ULTRA FAST SPEED MEASUREMENT BY ROTATING MAGNETIC FIELD

ABSTRACT

OF THE THESIS

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Abstract

Accurate and fast speed measurement is one of the important requirements of the industrial drives, trains, cars, ships, space vehicles, aeroplanes, and fast propulsion or transportation systems. In this thesis, novel rotating magnetic field (RMF) based measurement techniques are proposed to measure speed, variation in speed, very low speed, seismic vibrations, foreshocks and to calibrate tachometers. The rotating member whose speed is to be measured is coupled with the rotor of a synchro. The stator of the synchro is energized by a balance three phase ac voltage which produces RMF rotating at a very high speed in the air gap of synchro. The RMF generates electromotive force (EMF) in the rotor circuit of synchro whose frequency depends upon slip speed i.e. the speed difference of RMF with the rotor of synchro. The RMF rotates in the air gap at a very fast speed and completes several rotations even before completion of one rotation of the rotor, hence, speed measurement becomes very fast. The frequency/time period of the induced EMF in the rotor circuit is measured using a digital storage oscilloscope (DSO) and a microcontroller, which is converted to give the speed of the rotating member. A 16-bit digital output of the microcontroller is also made available corresponding to speed which can be used as a feedback signal for speed control applications. Now if the speed of the rotating member gets changed abruptly, the proposed method is able to sense the new speed in a very short time (within 2.5 ms) due to the high speed of RMF. The time response of the proposed scheme is compared with the time response of a dc tachogenerator.

The fast measurement at low speed becomes very difficult due to slow response of transducers. At low speed (below 10 r/min), normally, transducers take several seconds to give the required output signal. In the proposed method, since the RMF revolves at a high speed, hence the measurement becomes very fast even at 1 r/min for a low speed machine. For the measurement of low speed, a
one-shot monostable multivibrator (OS) and logic gate circuits are used to give a pulse whose width corresponds to the speed. The proposed method is compared with a conventional tachogenerator method which confirms the fast measurement of speed by the proposed method. The output is also obtained in terms of dc voltage and dc current, which can be used for feedback and control applications. Moreover, due to high accuracy of the proposed method, different types of tachometers, analog and digital, are calibrated using this technique.

The concept of fast RMF based measurement is also extended to measure the velocity and acceleration of seismic vibrations and foreshocks at high resolution and accuracy in millisecond range. To simulate the seismic vibrations and foreshocks mechanically, a microprocessor based rocking vibration arrangement is used. These vibrations are mechanically transmitted to the rotor of a synchro. According to the movement of the rotor of synchro, the RMF generates voltage signals at the rotor output and thereby a pulse train of variable pulse width is produced. The widths of these pulses are used to measure the instantaneous velocity of vibrations. The averaging circuits give the average velocity of vibrations in terms of dc voltage and dc current, corresponding to the widths of these pulses. The instantaneous values of acceleration of these vibrations are found from the related instantaneous values of velocity. The peak positive and negative velocity and acceleration of vibrations are also obtained with a resolution in millisecond range.

**Work Done in this Thesis**

The goal set for this thesis is in three important areas of instrumentation and measurement, namely; *fast measurement of angular speed of rotating machines, calibration of tachometers, and high resolution seismic vibration measurement*. The work done and the main contributions described in this thesis are explained below.
A novel technique of measurement using RMF is proposed for the fast and accurate measurement of speed.

A novel technique of measurement using RMF is proposed for the measurement of variation in speed.

Experimental setups with circuits are developed for the generation of RMF based measurement of speed in acceleration and deceleration mode.

A single-phase to three-phase convertor circuit is developed for the generation of RMF. To avoid the loading effect of the three-phase convertor circuit, a buffer amplifier circuit is designed to provide amplified signal to the stator winding of synchro.

A program is developed using microcontroller (PIC 16F877A), to measure the time period of the output pulse which corresponds to speed. Hence the digital output becomes available for high resolution speed measurement and can also be used as a digital feedback signal for speed control applications.

The proposed scheme is compared with the speed measurement by a dc tachogenerator in acceleration and deceleration mode.

The RMF based measurement scheme is used for the calibration of various tachometers. Three different types of tachometers, (an analog/mechanical type, a digital non-contact type, and a digital contact type) are calibrated with the proposed scheme.

The measurement technique is also extended for the fast and accurate measurement of low speed.

Experimental setup is developed to realize very low speed from 0 to 10 r/min, using a three-phase induction motor (as a prime mover) and a vector controller adjustable frequency ac drive system.

A digital logic circuit is designed to measure the pulse width corresponding to very low speed of the rotating member.

An amplifier with averaging circuit is developed to obtain dc output voltage as well as dc current as feedback signals for control applications.
• The RMF and synchro based measurement scheme is also proposed for the fast and accurate measurement of seismic vibrations and foreshocks.

• The velocity waveforms of various earthquakes are investigated. The waveforms of 2003 Lefkada (Greece), 1994 Northridge (USA), 1992 Landers (USA), and 1987 Whittier Narrows (USA) earthquakes are taken as reference for the simulation purpose.

• In order to mechanically simulate seismic vibrations in the laboratory, a microprocessor based vibration generation and measurement setup is developed to practically realize vibrations which resemble seismic vibrations of the reference earthquakes.

• Averaging circuits with amplifiers are used to obtain average velocity of vibrations in terms of dc voltage and dc current, corresponding to the widths of pulses generated due to these vibrations.

• A micro ammeter is calibrated in terms of velocity of vibrations.
Publications from the Thesis

Papers in International Journals


Filed and Published Patents


3. S. J. Arif and Shahedul Haque Laskar, “A rotating magnetic field based high resolution measurement of velocity and acceleration of seismic vibration,”

**Paper to be Communicated**

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CERTIFICATE

This is to certify that the thesis entitled "Ultra Fast Speed Measurement by Rotating Magnetic Field", submitted by me in the Department of Electronics Engineering, Zakir Husain College of Engineering and Technology, Aligarh Muslim University, Aligarh, India, for the award of the degree of Doctor of Philosophy in Electronics Engineering, is a record of my own work. The matter embodied in this thesis has not been submitted to any other University or Institute for the award of any other degree.

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Abstract

Accurate and fast speed measurement is one of the important requirements of the industrial drives, trains, cars, ships, space vehicles, aeroplanes, and fast propulsion or transportation systems. In this thesis, novel rotating magnetic field (RMF) based measurement techniques are proposed to measure speed, variation in speed, very low speed, seismic vibrations, foreshocks and to calibrate tachometers. The rotating member whose speed is to be measured is coupled with the rotor of a synchro. The stator of the synchro is energized by a balance three phase ac voltage which produces RMF rotating at a very high speed in the air gap of synchro. The RMF generates electromotive force (EMF) in the rotor circuit of synchro whose frequency depends upon slip speed i.e. the speed difference of RMF with the rotor of synchro. The RMF rotates in the air gap at a very fast speed and completes several rotations even before completion of one rotation of the rotor, hence, speed measurement becomes very fast. The frequency/time period of the induced EMF in the rotor circuit is measured using a digital storage oscilloscope (DSO) and a microcontroller, which is converted to give the speed of the rotating member. A 16-bit digital output of the microcontroller is also made available corresponding to speed which can be used as a feedback signal for speed control applications. Now if the speed of the rotating member gets changed abruptly, the proposed method is able to sense the new speed in a very short time (within 2.5 ms) due to the high speed of RMF. The time response of the proposed scheme is compared with the time response of a dc tachogenerator.

