

Instantaneous Angular Speed Measurement for Low Speed Machines

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Abstract

For early fault detection and health monitoring of low speed machines the instantaneous angular speed (IAS) measurement is required at high accuracy and resolution. It has already been established that IAS measurement is much more superior to the conventional methods i.e. analyzing acoustic waveforms, current signatures, temperature variations, and vibrations etc. However, an accurate IAS measurement becomes very difficult due to slow and noisy response of the rotary transducers of low speed rotating machines. In the proposed technique, an adjustable frequency ac drive system and a three-phase induction motor is used to mechanically simulate the different IAS values, corresponding to fault conditions. A fast rotating magnetic field (RMF) is used to measure the IAS for low-speed machines. An independent ac source is used to generate a balanced three-phase ac voltage, which is applied to the stator windings of a synchro whose rotor is coupled with the rotating member or rotor of a synchro. The RMF in the air gap generates emf in the rotor of synchro whose frequency depends upon the slip speed. Since the RMF revolves at a speed, several times the speed of the rotating member or the rotor of synchro, hence the IAS measurement becomes very fast and accurate. The proposed scheme is tested successfully for instantaneous change of speed within a range of 0-10 rpm and the overall performance is recorded at dynamic conditions.

Keywords: Speed measurements, IAS measurement, tachometers, rotating machines, low angular speed, transducers

1. Introduction

The instantaneous angular speed (IAS) measurement is one of the important issues for applications in the area of fault diagnosis, condition monitoring and control of rotating machines. According to the Monitoring and Diagnostics Research Group at the University of Manchester, the term IAS is referred to the variations of angular speed within a single shaft revolution [1]. Also in IAS terminology, the word 'instantaneous' refers to two distinct quantities i.e. angular displacement and time duration. The IAS with respect to angular displacement refers to a very small fraction of angular displacement over which the angular speed is measured. Whereas the IAS with respect to time refers to a very small duration of time over which the angular speed is calculated. In case of fault detection and overall condition monitoring, a very small fraction of angular displacement from angular speed signal is obtained to get the required information. Typical applications of IAS measurement include the fault detection in natural roller bearings [2], shaft misalignment and crack detection in rotating equipments [3], vibration measurement in electric machines [4]-[5], prediction of rotor bar failure in squirrel cage induction motors [1] and monitoring the overall conditions of the machines with time [6]. J.G. Yang et al. [7] investigated the use of the IAS for fault detection and condition monitoring of diesel engines. Feldman and Seibold explored the use of IAS in diagnosing the size and location of damage in rotating machines [8]. These applications and investigations reveal how IAS is useful in fault diagnosis and health monitoring of different types of machines. The IAS measurement is much more useful for low speed machines of cement kilns, paper mills, textile mills and heavy stone crushing machines where the fault diagnosis and condition monitoring is very critical as the abrupt shutdown of these machines would result in serious consequences [9]. Therefore for fault diagnosis and real time condition monitoring applications, a simple, high resolution, accurate and fast measurement technique for IAS is highly desirable.

A number of methods have been proposed for the measurement of IAS in literature [10]-[11]. A high resolution method is proposed for instantaneous position and speed sensing but the resolver-to-digital converter along with hardware circuitry like ADSP processor card, DAC/ADC with sample and hold interface card, microcontroller and resolver simulator card makes the method very complex [10]. Analog-to-digital converter ADC-based methods and timer/counter-based methods are commonly used for IAS measurement. The ADC-based methods require longer period of the measurement as the methods are based on averaging processes [11]. Also in ADC-based methods, the rotary sensors/encoders are used to generate electrical signals corresponding to angular speed. The capacitive sensors and resistive potentiometric sensors are used for tapping the signals corresponding to IAS. But these sensors are not suitable for high resolution measurement at low angular speeds [12]-[13]. The optical encoders show very good resolution for angular speed measurement. However, these methods are not suitable for the fast measurement of low angular speed, as these methods are costly and complex, [14]-[15]. In fact, they require additional accessories like serial encoder interface (SEI) bus adapter, power supply and a PC with supporting software to monitor the displacement and position of the rotating member [16]-[17]. Moreover it may be noted that in noisy and heavy machinery environments, long cables with shields, line drivers, opto-couplers, RC low pass filters and Schmitt-trigger input devices are also required for proper high resolution and accurate measurement. These devices further increase the complexity of the optical encoder based measurement system [17]. In case of a timer/counter based method, the pulses of a pulse-train are counted over a fixed duration of the measurement time. At low speed, this duration is kept large; therefore, a significant delay appears in the response time of the measurement. Moreover, the method results in a loss of one pulse during the count of the pulses. At high speed, as the number of pulses are large, the loss of one pulse is insignificant, therefore, the accuracy of the measurement is least affected. But, at low speed, the loss of one pulse causes significant error [18]. A significant improvement is made in the above method by the *constant elapsed time method*. However, this method has a serious limitation of *minimum measurable speed,* within a given maximum response time. Therefore, it does not work effectively for a speed below 30 rpm [11].

