A Performance Measurement Device for Synchronous Machines Stability

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Abstract

A device for measurement of power angle, rotor speed and terminal voltage 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 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.

Key Words:

Performance of synchronous machines; Power electronics; Phasor measurement unit

1. 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 phasor measurement unit (PMU) is defined as the phase angle between the terminal voltage and induced e. m. f. of the machine. The value of the power angle, which changes in both steady state and transient conditions, are most important merits of stable operation of synchronous machines [3, 4].

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 system. Tachogenerator is usually used as a sensor to produce voltage signal proportional to rotor speed, since their mechanical assembly requires certain arrangement; optical transducers are preferred for rotor position detection [5].

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, senses the rotor position. It transmits an infrared beam to the rotor axis and then 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 research 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 tests and calibration results show that the device is accurate and simple and it can be used for both measuring and control purposes [6,7].

2. Optical transducers

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 these pulses represents the rotor speed. It is composed of an infrared transmitter, infrared receiver and shaping circuit. These components are assembled together on a 2.5 × 6 cm printed circuit board and inserted into a cylindrical probe with 2.5 cm diameter and 7 cm long. A holder at a right angle to the rotor axis fixed the probe to the machine. 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 numbers 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 black strip. The duration of this pulse depends on the width of the black strip as well as the speed of the rotor.

The circuit diagram of the optical transducer is shown in figure (1). Infrared diode D1 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 phototransistor TR1. This transistor is sensitive to the infrared wave band and will conduct to pass small amount of current. This is amplified by transistor TR2. The amplified current is passed through resistor R2 that acts as emitter load for TR2. The voltage generated across R2 is applied to inverted input of the comparator COMP1. The non-inverted input of COMP1 is biased to some positive voltage, which can be adjusted by potentiometer VR1. In normal operation VR1 is adjusted such that the voltage drop across R2 is larger than that across VR1. Therefore, the output voltage of the comparator in this case is near zero voltage. Transistor TR3 in this case is turned off and a zero voltage appear across emitter resistor R5. The L.E.D., which is connected to the collector of TR3, will be in off state. When the probe is in front of the black strip, no light will be reflected on phototransistor TR1. And therefore the voltage drop across R2 is zero voltage and hence the comparator COMP1 will generate a pulse. Transistor TR3 will be turned on and a pulse appear across R5 in this case the L.E.D. will be lighted. This sequence is repeated during the rotation of the rotor.

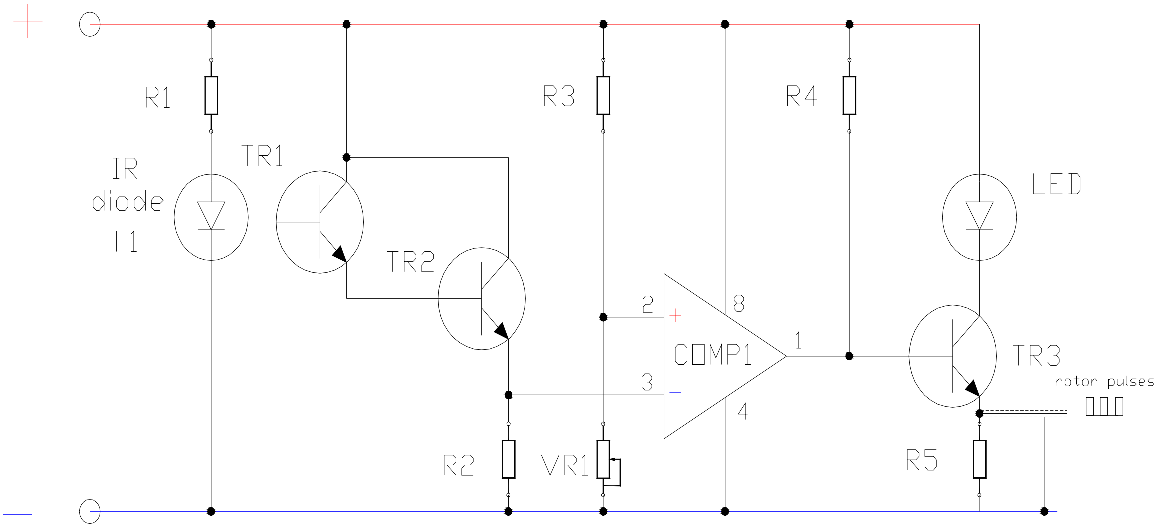

Figure 1: Circuit diagram of the optical transducer

3. Power angle measuring device

The block diagram for the power angle (δ) measurement is shown in figure (2). 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 circuit 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 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 (δ), 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. Using this signal as a stabilizing signal to be used in conjunction with automatic voltage regulators or speed governing systems can do this. The complete circuit diagram of the power angle device is shown in figure (3) the circuit diagram of each block in the figure will be explained in the following sections.