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List of Acronyms and Abbreviations

ADC : analog to digital convertor
A\textsubscript{1} : instantaneous acceleration of vibrations
ASIC : Application Specific Integrated Circuit
A\textsubscript{p+} : peak positive acceleration
A\textsubscript{p-} : peak negative acceleration
C : capacitance
\textdegree C : degree centigrade
CH : channel
cm/s : centimeter per second
CSDT : constant sample-time digital tachometer
dc : direct current
DSO : digital storage oscilloscope
EMF : electromotive force
EMI : electromagnetic interference
EX-OR : Exclusive OR
f\textsubscript{r} : frequency of induced EMF in the rotor circuit of synchro
f\textsubscript{R} : frequency of signal V\textsubscript{R} at the output of zero crossing detector
f\textsubscript{s} : frequency of voltage or current in the stator winding of synchro
f\textsubscript{z} : frequency of signal V\textsubscript{Z} at the output of zero crossing detector
F.G : function generator
FPGA : field programming gate arrays
FSR : full scale reading
G-1 : Exclusive OR gate
H : Hexadecimal
Hz : Hertz
I\textsubscript{dc} : dc current
k\Omega : kilo ohms
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<th>Abbreviation</th>
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<tr>
<td>LED</td>
<td>light emitting diode</td>
</tr>
<tr>
<td>LSB</td>
<td>least significant bit</td>
</tr>
<tr>
<td>ms</td>
<td>milliseconds</td>
</tr>
<tr>
<td>MSB</td>
<td>most significant bit</td>
</tr>
<tr>
<td>mV</td>
<td>milivolts</td>
</tr>
<tr>
<td>NGT</td>
<td>negative going transition</td>
</tr>
<tr>
<td>n_r</td>
<td>speed of the rotating member or rotor of synchro</td>
</tr>
<tr>
<td>n_s</td>
<td>synchronous speed of rotating magnetic field</td>
</tr>
<tr>
<td>OS</td>
<td>one shot mono-stable multi-vibrator</td>
</tr>
<tr>
<td>OP-AMP</td>
<td>operational amplifier</td>
</tr>
<tr>
<td>P</td>
<td>number of poles</td>
</tr>
<tr>
<td>PC</td>
<td>personal computer</td>
</tr>
<tr>
<td>PGT</td>
<td>positive going transition</td>
</tr>
<tr>
<td>ppm</td>
<td>parts per million</td>
</tr>
<tr>
<td>Q</td>
<td>output of one shot mono-stable multi-vibrator</td>
</tr>
<tr>
<td>Q'</td>
<td>inverted output of one shot mono-stable multi-vibrator</td>
</tr>
<tr>
<td>r</td>
<td>radius of rotor of synchro</td>
</tr>
<tr>
<td>R</td>
<td>resistance</td>
</tr>
<tr>
<td>R_{ex}</td>
<td>external resistance of the armature circuit of dc motor</td>
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<tr>
<td>RMF</td>
<td>rotating magnetic field</td>
</tr>
<tr>
<td>r/min</td>
<td>revolution per minute</td>
</tr>
<tr>
<td>s</td>
<td>seconds</td>
</tr>
<tr>
<td>SEI</td>
<td>serial encoder interface</td>
</tr>
<tr>
<td>SW</td>
<td>switch</td>
</tr>
<tr>
<td>T</td>
<td>time period of pulse at the output of gate G-1</td>
</tr>
<tr>
<td>t_{on}</td>
<td>on time of pulse at the output of gate G-1</td>
</tr>
<tr>
<td>T_R</td>
<td>time period of the signal V_R at the input of One Shot</td>
</tr>
<tr>
<td>T_{W_{G^-}}</td>
<td>negative width of the pulse at the output of Exclusive OR gate</td>
</tr>
<tr>
<td>T_{WQ^+}</td>
<td>positive width of signal Q</td>
</tr>
<tr>
<td>T_{WQ^-}</td>
<td>negative width of signal Q'</td>
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<tr>
<td>T_{WR^-}</td>
<td>negative width of the signal V_R</td>
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$T_{WR}^+$ : positive width of the signal $V_R$

$T_z$ : time period of rectangular waveform of zero crossing detector

$V$ : volts

$V_1, V_2, V_3$ : three-phase voltages at the output of phase-split circuit

$V_4, V_5, V_6$ : three-phase voltages at the input of power amplifiers

$V_7, V_8, V_9$ : three-phase voltages at the output of power amplifiers

$V_{dc}$ : dc voltage

$V_1$ : instantaneous velocity of vibrations

$V_{p+}$ : peak positive velocity of vibrations

$V_{p-}$ : peak negative velocity of vibrations

$V_{max}$ : maximum amplitude of pulse at the output of gate G-1

$V_r$ : single-phase voltage of rotor winding of the synchro

$V_R$ : square waveform at the output of zero crossing detector

$V_s$ : three-phase voltages of stator winding of the synchro

$V_z$ : rectangular waveform at the output of zero crossing detector

ZCD : zero crossing detector

$\mu A$ : micro ampere

$\mu F$ : micro Farad

$\mu Hz$ : micro Hertz

$\mu s$ : micro seconds

$\Omega-m$ : ohm meter

$\omega$ : angular speed of rotor of synchro in radian per second
Chapter 1

Introduction

1.1 Background and Motivation from Literature

Feed back control systems require fast measurement of speed and generation of control signals. Accurate and fast speed measurement is one of the important requirements of space vehicles, aeroplanes, warships, rocket propellers, high speed trains, high speed cars, fast synchronous motors, induction motors, dc motors and fast propulsion or transportation systems. Very fast and accurate speed measurement is also one of the important requirements of low speed machines like rotors of cement kilns, rolling machines in paper mills, mining industries, textile mills and heavy stone crushing machines, where the speed varies from 0 to 10 revolutions per minute (r/min) [1]-[4]. Even the drives with speed less than 2 r/min are very common in industries [1]. Different contact type and non-contact type tachometers are used for speed measurement as well as for generation of feedback signals for control applications. Usually these tachometers suffer from calibration drift and they have also got drawbacks of low resolution and noise contaminations [5]-[11]. Moreover, several revolutions are required to detect the deviation in speed and therefore only after a significant delay, the outputs of these tachometers become stable. In case of many non-contact type transducers, several seconds are required due to delay in time response [8]-[11]. Both ac and dc tachogenerators are commonly used for speed measurement. But the commutator and brushes in dc tachogenerators need periodic maintenance [12]. Also, if the armature current is large, it distorts the field of the permanent magnet and hence causes non-linearity [13]. Similarly, in case of ac tachogenerators, the ripples of
the output voltage are susceptible to speed variations and therefore smoothening filters become necessary [7]. These filter circuits increase the delay in time response of ac tachogenerators. On the other hand, the digital tachometers are preferred over their analog counterparts as they have better accuracy and give immunity to noise. Thus the delay in time response due to analog filters is avoided. The digital tachometers are generally of two types. One is based on counting the pulses of a pulse-train over a fixed duration of measurement time, which exhibits very accurate result at high speed but the errors are dramatically increased at lower speed [14]-[16]. 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 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 not affected. At low speed, the loss of one pulse causes significant error. An appreciable improvement is made in the above method by the constant elapsed time method [14]-[15]. 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 r/min [15]. The Application Specific Integrated Circuit (ASIC) method of digital tachometers combines the advantages of both the above mentioned methods and gives high accuracy of measurement over a wide range of speed. However, the response time of ASIC method is slow which is of the order of seconds [16]. The ADC based methods are also commonly used in angular speed measurement [17]-[19]. They require longer period of measurement as these methods are based on averaging processes [18]-[19]. In optical encoder based methods, the increase in sampling time improves the read-out accuracy but these methods are costly and intricate [20]-[23]. 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 [24]-[25]. Moreover, the encoder coupling to the machine shaft has rubber inserts which gives heavy damping and backlash [23]. For accurate measurement of speed, Hall sensors and optical sensors have also been reported in
the literature. However, they have large response time, which is of the order of seconds [26]-[27]. The speed measurement by sensor less methods has got momentum in last decade [28]-[40]. The drives with sensor less control have advantages of increased reliability (no tachometer failure), elimination of sensor cables and reduced size of drive systems. However, these measurement methods experience problems due to variation in machine parameters (stator and rotor resistances etc), resulting in deterioration of accuracy [36]. Moreover, the delay in time response becomes high due to output filters [36], [38]. Also, the output filters, may alter the information output at low speed [39]-[40]. The Constant Sample-time Digital Tachometer (CSDT) method is used to measure both low and high speeds. However, the non idealities in optical incremental encoders and sensors produce very large errors. Also, the phasing between encoding channel generates significant errors at the output of tachometer [41]-[44]. With the help of FPGA, CSDT method is improved, however, it gives faster response at low speed only [45]. The contact type measurement methods are simple and cost effective. They are being used in remote locations, for example, off shore wind turbines, and cost effective condition monitoring [46]. With the advancement in technology, the measurement using contact type methods is not a problem anymore. The true zero backlash flexible shaft couplings are available for the shaft coupling up to 30,000 r/min for continuous use in a temperature range of -40 °C to +120 °C [47].