A number of sensor-less speed measurement techniques are also proposed in the literature for measurement of speed, but the output filters, slow down the response as well as may alter the information output at low angular speed [19]-[21]. In general these techniques are not suitable for high resolution and accurate IAS measurement of low speed rotating machines.

In the proposed method, the rotor of the synchro is mechanically coupled with the rotating member. An adjustable frequency ac drive system with three-phase induction motor is used to produce different values of IAS to mechanically simulate the fault conditions of motor, within a range of 0-10 rpm. A fast rotating magnetic field (RMF) is used to generate an emf in the rotor circuit of a synchro [22]. Both the magnitude and frequency of the output voltage depend upon of the speed and difference in the speed. The effect of variation in the magnitude of the output voltage is eliminated by using a zero crossing detector (ZCD) in open-loop mode at the output. Moreover, the RMF is kept faster (several times) than the rotor, therefore, before the completion of even one revolution of the rotor or the rotating member, the RMF rotates several times. Thus a slight deviation in IAS causes a very fast deviation in frequency of the induced emf in rotor circuit of synchro; hence the IAS measurement becomes extremely fast and accurate. The proposed method measures IAS with respect to time as well as displacement.

2. Theory

The speed (revolution) of a rotating magnetic field in the air-gap of a stator, produced by a balanced three-phase ac supply is given by

$$n_S = \frac{120\, f_S}{P} \qquad (1)$$

Where P is number of poles and f_s is frequency of the stator input voltage or current, in Hz [14], [23].

For a synchro whose rotor is rotating at n_r rpm, the relative speed or the slip is (n_s – n_r), in the direction of n_s. However, if it rotates in opposite direction, the slip becomes (n_s + n_r). The frequency of the induced emf in the rotor circuit is given by

$$f_r = \frac{(n_s \mp n_r)P}{120} \qquad (2)$$

$$and \quad f_r = f_s \mp \frac{n_r P}{120} \qquad (3)$$

Since the supply frequency (f_s) and the number of stator poles (P) are constant, therefore, the frequency of the induced emf in the rotor circuit varies linearly with the variation of the rotor speed, n_r. For this purpose, a three-phase balanced voltage supply is realized with the help of a sine wave oscillator and a single-phase to three-phase converter using three audio amplifiers as shown in Fig. 1. These voltage signals are applied to the stator windings of a synchro (Fig. 2). When the rotor of the synchro (rotating member) is standstill, the synchro acts as a transformer. Therefore the frequency of rotor emf (f_r), is same as that of stator ($f_r = f_s$). When the rotor rotates, the frequency is proportional to the slip ($n_s \mp n_r$), where n_s is constant.

3. Realization

Figure 2 shows the set up/test rig to generate different values of IAS to mechanically simulate the fault conditions of low speed rotating machines. To obtain low instantaneous angular speed within a range of 0 to 10 rpm, a three-phase induction motor is used as a rotating member. The speed of this motor is first reduced to a maximum limit of about 10 rpm with the help of a programmable and adjustable frequency ac drive system [24]. To reduce the speed further (up to 1 rpm), a pulley and wheel arrangement is used (Fig. 3), which is mechanically coupled with the synchro. The pulley belt transmission ratio of this arrangement is kept as 30:1, for a precise transmission of speed to the rotor of synchro, at low values. A sine wave signal of 40 Hz (18 V peak to peak) from a stable arbitrary function generator is supplied to a centre-tapped transformer. The output of transformer is applied to an RC network (R=100 kΩ and C = 0.1μF), to generate a balanced three phase, 40 Hz voltages V_{a1}, V_{b1}, and V_{c1} (Fig. 1). These voltages are attenuated to a value of about 100 mV as V_{a2}, V_{b2}, and V_{c2} (Fig. 4), before feeding into three audio power amplifiers (LM 384N). The outputs of these amplifiers, V_A, V_B and V_C are in turn applied to the stator windings of synchro. Therefore at stationary condition, a sine wave, V_r (40 Hz) is generated at the rotor of the synchro (Fig. 5).