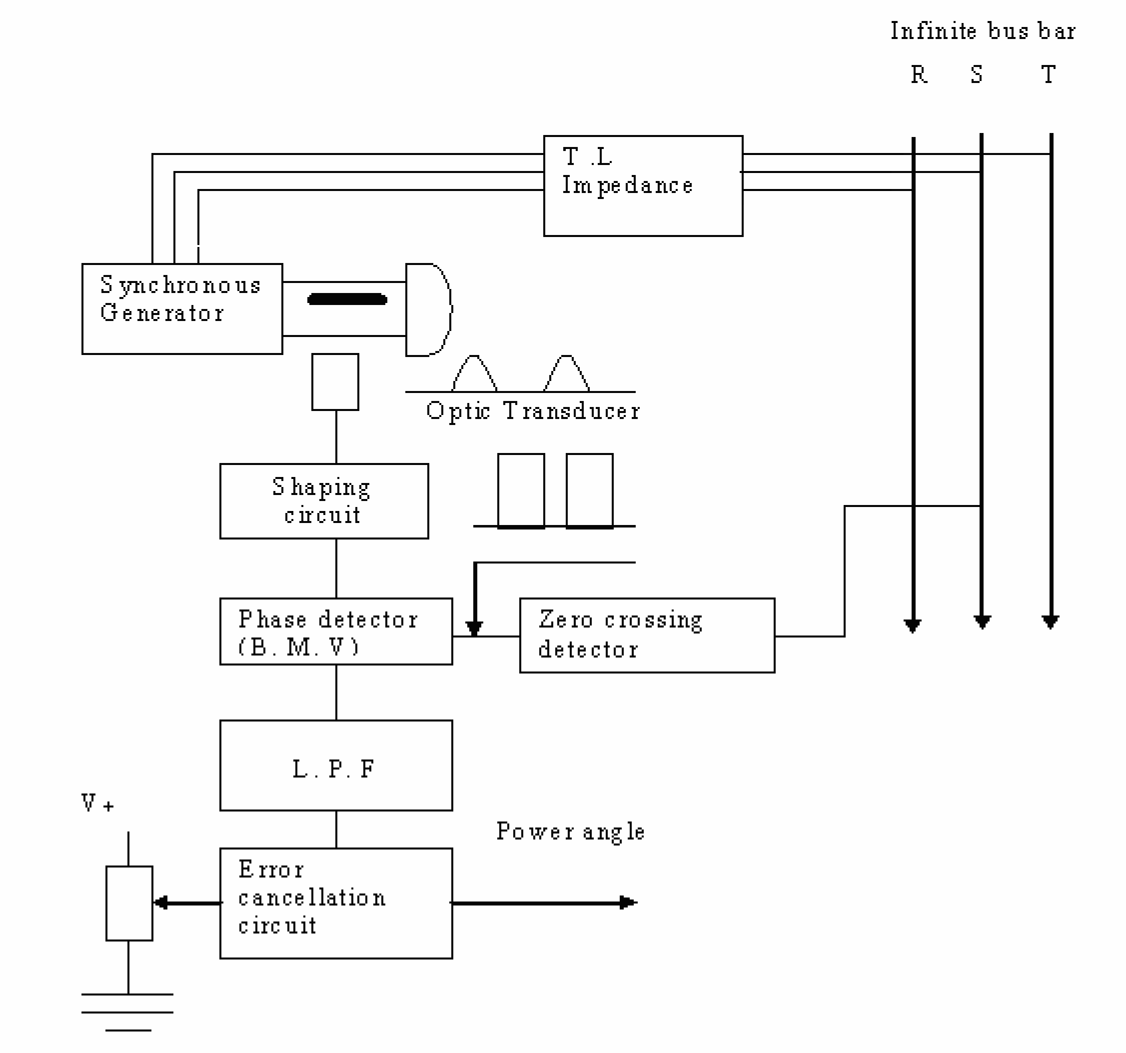

Figure 2: Block diagram for forming the power angle

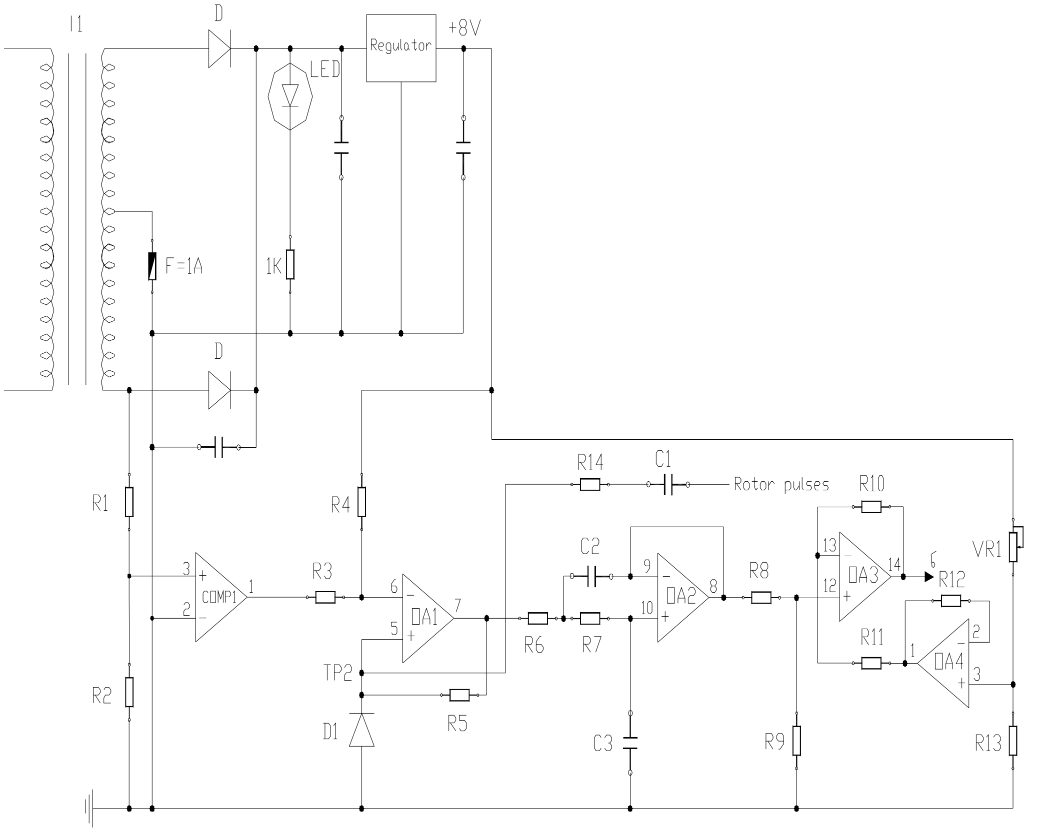

Figure 3: Circuit diagram of the power angle device

3.1 Zero crossing detector circuit

The circuit diagram of the zero crossing detector is composed of, a step-down transformer T1, comparator COMP1, resistors R1 and R2. Infinite bus voltage is stepped-down to 6 Vrms by the transformer T1. The resistors R1 and R2 are used as a potential divider, which attenuates the stepped sine wave voltage to about 1 Vrms. This voltage is applied to the non-inverting input of the comparator COMP1, 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 COMP1 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 wavelength (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.