The delay in time response of the existing methods varies from one tenth of a second to several seconds as detailed earlier. Therefore, these techniques are not suitable for fast speed measurement or where fast feedback signals are required for control applications. To overcome these drawbacks, a novel technique of measurement using rotating magnetic field (RMF) is proposed in this thesis for fast and accurate measurement of speed and variation in speed [48]-[49]. A balanced three-phase ac voltage with a frequency of 400 Hz is applied to the stator winding of a synchro which produces an RMF rotating at a very fast speed in the air gap of synchro. Consequently, an electromotive force (EMF) is generated in the rotor circuit of synchro which is coupled with a rotating member
whose speed is being measured. The frequency of the induced EMF in the rotor circuit of synchro depends upon slip speed i.e. the speed difference of RMF with the rotor of synchro. With a frequency of 400 Hz, the RMF revolves at a speed of 24000 r/min which is purposely kept very high in comparison to the speed of the rotor or rotating member. Thus the measurement becomes very fast and the change in speed is sensed within 2.5 ms. The synchro and a dc shunt motor with a zero crossing detector (ZCD) are used for the measurement. Separate circuits are designed for the measurement of speed in acceleration and deceleration mode. The time response of the proposed scheme is compared with the time response of a dc tachogenerator. A program is developed using microcontroller (PIC 16F877A), to measures the time period which corresponds to speed and deviation in speed of the rotating member. The 16-bit digital output of the microcontroller is made available as a feedback signal for control applications.

The effect of fast rotation of magnetic field is much more pronounced at low speed. Hence, the method of RMF based fast measurement is highly suitable for low speed machines [50]-[51]. Since the time of measurement depends on the slip speed of RMF with the rotor/rotating member, very fast measurement is achieved even at very low speed (1-10 r/min). Here, the frequency of the balanced three-phase ac voltage applied to the stator winding of synchro is taken as 40 Hz. At this frequency, the RMF rotates at a speed of 2400 r/min. Hence, even at 1 r/min the speed is measured at the speed of RMF (2400 r/min), which is 2400 times faster than the speed of rotating member. An experimental setup is developed to realize low speed from 0 to 10 r/min, using a three-phase induction motor (as a prime mover) and an adjustable frequency ac drive system. A digital logic circuit is designed to measure the pulse width corresponding to very low speed of the rotating member. An amplifier with averaging circuit is also developed to obtain dc output voltage or dc current as feed-back signals for control applications. The proposed scheme is compared with the speed measurement by a dc tachogenerator.
Fast and accurate method is also required for the calibration of tachometers. Different tachometers which include contact type, non-contact type, and both analog and digital tachometers are being used for speed measurement in the industries and laboratories etc. The calibration of a tachometer refers to comparing its readings (speed) with a more accurate (standard) speed measuring instrument than the tachometer being calibrated [52]-[53]. The tachometers are manufactured by physical materials and they are used in the real world of humidity, heat, physical stress, noise and vibrations etc., and as a consequence their performance gets affected and deteriorates. Hence, regular calibration of tachometers is required to maintain their accuracy within the manufacturer's specifications.

Several state-of-the-art methods are being used in industries for calibration of both contact type and non-contact type tachometers [54]-[58]. The contact type tachometers are calibrated using pulse generator, electronic counter along with discrete variable components (like resistors). The performance of these components deteriorates with aging and causes inaccuracies in calibration [54]. A simple method has also been reported to calibrate the contact type tachometers, using a computer with tone generating program [55]. The method calibrates the tachometers up to 8500 r/min. In the lower range of speed the calibration is limited to 200 r/min. The non-contact optical tachometers are calibrated up to a range 12000 r/min to 60000 r/min using universal frequency counter and pulse signals of laser diode, and LEDs, driven by very accurate and calibrated function generator [56]-[58]. These methods are complex and the instruments and software involved with attachments like calibration adapter are costly. The non-contact optical tachometers are also calibrated using a stroboscope. However, the high light of stroboscope sometimes makes the results of calibration unacceptable [59].

An improved method is developed using the RMF based measurement technique using a synchro, coupled with a dc motor (rotating member) for the calibration of tachometers. The calibration is based on the fundamental principle where the frequency of the induced EMF in the rotor circuit of synchro is directly
proportional to the speed of rotating member. For a particular speed the exact frequency is found and thereby, the actual time period is calculated for this speed. The rotating member (dc motor) is allowed to run and the speed is controlled by varying the voltage across its armature winding. The exact time period is adjusted and set accurately, by varying the speed of dc motor. Consequently, the speed of dc motor becomes exactly equal to the theoretical value. Three different types of tachometers (an analog/mechanical type, a digital non-contact type, and a digital contact type) are calibrated with the proposed method [60]-[62].

High resolution, fast and accurate measurement is equally important for measuring the speed/velocity of seismic vibrations. The earthquake is one of the prime causes of natural disasters, human loss, technological disasters, and damage to heavy building structures, electric power and water delivery system. Enormous destruction and economic losses are common due to earthquakes and landslides provoked by geological instabilities and rock impacts [63]. The earthquake of Japan on March 11, 2011 has raised alarm worldwide regarding nuclear power generation. The earth quake in Haiti on January 12, 2010 has killed more than 230,000 people. The earth quake of Sumatra (Tsunami) on December 26, 2004 killed more than 300,000 people in 11 countries. The heavy destruction from big earthquakes [Friuli, Mexico City 1985, Aegion 1995, Umbria 1997, Turkey 1999, Sumatra (Tsunami) 2004, Sichuan 2008, Samoa 2009, Chile 2010 and Japan 2011] is beyond contemplation. The instruments like seismometers and accelerometers, used for monitoring seismic vibrations have been mainly developed in view of measuring acceleration, which is only one of the parameters [64]. Furthermore, the present seismometers fail to record the peak values of acceleration, displacement, speed, rise time caused by strong motions in the critical area near field of strong earthquakes, with high resolution [65]. Hence, due to poor resolution, the peak values of seismic wave’s parameters are missed, which causes problems in the reliable design of nuclear power plants, industrial plants and buildings, resistant to strong earthquakes. This fact has been demonstrated by the destruction of heavy constructions in the recent strong earthquakes. Therefore, for a more consistent design of buildings, it would be an
advantage to measure directly the seismic waves acting on the buildings.

A reduction in disasters due to earthquakes requires a rigorous effort over a wide range of solutions-oriented multi-disciplinary, multi-institutional research. An accurate prediction of earthquake will minimize the loss of life, severe injuries, and disruption of important services. Therefore, the prediction of location and time, of large earthquakes, has regained a great importance. A high resolution measurement of velocity and acceleration of foreshocks helps more accurate prediction of earthquakes [66]-[67].