4. Experimental Results

4.1. When the rotating member is at rest

As long as the rotating member is stationary, the speed of rotor of synchro is zero. The frequency f_r of V_r of the rotor circuit is equal to f_s of V_s of the stator circuit (Fig. 5). The signal V_r is now passed through a ZCD to produce a square waveform, V_R with the same frequency ($f_R = f_r$), as shown in Fig. 6. The positive going transition (PGT) of signal, V_R with a positive width (T_{WR+}) of 12.5 ms is used to trigger a one shot mono-stable multi-vibrator (OS) as shown in Fig. 7. The components of OS (74LS121N) are chosen to give a signal Q with stable positive pulse width (T_{WQ+}) of 12.5 ms. These two signals are applied to an EX-NOR gate (G-1). The output of G-1 becomes HIGH as the positive width of both the signals, V_R and Q is equal as shown in DSO record of Fig. 8 (a)

This is also shown as follows.

f_r = Frequency of induced emf (V_r) of rotor of synchro.

f_s = Frequency of induced emf (V_s) of stator of synchro.

f_R = Frequency of signal V_R at the output of ZCD ($f_R = f_r$).

T_R = Time period of the signal V_R at the input of OS.

T_{WR+} = Positive width of the signal V_R.

T_{WQ+} = Positive width of signal Q

T_{WG-} = Negative width of the pulse at the output of G-1

$T_{WG-} = T_{WR+} - T_{WQ+}$

When $n_r = 0$ rpm

$f_R = f_s = 40$ Hz

$T_R = (1/f_R) = 25$ ms

$T_{WR+} = (T_R / 2) = 12.5$ ms

$T_{WQ+} = 12.5$ ms

$T_{WG-} = T_{WR+} - T_{WQ+}$

$T_{WG-} = 12.5 - 12.5$ ms

$T_{WG-} = 0$

Therefore output of EX-NOR gate G-1= HIGH (Fig. 7)

The wave forms V_r, V_R, Q and T_{WG-} for 0 rpm are also shown in the DSO records of Fig. 8 (a).

4.2. When the rotating member or rotor of synchro runs at constant speed with healthy condition of machine (f_R is constant)

When the frequency of ac drive system is kept constant, the speed of rotating member (three-phase induction motor) also remains constant. Hence the speed of rotor of synchro is also constant. This condition is equivalent to fault free or healthy condition of a machine.

When n_r is fixed at 4 rpm by adjustable frequency ac drive

The value of f_r is obtained using (3)

$$f_r = 40 - \frac{4 \times 2}{120}$$

$f_R = f_r = 39.933$

$T_R = (1/f_R) = 25.0417$ ms

$T_{WR+} = T_R/2 = 12.52087$ ms

$T_{WQ+} = 12.5$ ms

$T_{WG-} = T_{WR+} - T_{WQ+}$

$T_{WG-} = 12.52087 - 12.5$ ms

$T_{WG-} = 20.87\ \mu s$ (Theoretical)

Practically the observed wave forms V_r, V_R, Q and T_{WG-} for healthy condition of machine at a constant speed of 4 rpm are also shown in the DSO records of Fig. 8 (b).