3.2 Phase detector circuit

The circuit diagram of the phase detector (bistable multivibrator) is composed of an operational amplifier OA1, resistors R3, R4, R5, R14, condenser C1 and diode D1. The rotor pulses from optical transducer are differentiated by the series circuit R14 and C1. The differentiated positive pulses are applied to the non-inverting input of the OA1. While the negative differentiated the voltage drop of the diode D1 limits pulses. During the negative half cycle of the infinite bus voltage the output of the comparator COMP1 is low and the resistors R3 and R4 work as a potential divider. The resistor R3 is chosen smaller than R4, so that a small positive voltage is applied to the inverting input of OA1. This voltage is less than the amplitude of the positive edge of the differentiated pulse so the output of OA1 is jumped to the positive saturation level. The feedback resistor R5 maintains the output of OA1 in saturation condition. When the trailing edge of the infinite bus voltage signal is applied to the non-inverting input of COMP1, its output will jump to positive saturation. This voltage is applied to the non-inverting input of OA1, so its output falls to the zero potential. Hence a positive pulse is obtained from the output of the OA1, whose leading edge coincides with the positive edge of the rotor pulse and its trailing edge coincides with the positive edge of the infinite bus voltage as shown in figure (4). The pulse width obtained from OA1 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 OA2, R6, R7, C2 and C3. The output signal is a DC voltage level, which is proportional to the input pulse width.

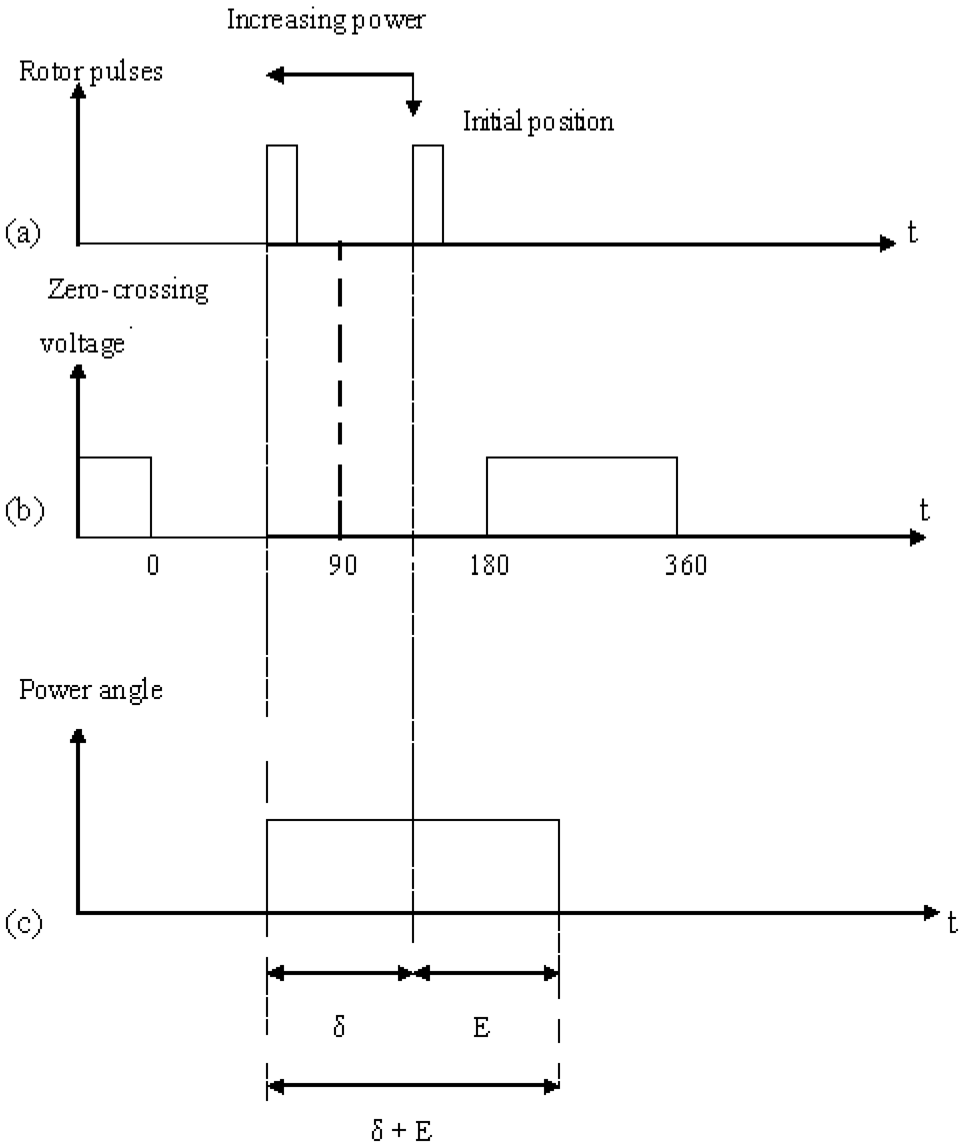

Figure 4: Pulse waveform for generating the power angle

4. Rotor speed measuring device

As we have mentioned previously, the output pulses from the optical transducer probe are used for generating both power angle and the rotor speed. The rotor speed-measuring device is based on counting of the optical transducer pulses.

This device is composed of a single 14-pin I.C. (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 equal to the exact value of the rotor speed ($\dot{\delta}$), it gives a zero output voltage at zero input frequency. The circuit diagram for the rotor speed is shown in figure (5). The integrated circuit used in this device contains an input amplifier with built-in hysteresis, a charge pump frequency to voltage converter, and an operational amplifier with an output transistor [6].