Generally, before any earthquake, there are foreshocks with hidden signatures of velocity and acceleration. The fact has been established recently that the foreshocks are the best accredited forecaster of earthquakes [68]. This thinking has been supported by the seismic response time histories and comparison of measured and identified data records of seismic vibrations [69]. The researchers have found that there is a strong correlation and resemblance in the pattern of velocity and acceleration of foreshocks and main shock. This is helpful in the prediction of earthquakes [70]-[74]. The foreshocks consist of very low frequency waves with superimposed high frequency spikes, which have extremely high instantaneous velocity and acceleration. Due to this adverse combination, the existing low resolution accelerometers and seismometers are unable to get an insight of signatures of these foreshocks [68]-[69], [75].

For the prediction of earthquakes, several experiments have been carried out in Greece, based on the change of electric current in dielectric media and soil [76]-[80]. However, the prediction is too vague and no feasible decision such as to evacuate the population of a certain area for a given period of time, can be made [64], [81]-[82]. The VAN method gives a good prediction of earthquake to vacate a certain area. However, the large numbers of dipoles (buried at the depth of 2 meters) are required at a distance of 100 meters to 10 km. Therefore, large connecting wires required to supply the signal to a difference amplifier, make the system costly and intricate [83]. Attempts were also made in Japan for the
prediction of earthquakes, based on chemical changes in mineral water [84]-[85]. However, the implementation of the technique is very expensive and complex [86]. Various techniques, for measuring the velocity and acceleration of foreshocks and main shock, have been proposed in the literature. The resolution of measurement of existing methods is in the range of few seconds to tens of seconds. Moreover these methods are slow, less accurate, and unreliable for the prediction of earthquakes [75], [87]-[90]. Hence a high resolution measurement technique for the measurement of seismic vibrations and foreshocks is required.

In this thesis, the RMF based measurement scheme is proposed for fast and accurate measurement of velocity of seismic vibrations and foreshocks [91]-[93]. In order to mechanically simulate seismic vibrations in the laboratory, the velocity waveforms of various earthquakes are investigated [87]-[90]. Some of these earthquake waveforms [2003 Lefkada (Greece), 1994 Northridge (USA), 1992 Landers (USA), 1987 Whittier Narrows (USA)] are taken as reference for the simulation of seismic vibrations [90]. A microprocessor based system with stepper motor and a synchro is developed to practically realize vibrations which resemble seismic vibrations of these earthquakes. The fast back and forth movement of different angular length, which resembles the seismic vibrations, is generated by stepper motor and transmitted to the rotor of the synchro. Consequently, the movement varies the frequency of rotor voltage of synchro. Thereby, a pulse train of variable pulse width is obtained and recorded in millisecond range. A digital logic circuit measures the width of these pulses which corresponds to the instantaneous velocity of vibrations. The averaging circuits are also developed and the average velocity of vibrations is obtained in terms of dc voltage and current. The instantaneous values of acceleration of these vibrations are found using the corresponding instantaneous velocity. The values of peak positive and negative velocity and acceleration of vibrations are also obtained with a resolution in millisecond range.
1.2 Work Done in this Thesis

The goal set for this thesis is in three important areas of instrumentation and measurement, namely; fast measurement of angular speed of rotating machines, calibration of tachometers, and high resolution seismic vibration measurement. The work done and the main contributions described in this thesis are explained below.

- A novel technique of measurement using RMF is proposed for the fast and accurate measurement of speed.
- A novel technique of measurement using RMF is proposed for the measurement of variation in speed.
- Experimental setups with circuits are developed for the generation of RMF based measurement of speed in acceleration and deceleration mode.
- A single-phase to three-phase convertor circuit is developed for the generation of RMF. To avoid the loading effect of the three-phase convertor circuit, a buffer amplifier circuit is designed to provide amplified signal to the stator winding of synchro.
- A program is developed using microcontroller (PIC 16F877A), to measure the time period of the output pulse which corresponds to speed. Hence the digital output becomes available for high resolution speed measurement and can also be used as a digital feedback signal for speed control applications.
- The proposed scheme is compared with the speed measurement by a dc tachogenerator in acceleration and deceleration mode.
- The RMF based measurement scheme is used for the calibration of various tachometers. Three different types of tachometers, (an analog/mechanical type, a digital non-contact type, and a digital contact type) are calibrated with the proposed scheme.
- The measurement technique is also extended for the fast and accurate measurement of low speed.
- Experimental setup is developed to realize very low speed from 0 to 10 r/min, using a three-phase induction motor (as a prime mover) and a vector controller adjustable frequency ac drive system.
- A digital logic circuit is designed to measure the pulse width corresponding to very low speed of the rotating member.
- An amplifier with averaging circuit is developed to obtain dc output voltage as well as dc current as feed-back signals for control applications.
- The RMF and synchro based measurement scheme is also proposed for the fast and accurate measurement of seismic vibrations and foreshocks.
- The velocity waveforms of various earthquakes are investigated. The waveforms of 2003 Lefkada (Greece), 1994 Northridge (USA), 1992 Landers (USA), and 1987 Whittier Narrows (USA) earthquakes are taken as reference for the simulation purpose.
- In order to mechanically simulate seismic vibrations in the laboratory, a microprocessor based vibration generation and measurement setup is developed to practically realize vibrations which resemble seismic vibrations of the reference earthquakes.
- Averaging circuits with amplifiers are used to obtain average velocity of vibrations in terms of dc voltage and dc current, corresponding to the widths of pulses generated due to these vibrations.
- A micro ammeter is calibrated in terms of velocity of vibrations.

1.3 Organization of Thesis

The thesis is organized such that the background of the work done in this thesis is discussed in chapter 1. Also the contribution and organization of the thesis is given in this chapter.

In chapter 2, an RMF based measurement technique is proposed which provides fast measurement of speed and deviation in speed. The time response of the proposed scheme is compared with the time response of a conventional dc
tachogenerator. The use of a microcontroller is also discussed which generates a 16-bit digital output, corresponding to speed.

The chapter 3 describes the proposed technique which was discussed in chapter 2, is successfully applied for the calibration of different contact type and non-contact type tachometers. The calibration of three different types of tachometers (an analog/mechanical type, a digital non-contact type, and a digital contact type) is discussed.

The chapter 4 describes the application of the RMF based speed measurement technique for the fast measurement of very low speed. The proposed method is compared with a conventional tachogenerator method which confirms the fast response of the proposed method. The output measurand is also made available in terms of dc voltage and current for feedback control applications.

In chapter 5, a seismic vibration measurement technique is proposed using RMF which provides fast measurement of seismic vibrations including foreshocks with high accuracy and high resolution. The use of a microprocessor based system is discussed to simulate or generate the vibrations in the range of -20 cm/s to +20 cm/s, with a frequency of about 1 Hz. Here, the use of an amplifier circuit for the measurement of vibrations is also discussed. The output is obtained in terms of dc voltage and current for the direct measurement of the vibrations.

Chapter 6 of the thesis contains the conclusion of work as well as possible future investigations.
Chapter 2

Ultra Fast Measurement of Speed and Deviation in Speed Using Rotating Magnetic Field

2.1 Introduction

In this chapter, the concept of using RMF for fast measurement of speed is being proposed. RMF based measurement technique for fast and accurate measurement of speed and the variation in speed is described. A contact type synchro is used as a primary transducer. A balanced three-phase ac voltage is applied to the stator winding of synchro which produces an RMF in the air gap. An EMF is generated by RMF in rotor circuit of the synchro which is coupled with the rotating member whose speed is being measured. The frequency of induced EMF in the rotor circuit of synchro depends upon the slip speed of RMF with the rotor/rotating member. An operational amplifier in open-loop mode is used as a ZCD to eliminate the effect of noise, distortion in waveform and varying magnitude of EMF. Moreover, as the rotation of magnetic field is kept as fast as possible (24000 r/min, 400 Hz), the speed and the change in speed are quickly monitored by the deviation in frequency of rotor circuit. Since the RMF rotates at very high speed and it completes one revolution within 1/400 s, therefore, the deviation in speed is immediately detected in the very next cycle i.e., within 2.5 ms. A digital storage oscilloscope (DSO) and a microcontroller are used for the measurement of time period and frequency, corresponding to the speed and the change in speed of
the rotating member. The digital output of microcontroller is made available as a
digital feedback signal for controlling the speed and the deviation in speed. The
time response of the proposed scheme is also compared with the time response of
a dc tachogenerator.

