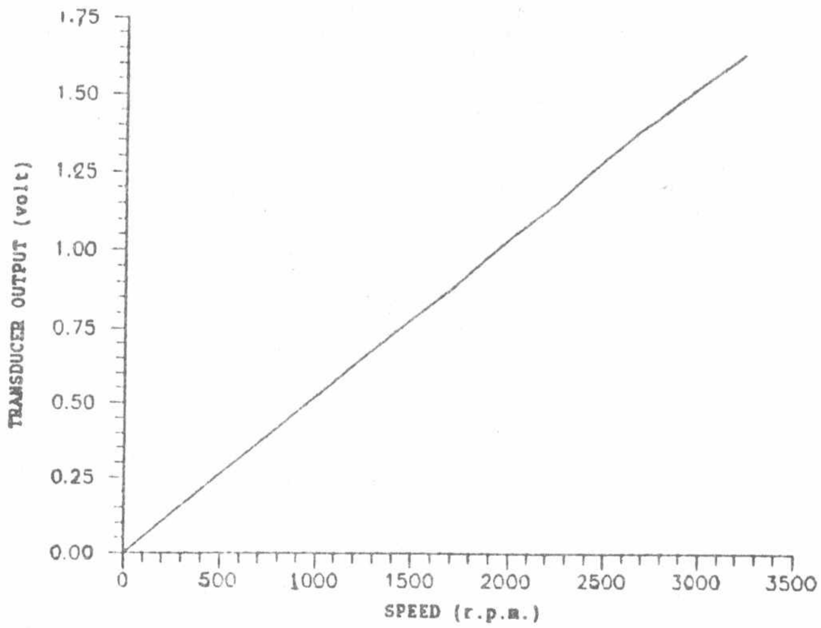

FIG. 13 Input frequency - transducer output curve .