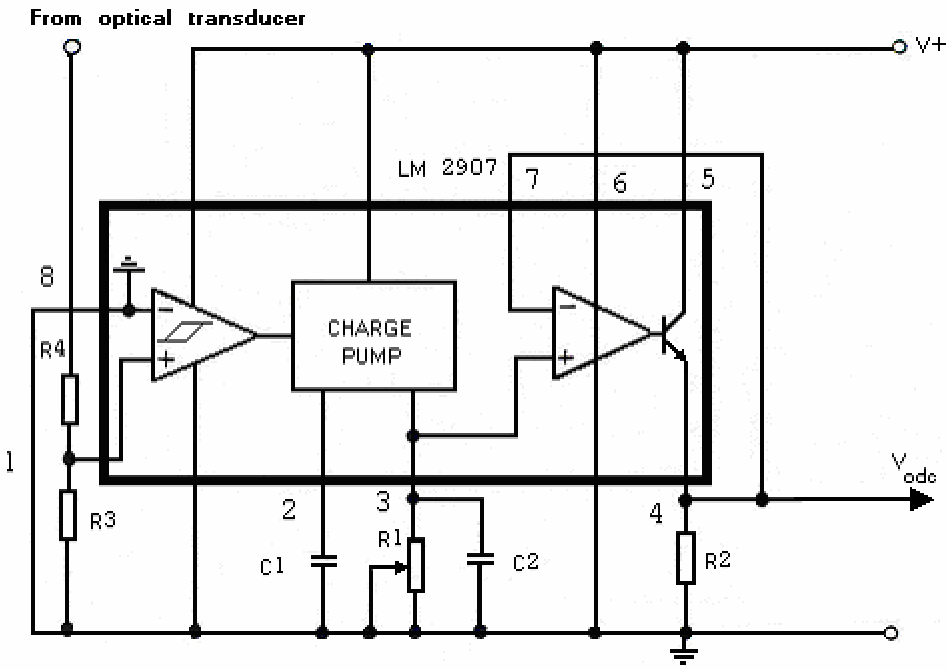

Figure 5: Circuit diagram of the rotor speed measuring unit.

5. Basic design steps

The input amplifier has a built in hysteresis at positive and negative 15 mV. This provides clean switching when 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 R3 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 [7]:

$$V_{odc} = K.V_s.F_{in}.C_1.R_1 \tag{1}$$

Where:

K….is the gain constant (normally equal to 1)

V_s…is the power supply voltage (volt)

F_{in}...is the input frequency (Hz)

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 , therefore 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.

From equation (1), it can be noticed that V_s, C1, 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 values of R_1, C_1, and C_2 for optimum performance [8].

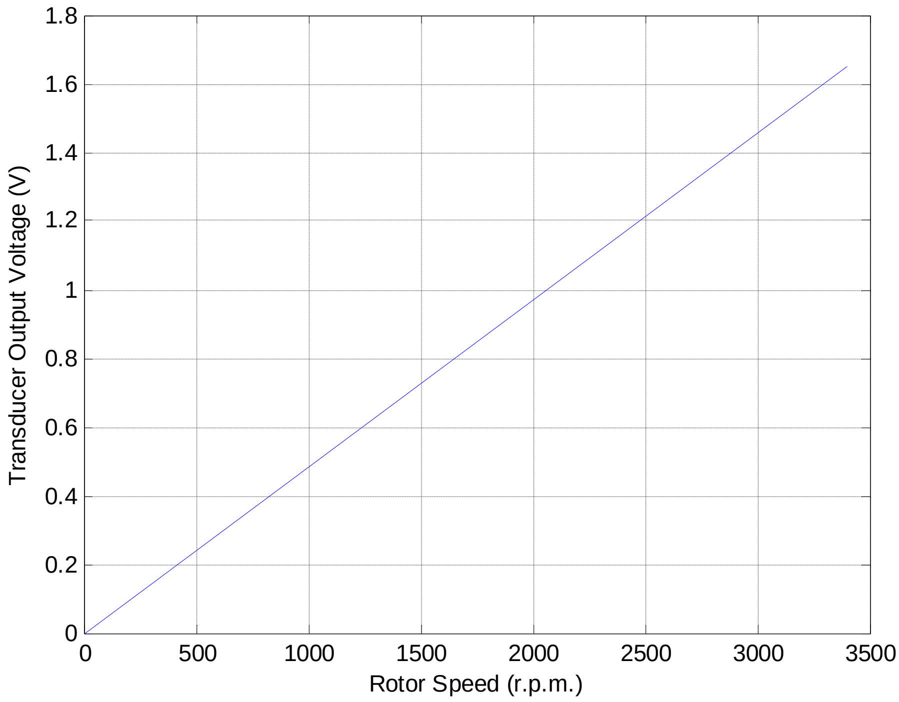

Figure 6: The rotor speed transducer output voltage curve

The values of R_1 should be obtained from the inequality:

$$R_1 > V_{max} / I_{norm} \tag{2}$$

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 and it equal to $150\,\mu A$ approximately. The value of C_1 is selected according to:

$$C_{1=} V_{max} / (F_{max} . R_1 . V_s) \tag{3}$$

Where F_{max} is the maximum input frequency. The value of C2 is selected according to the following equation:

$$C2 = (V_s / 2).(C_1 / Vr).(1 - V_{max} / 2) \tag{4}$$

Where: V_s 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.

Figure (6) shows the relation between the input frequency and the obtained DC output voltage from the rotor transducer. The linearity is evident from this figure.

6. Terminal voltage measuring unit

The principle operation of the voltage transducer is to convert the r.m.s. value of the terminal voltage of the synchronous generator to a DC voltage level (Vt) suitable to be fed to the A/D converter. The circuit diagram of the voltage transducer is shown in figure (7). The step-down stage is composed of a step-down transformer T1 and a voltage divider composed of R1 and VR1. The attenuated voltage is fed to the full wave precision rectifier (F.W.P.R.) stage, which is composed of a half wave precision that consists of OA1, diodes D1, D2, resistors (R2, R3, R4 and R5) and a scaling subtractor, which is composed of an operational amplifier of OA2, resistors R6 and R7. The output voltage from the F.W.P.R is a train of positive halves of sine waves. These waves are fed to an active low pass filter (L.P.F), which converts these waves to a purely DC voltage level proportional to the R.M.S value of the terminal voltage. The L.P.F is composed of OA3, resistors R8, R9, capacitors C1, C2. The obtained output voltage is fed to the A/D converter through a buffer stage composed of OA4, R10 and R11.