2.2 Theory

A synchro is an electromechanical device which has a three-phase stator winding
and a single-phase rotor winding. Its physical construction is similar to a three-
phase alternator. A synchro is suitable for the operation in heavy noise industrial
environment as it can tolerate high temperature, high shock, vibration and
humidity [94]. When the three-phase stator winding of a synchro is energized by a
three-phase balanced current, the RMF is produced in the air gap [48], [51], [94].
The RMF in the air gap rotates at synchronous speed (in r/min) is given by

\[
ns = \frac{120 f_s}{P}
\]  

(2.1)

where \( f_s \) is the frequency of voltage or current in the stator winding, in Hz and \( P \) is
the number of poles of the stator winding.

The RMF generates EMF in the rotor circuit of synchro whose frequency
depends upon slip speed i.e. the speed difference of RMF with the rotor of
synchro. Here, for the speed measurement, this principle is employed and a
synchro is used as a part of the speed transducer.

If the rotor of a synchro is mechanically connected or linked with a rotating
member, the frequency of induced EMF, in the rotor circuit of synchro is given by

\[
f_r = \frac{(n_s \pm n_r)P}{120}
\]  

(2.2)

where \( n_r \) is the speed of the rotating member or rotor of synchro in r/min
From (2.1) and (2.2),

\[ f_r = \frac{n_s P}{120} + \frac{n_r P}{120} = f_s + \frac{n_r P}{120} \]  \hspace{1cm} (2.3)

Since \( P, n_s \) and \( f_s \) are constant, \( f_r \) linearly varies with the rotor speed \( n_r \). When the rotating member or the rotor of synchro is stationary, \( f_r \) becomes equal to \( f_s \). However, when the rotating member rotates along with (direction of) RMF, \( f_r \) is proportional to the slip \( (n_s - n_r) \). Whereas, if the direction of rotation is opposite, \( f_r \) is proportional to the slip \( (n_s + n_r) \). Here, the speed of the rotor of synchro or rotating member (dc motor) is few hundred r/min only, whereas, the speed of RMF is 24000 r/min for a supply frequency of 400 Hz. At this frequency, for each revolution of the rotating member, the RMF rotates 24000 times. Therefore, any change in speed is sensed immediately, within the completion of one revolution of the RMF i.e. within 1/400 seconds. Consequently, the measurement becomes very fast. In the proposed method, the high resolution of speed measurement depends upon the high resolution of the pulse-width (time period) measurement. Here, both microcontroller and DSO based measurement offer high resolution. For example, for 1500 r/min, the resolution of a 16-bit microcontroller is very high, i.e. \( 1500/2^{16} \) or 0.0225 r/min.

### 2.3 Realization of the Scheme for Fast Measurement of Speed

The shaft of the rotating member (dc shunt motor) is mechanically coupled to the rotor of synchro. The detailed specifications of dc shunt motor and synchro are given in appendix A.1. An adjustable dc voltage is realized by using an adjustable ac voltage source and a bridge rectifier. The field winding of the dc motor is energized by a constant dc voltage. The dc voltage of the armature winding of the motor is adjustable which is controlled by an auto transformer. Figure 2.1 shows the circuit diagram of setup for the measurement of speed. A switch (SW) is connected across the external resistance \( R_{ex} \) to change the dc voltage of the armature circuit which changes the speed of motor promptly.
Figure 2.1 Setup for RMF based speed measurement (acceleration mode).

A sine wave signal of 400 Hz (20V peak-to-peak) from a stable arbitrary function generator (F.G) is supplied to a center-tapped transformer with two phase-split circuits (Figure 2.2). It generates two voltage waveforms as shown in Figure 2.3. The phase-split circuits are adjusted to get two signals $V_2$ and $V_3$ which lag and lead by $120^\circ$ with respect to $V_1$. These output signals $V_1$, $V_2$ and $V_3$ are balanced three-phase 400 Hz voltages (Figure 2.4). These voltage signals are reduced to a value of about 100 mV ($V_4$, $V_5$ and $V_6$), before feeding into three buffer amplifiers (Figure 2.5). Since, the synchro requires sufficient current to generate the desired RMF. Therefore, to avoid the loading effect of the single-phase to three-phase conversion circuit, a buffer amplifier (LM 384 N) is used to amplify each voltage signal (Figure 2.2). These amplified signals ($V_7$, $V_8$ and $V_9$), with frequency $f_s$, are applied to the stator winding of the synchro and marked as $V_s$ (Figure 2.1).

As long as the synchro is standstill, it acts as a transformer and generates a sine wave with the same frequency in its rotor circuit ($f_r = f_s$) as shown in Figure
2.6. A ZCD using LM 311 of very high slew rate [95] gives a rectangular waveform $V_z$ with the same frequency ($f_z = f_r = f_s$), as shown in Figure 2.7. A microcontroller (PIC 16F877A [96]) is used to measure the time period $T_z$ of signal $V_z$ which corresponds to speed and deviation in speed of the rotating member. The 16-bit digital output of microcontroller is recorded on 16-digital channels of DSO.

![Figure 2.2](image.png)

**Figure 2.2** Single-phase to three-phase conversion circuit with a centre-tapped transformer and power amplifiers.
**Figure 2.3** Waveforms of the input and output voltages of center-tapped transformer.

**Figure 2.4** Waveforms $V_1$ (CH#1), $V_2$ (CH#2) and $V_3$ (CH#3) at the output of phase-splitting circuits, respectively.
Figure 2.5 Waveforms $V_4$ (CH#1), $V_5$ (CH#2), and $V_6$ (Ch#3) applied at the input of power amplifiers, respectively.

Figure 2.6 $V_7$ (CH#1), $V_8$ (CH#2), and $V_9$ (Ch#3) of stator winding of synchro with frequency $f_s$, and rotor output $V_1$ (CH#4) with frequency $f_r$. 
2.4 Speed Measurement

The experiments are carried out for measurement of speed and the variation of speed in acceleration as well as deceleration mode. The speed of rotating member is measured at different values within a range of 0 to 1500 r/min. For each speed of the rotating member, time period of the rotor EMF of synchro is measured using a high resolution DSO. The same time period is also measured by a microcontroller.

The accuracy of measurement is related with the stability in output frequency of function generator. Thus a high resolution arbitrary function generator (Tektronix, AFG-2022 B), is used [± 1 parts per million (ppm) ± 1µHz, 0 °C to 50 °C]. However, the output level of signal, at zero crossing point may change due to the ambient noise caused by electromagnetic interference (EMI). This problem may be solved by properly shielding the setup with low carbon steel casing having a saturation permeability of 276.81, a linear permeability of 1161.36, resistivity of $10^8 \, \Omega\cdot m$ and a shielding efficiency of 67.89 %. The ambient temperature variation and the electrical noise in the common wire may also cause a voltage offset in the output of ZCD and consequently, its pulse width may vary. Therefore, an instrument grade operational amplifier (LM 311) is used which is immune to noise over large extent. Hence, the circuit operates satisfactorily for the proposed instrumentation.

2.4.1 Stationary Mode

In standstill condition, the frequency $f_r$ of signal $V_r$ of the rotor circuit is equal to $f_s$ (400 Hz). The ZCD produces a rectangular waveform $V_z$ with the same frequency ($f_z = f_r$) of 400 Hz (with a time period $T_z$ of 2.5 ms), as shown in Figure 2.7. $T_z$ is also measured by the microcontroller to produce a 16-bit binary weighted digital output 0618H (in Hexadecimal code), as shown in the oscillographic record (Figure 2.8). The label D0 indicates the least significant bit
(LSB) and D15 shows the most significant bit (MSB) of digital output of microcontroller (Figure 2.8).