4.3. When the rotating member or rotor of synchro instantaneously changes to different speeds (f_R varies)

This condition is equivalent to mechanically simulating the fault conditions of a machine where the IAS is suddenly accelerated due to misalignment of shaft, fault in bearing or rotor bar failure etc. Here, the frequency of ac drive system is instantaneously changed from zero to 0.1 Hz with a switch provided at its front panel. Consequently the speed of three-phase induction motor also changes. This in turn changes the speed of rotor of synchro (from 0 to 1 rpm), mechanically coupled to it with a pulley and wheel arrangement. Similarly, if the frequency of ac drives system is switched from zero to 0.2 Hz, the speed of the rotor of synchro changes from 0 to 2 rpm. In this way different values of IAS are obtained in the sequence 0-1, 0-2…up to 0-10 rpm. Even for this small variation of IAS, the RMF revolves in the air gap at a very fast speed of 2400 rpm for a 40 Hz, 2 pole machine (synchro, S). Hence a very small value of IAS variation (one tenth of a radian per second) generates an emf, V_r whose frequency, f_r in the rotor circuit immediately decreases. The associated time period T_R (or $1/f_R$) and hence the positive width T_{WR+} of signal, V_R at the output of ZCD quickly increases. The PGT of V_R triggers OS to produce a signal, Q with stable positive width T_{WQ+} of 12.5 ms. When the signals V_R and Q are applied to G-1, a pulse with negative width is generated at its output on the trailing edge of these signals (V_R and Q) as shown in Fig. 9. The width of this pulse depends on the sudden change in IAS at the rotor of synchro (or rotating member). The pulse with maximum negative width is proportional to the maximum instantaneous change in angular speed of rotor or rotating member. The calculations for the measurement of IAS (for a variation of 1 rpm) with various parameters are given by using equation (3).

When n_r instantaneously changes from 0 to 1 rpm

$$f_r = 40 - \frac{1 \times 2}{120}$$

$f_R = f_r = 39.983$

$T_R = (1/f_R) = 25.010$ ms

$T_{WR+} = T_R/2 = 12.505$ ms

$T_{WQ+} = 12.5$ ms

$T_{WG-} = T_{WR+} - T_{WQ+}$

$T_{WG-} = 12.505 - 12.5$ ms

$T_{WG-} = 5.210$ µs (Theoretical)

Figures 10(a)-(c) show the DSO records for IAS measurement within a speed range, 0 to 10 rpm in the sequence of 0-1, 0-2,….0-10 rpm. These results are also tabulated in Table 1.

The sensitivity of the proposed method is 3.25×10^{-6} s^2 per cm, obtained as a ratio of infinitesimal change in pulse width and angular motion of the rotor of synchro. The accuracy of the method may be affected by the pulley transmission arrangement. Here, we have used a very high resolution programmable ac drive system [24], coupled with the three-phase induction motor. A high pulley belt transmission ratio of 30:1, with precise ac drive system gives the required accuracy of measurement. The accuracy of the method may also be affected by the variation in frequency generated by the function generator. Therefore, we have used a very high resolution, arbitrary function generator (Tektronix, AFG-2022 B) with accuracy (Stability) of ± 1ppm ± 1µHz, 0 °C to 50 °C. Hence, our apparatus is sufficiently accurate for the proposed instrumentation. The noise level introduced in the apparatus by the power amplifiers (LM384N) is removed by connecting capacitors of high values (4700 µF) at different stages. However, the ambient noise by electromagnetic interference may change the level of output signal at zero crossing point of comparator, which may be taken care of by properly shielding the whole apparatus. The ambient noise in the common wire (ground terminal) and temperature variation of device (LM 311) may also cause the voltage offset in the comparator. This may cause a variation in the pulse width of signal generated by ZCD. Therefore an instrument grade, comparator (LM 311) is used, which is quite immune to spurious oscillations [25]. Hence the accuracy of the measurement system is enhanced.

5. Conclusions

A novel RMF and synchro based IAS measurement technique has been proposed for low speed machines. An adjustable frequency ac drive system with a three-phase induction motor is mechanically coupled to the rotor of synchro through a pulley and wheel arrangement. This arrangement is used to produce the different values of IAS to mechanically simulate the fault conditions of motor for low speed machines. The rotor output of synchro is used to measure the IAS within a range of 0-10 rpm. The results of table I show a wide range of change in IAS. This corresponds to the different values of IAS due to faults in bearings, shaft misalignment, cracks in rotating equipments, rotor bar failure and abnormal vibrations in the machines etc. The instantaneous change in angular speed changes the frequency of induced emf in the rotor circuit of synchro which is detected in terms of pulses of different pulse-width. As the IAS is measured at the speed of RMF (40 Hz, 2400 rpm), hence for a deviation of one rpm, the measurement is 2400 times faster than the speed of rotating member. While the RMF completes one revolution in 25 ms but due to the fast measuring mechanism, the deviation in speed is detected even in half cycle i.e. within 12.5 ms; hence it provides fast measurement with high accuracy and resolution. As the proposed method measures IAS with respect to time as well as displacement, it will be useful in more accurate and early detection of faults and condition monitoring for the low speed machines.