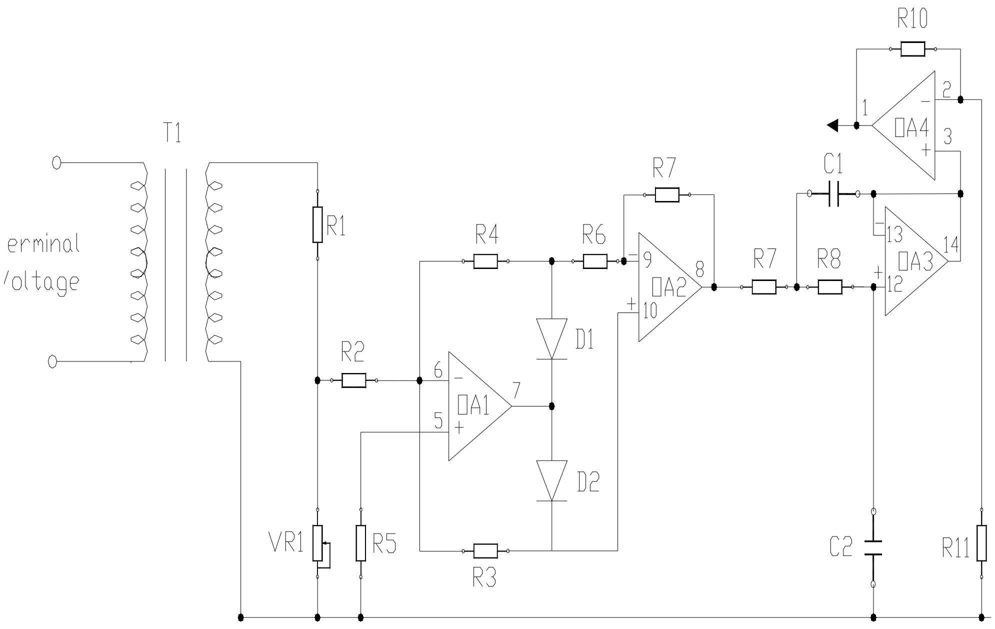

Figure 7: Circuit diagram of the terminal voltage transducer

7. Pulses waveform

Referring to the circuit diagram of the optical transducer seen in figure (1), the output pulses from the rotor transducer across resistor R5 are shown in figure (8). The time duration between pulses is 20 ms with 50 Hz pulse repetition rate and a peak value of 6v. The pulse width is 2.5 ms, which corresponds to 3000 r.p.m. and 1cm width of the black strip.

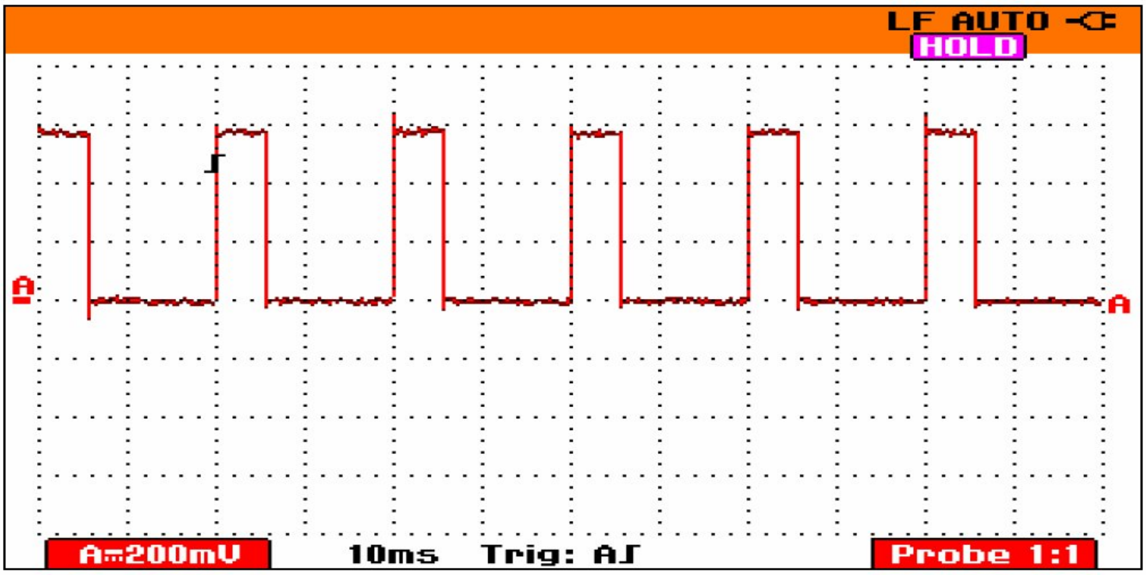

Figure 8: The output pulses waveforms from the optical rotor transducer

Referring to the circuit diagram of the power angle transducer seen in figure (3), the differentiated rotor pulses in the non-inverting input of OA1 are shown in figure (9). Also the output pulses obtained from zero crossing detecting circuit of the bus bar voltage (output of COMP1) are shown in figure (10). This output is a train of square pulses of 20 ms pulse width and 50 Hz frequencies. Figure (11) shows the output pulses obtained from the phase detector circuit (output from OA1), which represents the pulses of the power angle at no load.