![Figure 2.7](image1.png)

**Figure 2.7** $V_r$ (Ch#1) and $V_z$ (Ch#2) at standstill ($f_z = 400$ Hz).

![Figure 2.8](image2.png)

**Figure 2.8** Output of microcontroller (0618H) on 16 digital channels (D15-D0) of DSO at standstill.
2.4.2 Acceleration Mode

In acceleration mode, the dc motor (rotating member) is initially allowed to run at a particular speed. As long as the SW is open, the armature current of dc motor is limited by $R_{ex}$ and the dc voltage across armature winding is kept at a low level of about 20 V. The time period $T_z$ at this condition is 2.49 ms and therefore $f_z = 401.61$ Hz, as measured by DSO (Figure 2.9). $T_z$ is also measured by the microcontroller, which gives a digital output 0610H corresponding to 2.49 ms (Figure 2.10). The actual speed corresponding to this time period is 96.39 r/min which is found from (2.3) as shown in Table 2.1.

![Figure 2.9](image)

**Figure 2.9** $V_r$ (Ch#1), $V_z$ ($T_z = 2.49$ ms and $f_z = 401.61$ Hz) at 96.39 r/min (Ch#2), when the armature voltage (Ch#3) is 20 V (acceleration mode before switching).
Now, the SW is closed, the voltage across armature winding shoots up to a new level of about 85 volts (Figure 2.11). This sudden increase in the speed increases $f_z$ immediately. Hence, $T_z$ decreases to a value of 2.47 ms ($f_z = 404.86$ Hz), as shown in Figure 2.11. $T_z$ is also measured by the microcontroller (Figure 2.12) that gives a digital output 0604H corresponding to 2.47 ms. The speed corresponding to this time period is 291.6 r/min as shown in Table 2.1. It is evident from DSO records that the time period changes in the very next cycle which is measured here within a time frame of 2.5 ms (Figures 2.9 and 2.11). This is possible due to the fast movement of the RMF in the air gap around the rotor (24000 r/min) which register any change in the rotor speed quickly. For example, for a rotor speed of 100 r/min, the RMF revolves at a speed, 240 times faster than the speed of rotor. Thus, even before the completion of one revolution of the rotating member, the change in speed is exposed by the change in frequency. The DSO and the microcontroller senses the change in frequency immediately and gives the output accordingly, within 2.5 ms. Therefore, the speed measurement becomes extremely fast.
Figure 2.11 $V_1$ (Ch#1), $V_Z$ ($T_Z = 2.47$ ms and $f_Z = 404.86$) at 291.6 r/min (Ch#2), when the armature voltage (Ch#3) is 85 V (acceleration mode after switching).

Figure 2.12 Output of microcontroller (0604H) on 16 digital channels (D15-D0) of DSO ($T_Z = 2.47$ ms and $f_Z = 404.86$ Hz) at 291.6 r/min when the armature voltage is 85 V (acceleration mode after switching).
Experiments are also carried out for different levels of change in speed (in acceleration mode). The change in speed is measured in terms of time period or frequency using DSO. The microcontroller also measures the time periods which is represented in Hexadecimal code in Table 2.1. It is evident from the oscillographic records (Figures 2.13-2.24), that the change in speed is sensed in the very next cycle of signal $V_z$. The microcontroller generates a unique 16-bit digital output that can be used as a digital feedback signal for controlling the speed of motor. It also gives a high resolution of the speed measurement. The chance of error is there in the measurement with DSO due to gross error (human error). However this effect is eliminated using the microcontroller which measures the pulse width accurately. For the 16-bit digital output of microcontroller and 1500 r/min dc motor, the resolution becomes $1500/2^{16}$ i.e. 0.0225 r/min.
Table 2.1: Measurement of speed in acceleration mode

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Armature voltage for different values of $R_{ex}$ (V)</th>
<th>$T_z$ measured by DSO (ms)</th>
<th>Related frequency $f_z = 1/ T_z$ (Hz)</th>
<th>Actual speed from (3) (r/min)</th>
<th>$T_z$ measured by microcontroller (in HEX code)</th>
<th>Decimal equivalent of binary weighted output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 0</td>
<td>2.50 -</td>
<td>400.00 -</td>
<td>0 0</td>
<td>0618H -</td>
<td>1560 -</td>
</tr>
<tr>
<td>2</td>
<td>20 85</td>
<td>2.49 2.47</td>
<td>401.61 404.86</td>
<td>96.39 291.6</td>
<td>0610H 0604H</td>
<td>1552 1540</td>
</tr>
<tr>
<td>3</td>
<td>70 170</td>
<td>2.46 2.44</td>
<td>406.50 409.84</td>
<td>390.24 590.4</td>
<td>05FCH 05F0H</td>
<td>1532 1520</td>
</tr>
<tr>
<td>4</td>
<td>60 140</td>
<td>2.45 2.41</td>
<td>408.16 414.94</td>
<td>489.60 896.4</td>
<td>05F8H 05E0H</td>
<td>1528 1504</td>
</tr>
<tr>
<td>5</td>
<td>100 190</td>
<td>2.41 2.37</td>
<td>414.94 421.94</td>
<td>896.40 1316.4</td>
<td>05E0H 05C4H</td>
<td>1504 1476</td>
</tr>
</tbody>
</table>
Figure 2.13 $V_x$ (Ch#1), $V_z$ ($T_x = 2.46$ ms and $f_x = 406.5$ Hz) at 390.24 r/min (Ch#2), when the armature voltage (Ch#3) is 70 V (acceleration mode before switching).

**Figure 2.14** Output of microcontroller (05FCH) on 16 digital channels (D15-D0) of DSO ($T_z = 2.46$ ms and $f_z = 406.5$ Hz) at 390.24 r/min (acceleration mode before switching).
Figure 2.15 $V_r$ (Ch#1), $V_z$ ($T_z = 2.44$ ms and $f_z = 409.84$ Hz) at 590.4 r/min (Ch#2), when the armature voltage (Ch#3) is 170 V (acceleration mode after switching).

Figure 2.16 Output of microcontroller (05F0H) on 16 digital channels (D15-D0) of DSO ($T_z = 2.44$ ms and $f_z = 409.84$ Hz) at 590.4 r/min (acceleration mode after switching).
Figure 2.17 $V_r$ (Ch#1), $V_x$ ($T_z = 2.45$ ms and $f_z = 408.16$ Hz) at 489.6 r/min (Ch#2), when the armature voltage (Ch#3) is 60 V (acceleration mode before switching).

Figure 2.18 Output of microcontroller (05F8H) on 16 digital channels (D15-D0) of DSO ($T_z = 2.45$ ms and $f_z = 408.16$ Hz) at 489.6 r/min (acceleration mode before switching).
Figure 2.19  $V_r$ (Ch#1), $V_d$ ($T_z = 2.41$ ms and $f_z = 414.94$ Hz) at 896.4 r/min (Ch#2), when the armature voltage (Ch#3) is 140 V (acceleration mode after switching).

Figure 2.20  Output of microcontroller (05E0H) on 16 digital channels (D15-D0) of DSO ($T_z = 2.41$ ms and $f_z = 414.94$ Hz) at 896.4 r/min (acceleration mode after switching).
Figure 2.21 $V_x$ (Ch#1), $V_z$ ($T_z = 2.41$ ms and $f_z = 414.94$ Hz) at 896.4 r/min (Ch#2), when the armature voltage (Ch#3) is 100 V (acceleration mode before switching).