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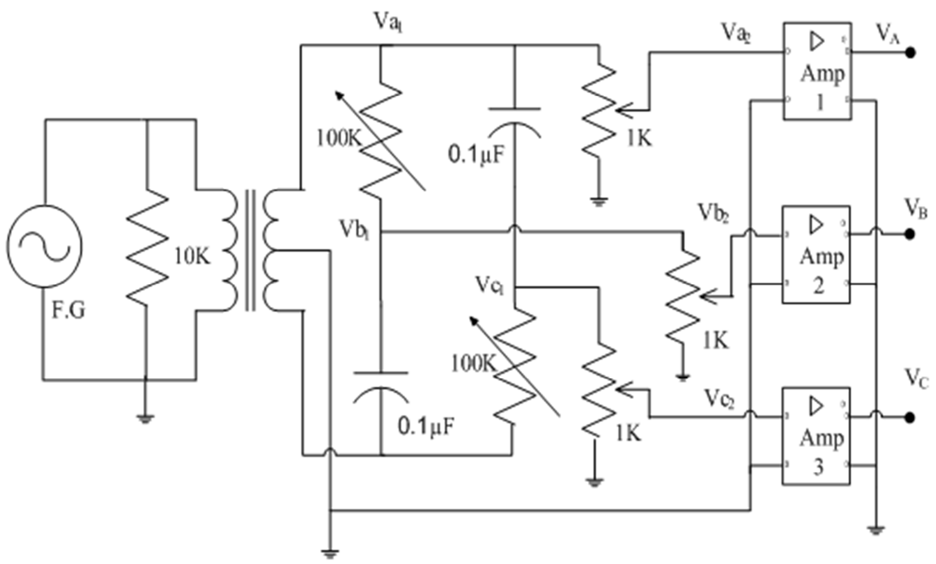

Fig. 1. Single-phase to three-phase conversion system.

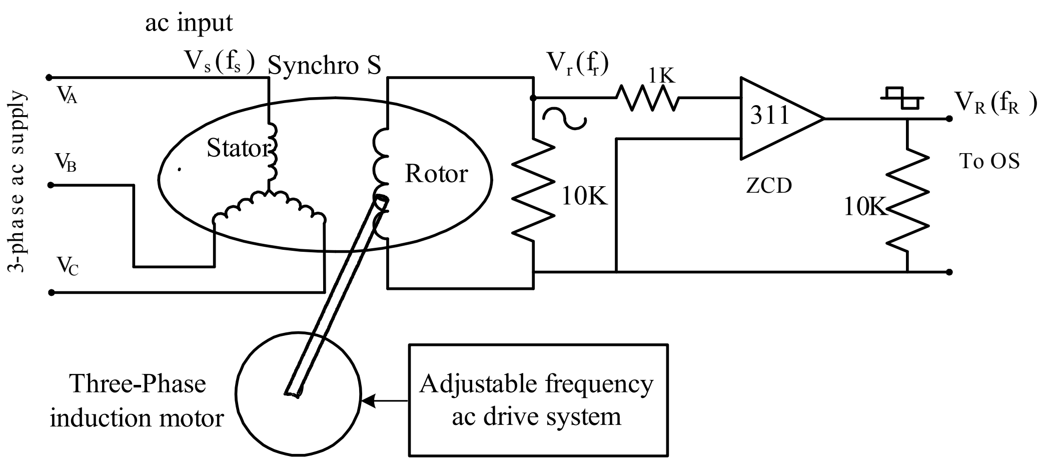

Fig. 2. RMF and synchro based IAS measurement setup.