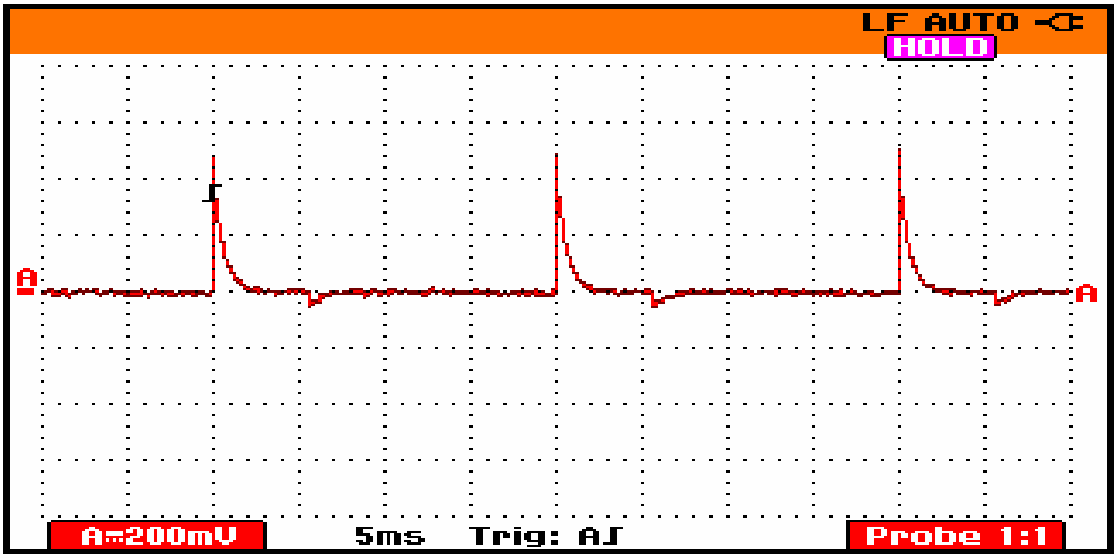

Figure 9: The differentiated rotor transducer pulses

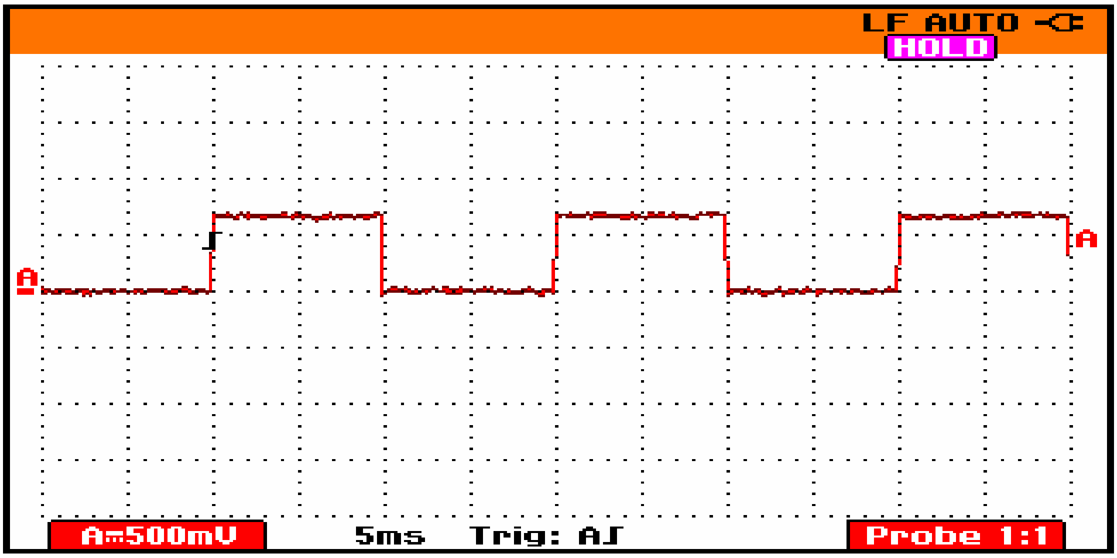

Figure 10: The output pulses from the zero detecting circuit of the bus bar voltage

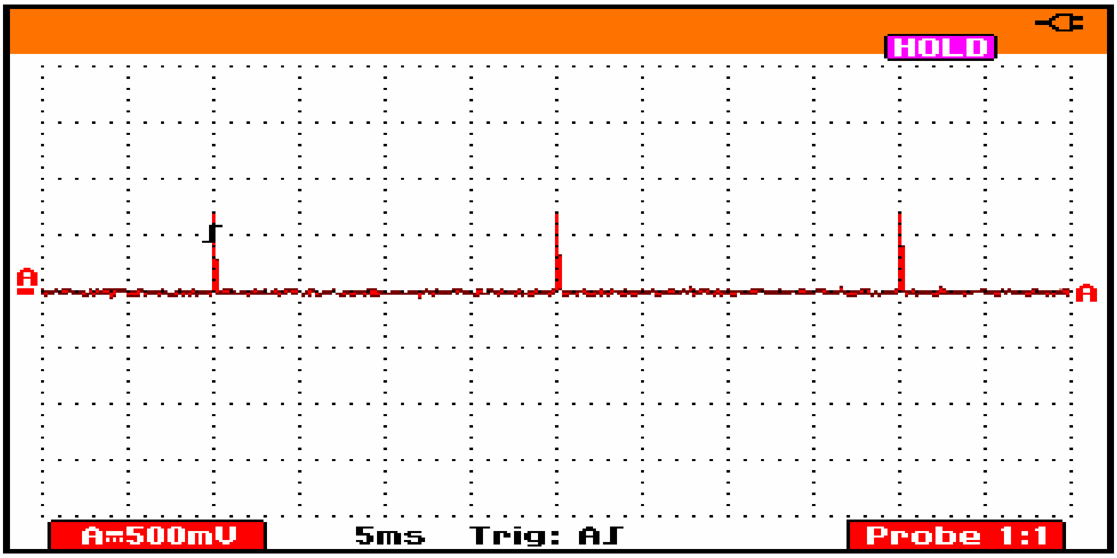

Figure 11: The power angle pulses at no load

In figure (12), the average DC voltage equivalent to the power angle pulses at 70 % of full load is obtained. This DC voltage is the output of the low pass filter OA2. The waveform of this output is a pure DC voltage with minimum amount of ripple. This is because the machine is operating at its steady state operating condition.

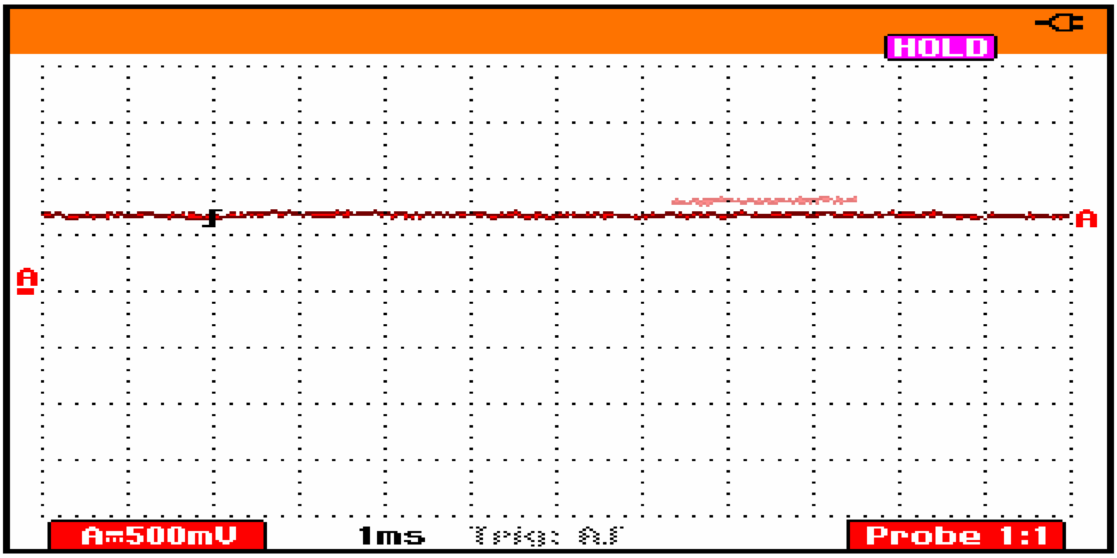

Figure 12: The DC output voltage equivalent to the power angle

Figure (13) shows the DC output voltage obtained from the rotor speed transducer. The magnitude of this voltage is proportional to the speed of the prime mover of the synchronous generator. As it can be seen in this figure the obtained voltage is a pure DC wave voltage.