Figure 2.22 Output of microcontroller (05E0H) on 16 digital channels (D15-D0) of DSO ($T_z = 2.41$ ms and $f_z = 414.94$ Hz) at 896.4 r/min (acceleration mode before switching).
Figure 2.23 $V_1$ (Ch#1), $V_2$ (Ch#2), when the armature voltage (Ch#3) is 190 V (acceleration mode after switching).

Figure 2.24 Output of microcontroller (05C4H) on 16 digital channels (D15-D0) of DSO ($T_z = 2.37$ ms and $f_z = 421.94$ Hz) at 1316.4 r/min (acceleration mode after switching).
2.4.3 Deceleration Mode

For the deceleration mode, the circuit shown in Figure 2.1 is slightly modified (highlighted by bold lines) as shown in Figure 2.25. Initially, the SW is kept closed and the armature winding of the dc motor is directly energized by a dc voltage source. The dc motor is allowed to run at an arbitrary armature voltage (40 V) and an arbitrary speed. At this speed, Tz is recorded which is 2.47 ms (fz = 404.86 Hz) as shown in Figure 2.26. Tz is also measured by the microcontroller, which gives a digital value 0604H corresponding to 2.47 ms (Figure 2.27). According to (2.3), the speed corresponding to this time period is 291.6 r/min. To decelerate the motor, the SW is opened. The speed and fz decrease instantly. Finally, the motor becomes standstill and Tz becomes equal to 2.50 ms (fz = 400 Hz) as shown in Figure 2.28. Tz is also measured by the microcontroller which gives a digital output 0618H corresponding to 2.50 ms (Figure 2.29).

![Figure 2.25 RMF based speed measurement setup in deceleration mode.](image-url)
Figure 2.26 $V_1$ (Ch#1), $V_2$ ($T_z = 2.47$ ms and $f_z = 404.86$ Hz) at 291.6 r/min (Ch#2), and the armature voltage (Ch#3) is 40 V before switching and 0 V after switching (deceleration mode).

Figure 2.27 Output of microcontroller (0604H) on 16 digital channels (D15-D0) of DSO ($T_z = 2.47$ ms and $f_z = 404.86$ Hz) at 291.6 r/min before switching (deceleration mode).
Figure 2.28 $V_r$ (Ch#1), $V_x$ ($T_x = 2.5$ ms and $f_x = 400$ Hz) at 0 r/min (Ch#2), when armature voltage (Ch#3) becomes zero after switching (deceleration mode).

Figure 2.29 Output of microcontroller (0618H) on 16 digital channels (D15-D0) of DSO ($T_x = 2.5$ ms and $f_x = 400$ Hz) at 0 r/min after switching (deceleration mode).
The program of microcontroller for the fast measurement of $T_z$ is given in Appendix A.2 and the flow chart of program is described as follows.

1. PIC 16F877A, an 8 bit microcontroller from Microchip is used for the measurement of time period of the square wave signal from ZCD.
2. OPTION_REG register is initialized for RB0 interrupt for every rising edge on the RB0 pin of port B.
3. Output is a 16 bit digital signal. Since all I/O ports are 8 bits, Port C and Port D are made output ports.
4. Enable the Global Interrupt Enable bit (GIE) and RB0/INT External Interrupt Enable bit (INTE). RB0/INT External Interrupt Flag bit (INTF) is cleared for RB0 interrupt to occur. All these bits are in INTCON register.
5. Pause till interrupt occurs.
6. When an interrupt occurs, check whether the interrupt is due to RB0, by checking the status of INTF bit of INTCON register.
7. For RB0 interrupt, move the value of TMR1L to PORTC and move the value of TMR1H to PORTD.
8. Initialize the TIMER1 in T1CON register.
9. Start the TIMER1.
10. Return from the interrupt routine.

### 2.4.5 Comparison with Time Response of Tachogenerator

The results of the proposed method are also compared with the response of a dc tachogenerator which generates 24.3 mV per r/min (Appendix A.2). Figures [2.31(a)-(d)] show the variation in time response of tachogenerator in acceleration mode for different speed. It is evident that the response of dc tachogenerator is slow and it takes sufficiently large time to show the change in speed. It is due to spikes at commutator segments which are low at lower speed [Figures 2.31 (a)-(b)] and becomes high at higher speed [Figures 2.31 (c)-(d)]. A significant variation in the output voltage of dc tachogenerator [Figure 2.31 (a)] is not
available unless armature moves to the next position of commutator segment. For example, in this case, the initial speed before switching is 96.39 r/min. Thus,

the time for one revolution = 60/96.39 = 0.62247 s
the time to pass (past) one commutator segment = 0.62247/12 = 51.8726 ms

Therefore at this speed, the maximum resolution of the measurement (time period) is 51.8726 ms for this dc tachogenerator. However, the proposed measurement system senses the change in speed immediately and gives the response accordingly within 2.5 ms. The response time of measurement is found by DSO records (Figures 2.9 and 2.11) for the proposed method and for the dc tachogenerator (Figures 2.31 and 2.32) which are tabulated in Table 2.2. Moreover, a significant amount of noise is present in the output dc voltage of tachogenerator which is evident from Figures 2.31 and 2.32. A smoothening filter is therefore required at the output which would further increase the delay in its response time. The rubber coupling between tachogenerator and motor may also cause the delay in response time. The complete setup of the measurement system is shown in Figure 2.33.
Figures 2.31 (a)-(d) Step change in input dc voltage (Ch#1), and time response of tachogenerator (Ch#2) for different variation in speed (acceleration mode).

Figure 2.32 Step change in input dc voltage (Ch#1) and time response of tachogenerator (Ch#2) for variation in speed (deceleration mode).
Table 2.2 Time response of proposed method and dc tachogenerator in acceleration mode and deceleration mode

<table>
<thead>
<tr>
<th>S. No.</th>
<th>( T_z ) measured by DSO (ms)</th>
<th>( f_z = 1/T_z ) (Hz)</th>
<th>Related frequency</th>
<th>Actual speed [from (3)] (r/min)</th>
<th>Speed variation (r/min) ( (S2 - S1) )</th>
<th>Output of dc tachogenerator ( V_{dc} )</th>
<th>Speed variation ( V_{dc}/0.0243 ) (r/min)</th>
<th>Settling time (s)</th>
<th>Proposed Scheme (ms)</th>
<th>Dc Tachogenerator (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.49</td>
<td>2.47</td>
<td>401.61</td>
<td>404.86</td>
<td>96.39</td>
<td>291.60</td>
<td>195.21</td>
<td>4.72</td>
<td>194.24</td>
<td>1.44</td>
</tr>
<tr>
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<td>2.46</td>
<td>2.44</td>
<td>406.50</td>
<td>409.84</td>
<td>390.00</td>
<td>590.40</td>
<td>200.40</td>
<td>4.88</td>
<td>200.82</td>
<td>1.46</td>
</tr>
<tr>
<td>3</td>
<td>2.45</td>
<td>2.41</td>
<td>408.16</td>
<td>414.94</td>
<td>489.60</td>
<td>896.40</td>
<td>406.80</td>
<td>9.80</td>
<td>403.29</td>
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<td>2.37</td>
<td>414.94</td>
<td>421.94</td>
<td>896.40</td>
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<td>420.00</td>
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<td>419.75</td>
<td>2.96</td>
</tr>
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<td>5</td>
<td>2.47</td>
<td>2.50</td>
<td>404.86</td>
<td>400.00</td>
<td>291.60</td>
<td>0</td>
<td>291.60</td>
<td>7.04</td>
<td>289.71</td>
<td>2.20</td>
</tr>
</tbody>
</table>
2.5 Conclusion