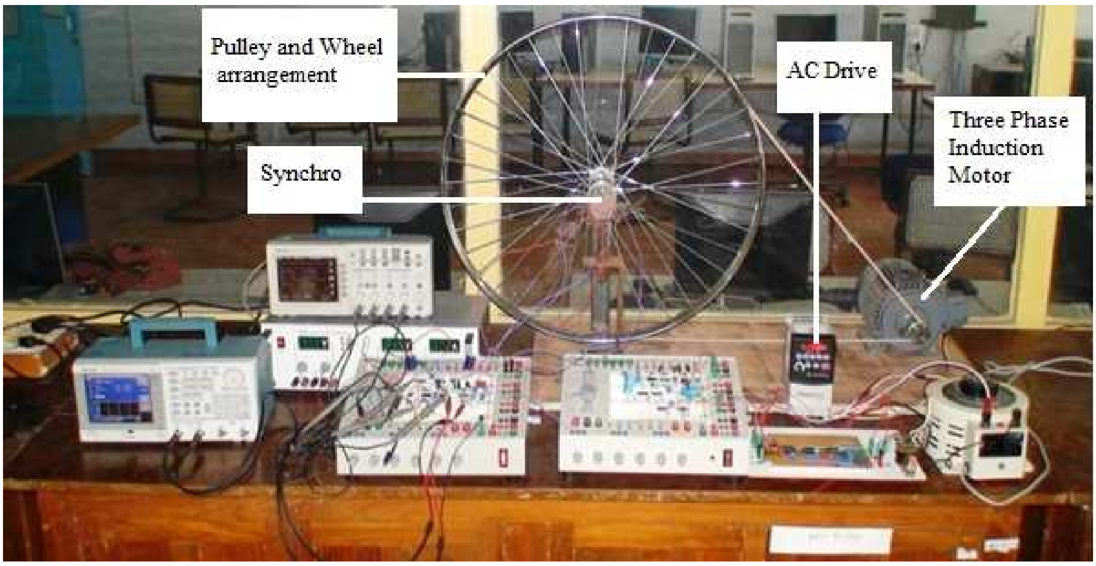

Fig. 3. Photograph of experimental setup for IAS measurement of low speed machines.

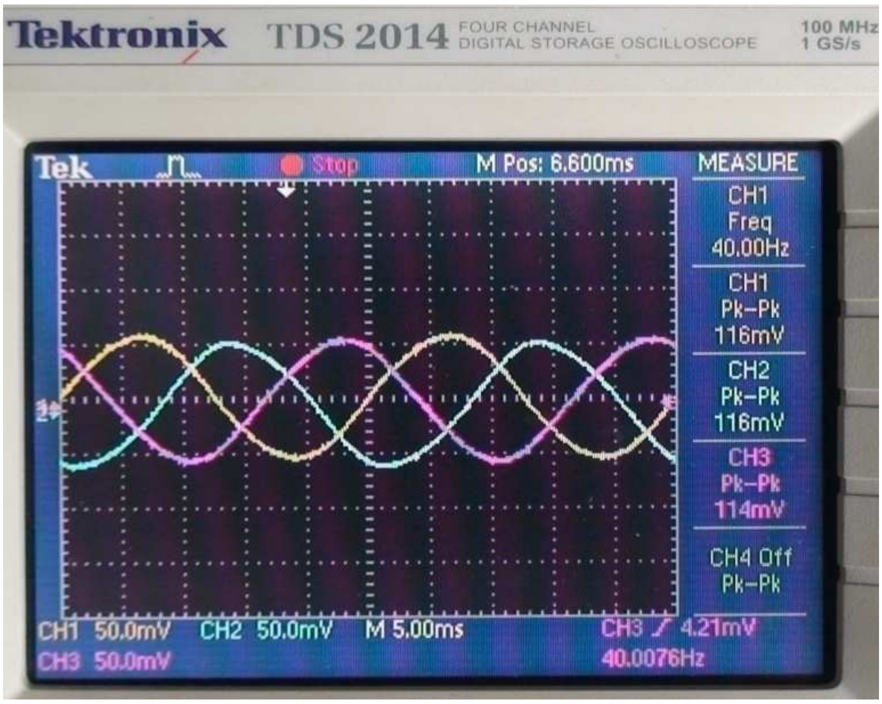

Fig. 4. Waveforms applied at the input of power amplifiers (CH#1, CH#2 and Ch#3 respectively).