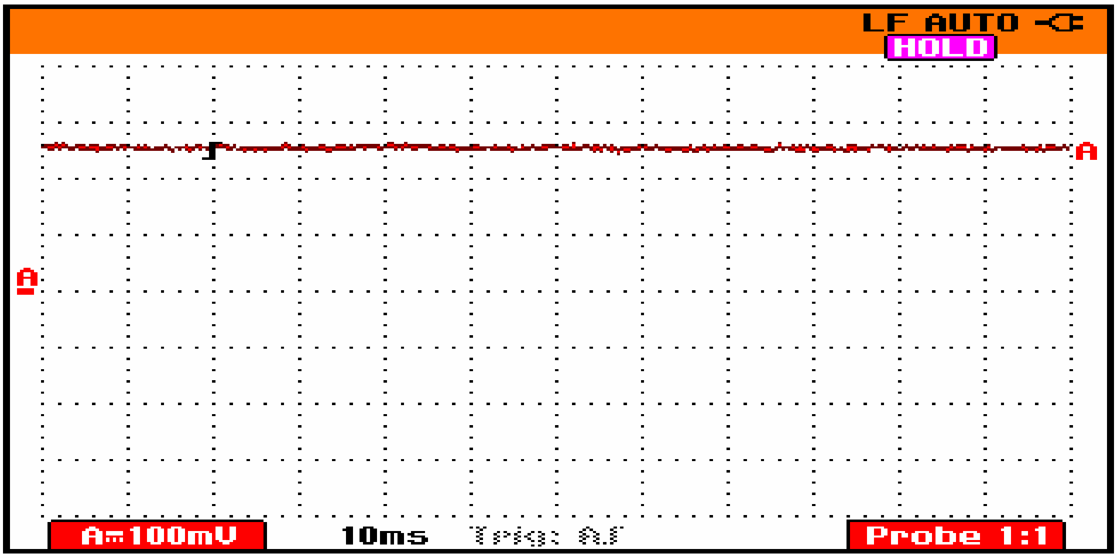

Figure 13: The DC output voltage equivalent to the rotor speed

Referring to figure (7), which represents the circuit diagram of the terminal voltage transducer (V_t), the output obtained from the full-wave precision rectifier (the output terminal of OA2) is shown in figure (14). The full-wave precision rectifier converts the sine wave signal representing the terminal voltage into accurate full- wave positive halves. This full-wave signal is fed into a low-pass filter in order to convert it into a pure DC voltage, the magnitude of which represents the value of the terminal voltage. The waveform of this signal is shown in figure (15). This DC voltage represents the terminal voltage signal which is fed to the A /D converter through a buffer stage OA4 (figure 7).

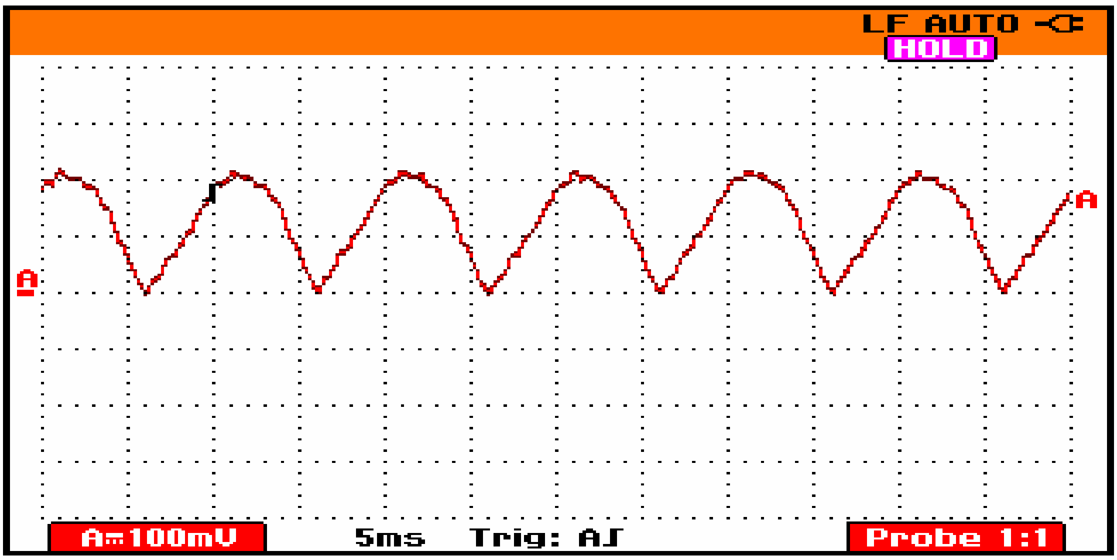

Figure 14: The output from the full-wave precision rectifier circuit

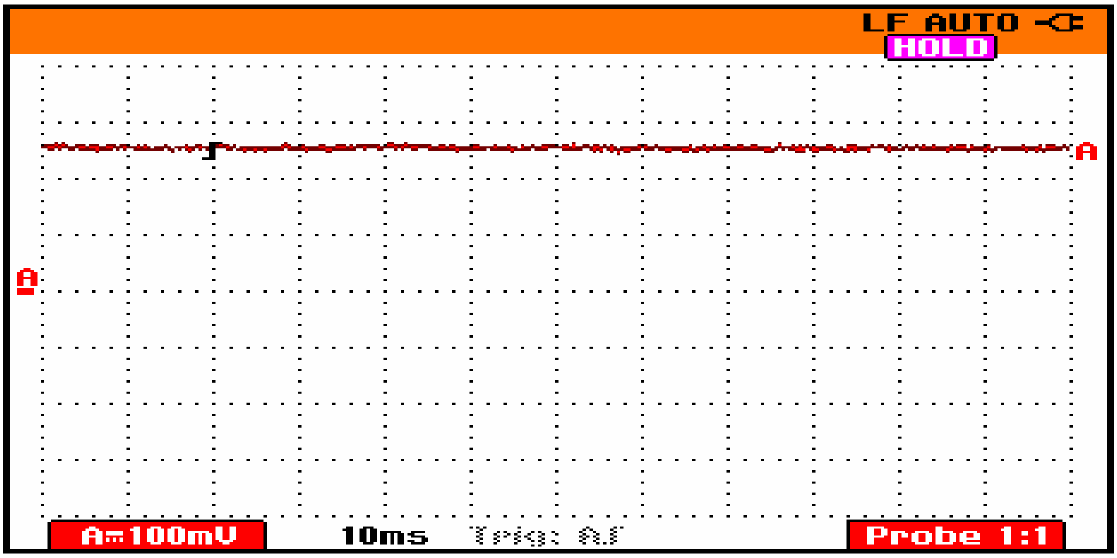

Figure 15: The output of the low pass filter of the terminal voltage transducer

8. Measurement technique

In order to test the linearity of various electronic transducers, curves between physical input quantities (rotor speed, power angle and terminal voltage) and the transducer output voltage are plotted. The curves reflect the ability of the transducer to produce output voltages similar to these physical input quantities. Figures (16), (17) and (6) explain this relation.

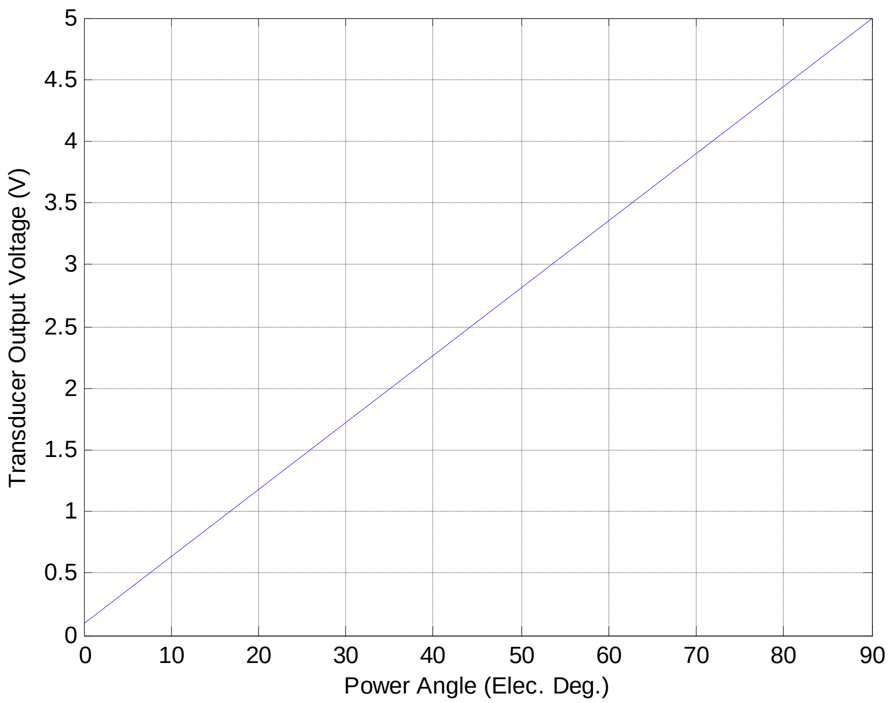

Figure 16: The power-angle transducer output voltage curve

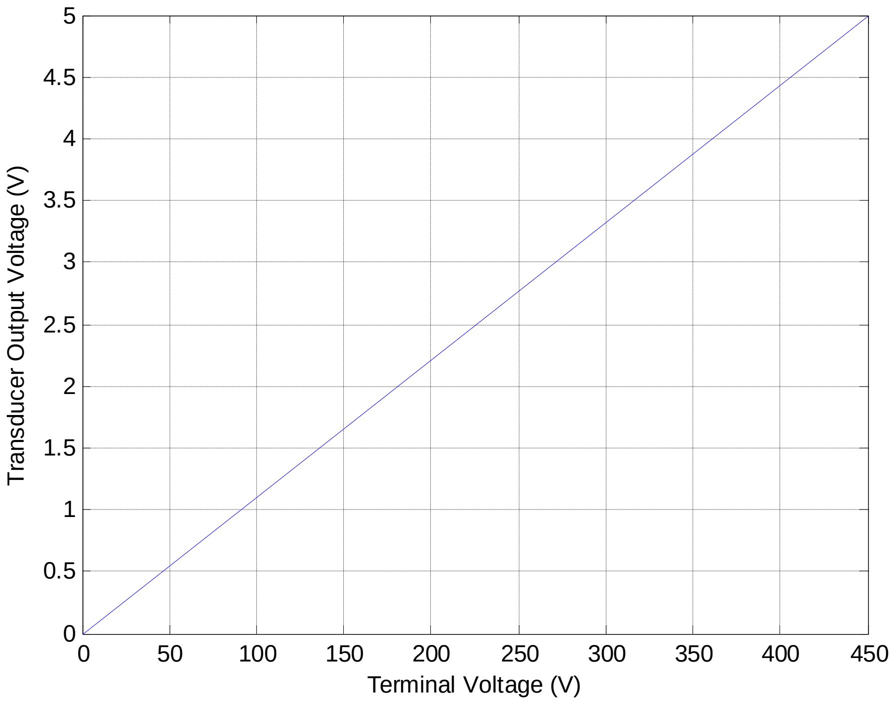

Figure 17: The terminal voltage transducer output voltage curve.

9. Conclusion

The 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 is simple in construction, reliable in operation, and has high accuracy. The realization of the power angle and rotor speed measuring device is based on 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.

10. References

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