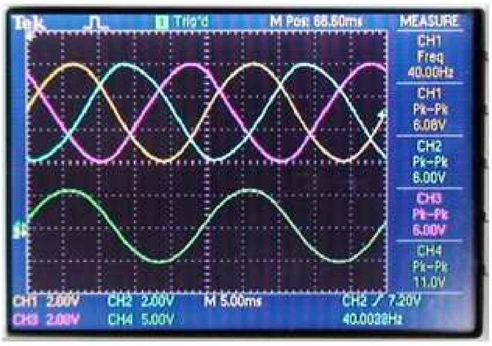

Fig.5.Three phase voltages, V_A, V_B, V_C at stator windings of synchro (CH#1, CH#2 and Ch#3), output voltage at rotor of synchro, V_r (CH#4).

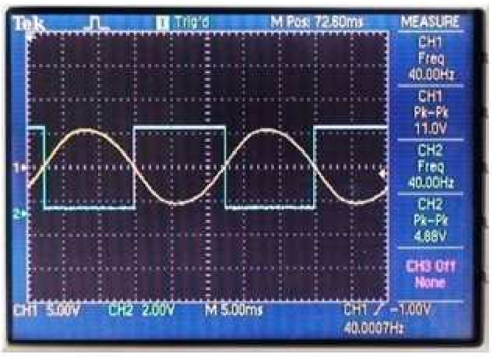

Fig. 6. Output of rotor, V_r of synchro (Ch#1) and output of ZCD, V_R (Ch#2) at 40 Hz.

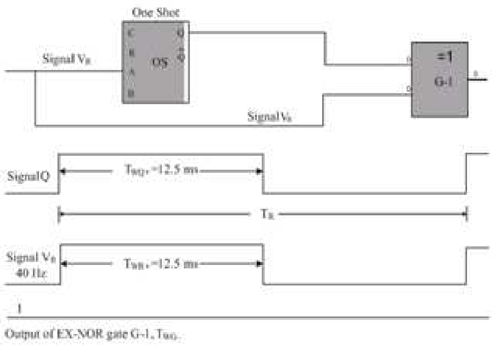

Fig. 7. Waveforms of signals, V_R, Q and output T_{WG-}

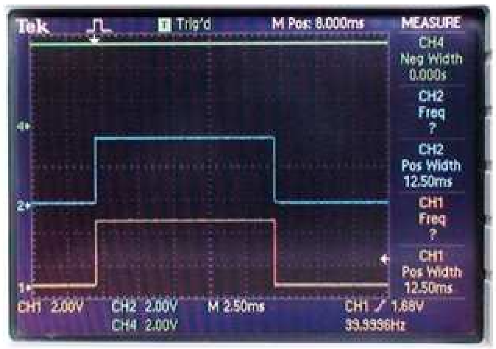

Fig. 8(a). Signal, V_R with T_{WR+} (Ch#1), signal Q with T_{WQ+} (Ch#2) and output T_{WG-} at G-1 for 0 rpm (Ch#4).

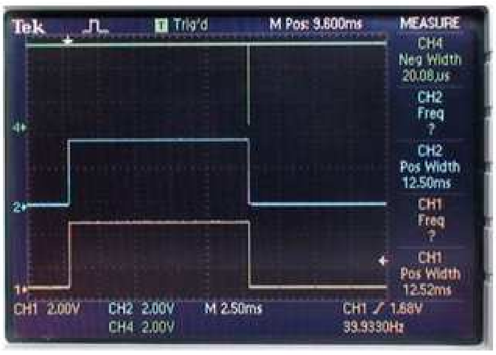

Fig. 8(b). Signal, V_R with T_{WR+} (Ch#1), signal Q with T_{WQ+} (Ch#2) and output T_{WG-} at G-1 for healthy condition at constant speed of 4 rpm (Ch #4).

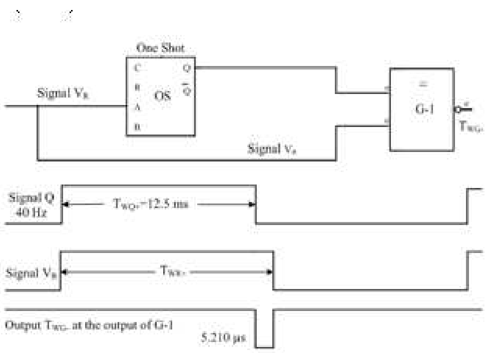

Fig. 9. Waveforms of signals, V_R, Q and output T_{WG-}.

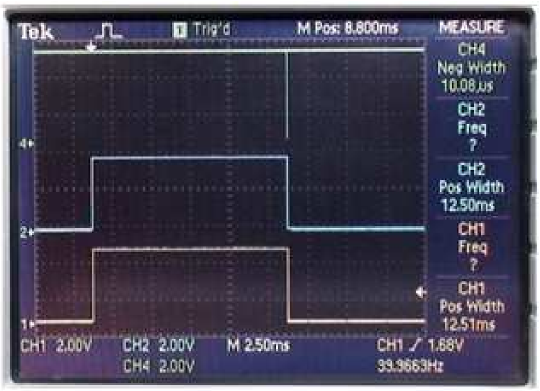

Fig 10(a)

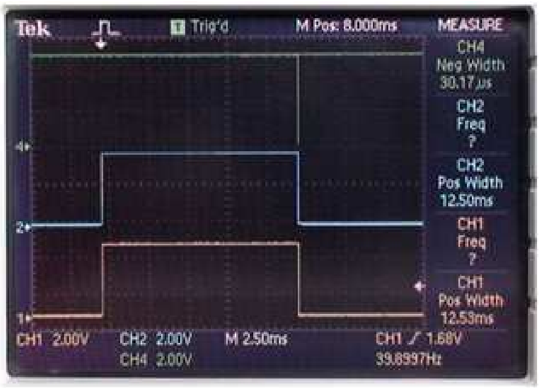

Fig 10(b)

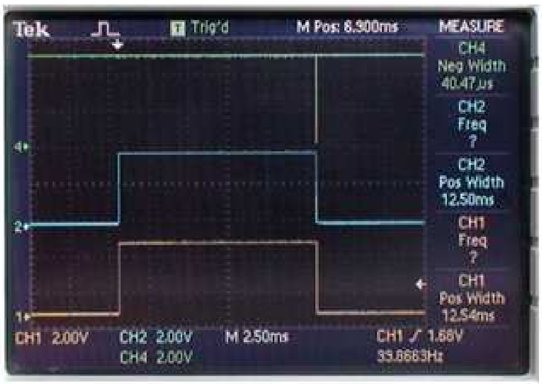

Fig 10(c)

Fig. 10(a)-(c) Signal, V_R with T_{WR+} (Ch#1), signal Q with T_{WQ+} (Ch#2) and output T_{WG-} at G-1 for instantaneous change of speed from 0 to 2, 6 and 8 rpm respectively (Ch#4).

Table 1: Theoretical and observed results of IAS measurement

T_{WQ+} ms	n_r rpm (IAS)	f_R (V_R) Hz (Theoretical)	f_R (V_R) Hz (Observed)	T_R=1/ f_R ms (Theoretical)	T_{WR+}= T_R/2 ms (Theoretical)	T_{WR+} = T_R/2 ms (Observed)	T_{WG-} (µs) = T_{WR}- T_{WQ+} (Theoretical)	T_{WG-} (µs) (Observed)
12.5	0	40	39.999	25.00	12.50	12.50	0	0
12.5	1	39.983	39.983	25.010	12.505	12.50	05.210	6.001
12.5	2	39.966	39.966	25.020	12.510	12.51	10.425	10.08
12.5	3	39.95	39.949	25.031	12.515	12.52	15.644	15.93
12.5	4	39.933	39.933	25.041	12.521	12.52	20.868	20.08
12.5	5	39.916	39.917	25.052	12.526	12.53	26.096	24.38
12.5	6	39.90	39.899	25.062	12.531	12.53	31.328	30.17
12.5	7	39.883	39.883	25.073	12.536	12.54	36.564	36.04
12.5	8	39.866	39.866	25.083	12.541	12.54	41.010	40.47
12.5	9	39.85	39.849	25.094	12.547	12.55	47.051	48.00
12.5	10	39.833	39.833	25.104	12.552	12.55	52.301	52.16