In this chapter, a novel contact type RMF based measurement technique is proposed which provides fast measurement of speed and deviation in speed while retaining high accuracy. The change in speed, changes the frequency of induced EMF in the rotor circuit of synchro instantly which is monitored by the change in pulse width corresponding to the time period. As the RMF rotates at a high speed (24000 r/min) for an input voltage frequency of 400 Hz, the measurement of speed and the deviation in speed are sensed in the very next cycle of the induced EMF (within 2.5 ms). In comparison to a dc tachogenerator, the time response of proposed method is very fast and the measurement is more accurate which is directly related to the frequency of rotor EMF of synchro. A microcontroller is also used for the measurement of speed and the variation in speed to give a 16-bit digital output, which also confirms the accuracy and the fast response of proposed method. The digital output of the microcontroller can be used as a feedback signal for controlling the speed and deviation in speed accurately. For fast speed motors, the resolution may be increased to a very high value by utilizing 32-bit digital output signal of microcontroller or by increasing the frequency of the input voltage which generates the RMF. However, practically the frequency of the input
ac voltage and current which produces RMF is restricted by the magnetic material of the synchro. For example, a synchro made of silicon steel can be used up to 400 Hz effectively. The high accuracy of measurement of the proposed technique is also successfully applied for calibration of different contact type and non-contact type tachometers and described in the following chapter.
3.1 Introduction

Fast and accurate method is also required for the calibration of tachometers. Different types of tachometers which include contact type, non-contact type, and both analog and digital tachometers are being used for speed measurement in the industries as well as laboratories. The calibration of a tachometer refers to comparing its readings (speed) with a more accurate (standard) speed measuring instrument whose accuracy should be at least four times better than the tachometer being calibrated [52]-[53]. The tachometers are manufactured by physical materials and they are used in the real world of humidity, heat, physical stress, noise and vibrations etc., hence their performance gets affected and deteriorates. Moreover the magnetic field strength of a dc tachometer as well as tachogenerator decreases due to aging effect. Therefore for accurate speed measurement and feedback control applications, a regular calibration of these devices is necessary according to manufacturer’s specifications. The main benefits of a calibrated tachometer include uniformity between measurements, assurance of measurement accuracy, and reduction in measurement errors.

Usually, instead of providing the error curve for the whole speed range, the manufacturers of tachometers supply the data of Absolute Error or Guarantee Error for a range of speed. For an analog tachometer which is calibrated by the
proposed method, the Maximum Point-Error provided by the manufacturer at different speed is given as [60]

<table>
<thead>
<tr>
<th>Speed of Tachometer #1</th>
<th>Point error</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 r/min</td>
<td>± 3 r/min</td>
</tr>
<tr>
<td>600 r/min</td>
<td>± 6 r/min</td>
</tr>
<tr>
<td>900 r/min</td>
<td>± 9 r/min</td>
</tr>
<tr>
<td>1500 r/min</td>
<td>± 10 r/min</td>
</tr>
<tr>
<td>3000 r/min</td>
<td>± 15 r/min</td>
</tr>
<tr>
<td>4500 r/min</td>
<td>± 23 r/min</td>
</tr>
</tbody>
</table>

The data does not tell anything about the error in between two given speeds. Similarly, the error of a digital non-contact tachometer is specified by the manufacturer as [62]

<table>
<thead>
<tr>
<th>Speed of Tachometer #2</th>
<th>Point error</th>
</tr>
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<tr>
<td>5 – 500 r/min</td>
<td>± 1 r/min</td>
</tr>
<tr>
<td>1000 r/min</td>
<td>± 5 r/min</td>
</tr>
<tr>
<td>2000 r/min</td>
<td>± 10 r/min</td>
</tr>
<tr>
<td>4000 r/min</td>
<td>± 20 r/min</td>
</tr>
<tr>
<td>8000 r/min</td>
<td>± 40 r/min</td>
</tr>
</tbody>
</table>

This does not indicate the actual error of measurement for the speed between specified ranges. The accuracy of measurement is also specified by the manufacturer's Guarantee Error in terms of percentage of full scale reading (FSR) for the entire range of speed. Hence, the absolute error remains same for the whole range of measurement. Consequently, at lower range, the percentage of error becomes significantly high. For a digital contact type tachometer with 5 digit display, the error at the maximum speed of 10000 r/min is 6 r/min (± 0.05 % + 1digit) [61]. However, for a lower speed of 10 r/min, the error (± 6 r/min)
becomes 60 %. Hence, it becomes necessary to calibrate the tachometer for the whole range to obtain the accuracy of measurement at any desired speed.

In this chapter, the proposed scheme (Figure 2.25) is used for the calibration of tachometers. For calibration of tachometers, the measurement is based on the fundamental principle of electromagnetic theory where the frequency of the induced EMF in the rotor circuit of synchro is directly proportional to the speed of rotating member [94]. Therefore, the proposed method of measurement can be used for the calibration of tachometers. Three different types of tachometers (an analog/mechanical type, a digital non-contact type, and a digital contact type) are calibrated with the proposed scheme. The detailed specifications of these tachometers are given in Appendix A.3. The calibration curves are also drawn for lower and higher speed ranges. The results of calibration are compared with the data specification sheets of these tachometers.

### 3.2 Realization of Scheme for the Calibration of Tachometers

It is evident from the equation (2.3), as discussed in chapter 2, that there is a unique output frequency for a particular speed of rotor of synchro or the rotating member. Therefore, for the calibration of tachometers, for a particular speed \( n_r \), the exact frequency \( f_r (f_r = f_i) \) of signal \( V_i \) is found using (2.3). Thereby, the actual time period \( (T_z = 1/f_z) \), is calculated for this speed (actual value). The rotating member (dc motor) is allowed to run and its speed is controlled by varying the voltage across the armature winding using the external resistance \( R_{ex} \) (Figure 2.25). For 100 r/min, the exact time period is 2.4896 ms according to (2.3). Now, by varying the speed of the dc motor, \( T_z \) is set accurately, equal to the exact time period i.e. 2.4896 ms. Thus, the speed of the dc motor becomes exactly equal to 100 r/min. The waveform at this condition is recorded by DSO and shown in Figure 3.1 (b).

Although the measurement technique is simple which is based on fundamental principle of frequency measurement. However, a negligible amount
of error may be introduced in the measurement due to a slight deviation in the frequency of signal generator and due to the measurement error of DSO. Here, a very high resolution, arbitrary function generator (Tektronix, AFG-2022 B) is used with an error of ± 1 ppm, ± 1 μHz at 0 to 50 °C [97]. Likewise, the DSO used (LeCroy, MSO-10MXs-B4), has the sampling rate of 10 GS/s with an update rate up to 22000 waveforms/s [98]. Moreover, the DSO has a very high resolution and measures Tz accurately up to nine decimal places [Figures 3.1 (a)-(e)]. At higher speed, the high frequency noise signals, superimposed over Vr, introduce error in the measurement of Tz. These noise signals are removed from Vr using a low pass filter (π filter) with a cut-off frequency of 478 Hz \( f_c = 1/(2\pi RC) \), \( R = 3.33 \) kΩ, \( C = 0.1 \) μF. It is also evident from figure 2.15, 2.21, 2.23 and 3.1 (e) that the measurement of output voltage of synchro is unaffected even in the presence of noise and spikes over large extent due to square wave shape of the output voltage of ZCD. As all the measurements are done with the output signal of ZCD instead of the ac output of synchro, hence, \( V_z \) and the measurement of \( T_z \) remain unaffected.

Three different types of tachometers (an analog/mechanical type, a digital non-contact type, and a digital contact type) are calibrated with the proposed method. The experiment is carried out for different speed of dc motor [Figures 3.1 (a)-(e)]. The readings of these three tachometers deviate from the actual speed as shown in Table 3.1 and the errors are shown in Figure 3.2. The percentage errors shown in Fig. 3.2 are calculated using basic relationship [22], [53].

\[
\text{Percentage Error} = \frac{(\text{Observed speed} - \text{Actual speed})}{\text{Actual speed}} \times 100
\]

where, the actual speed is the measured speed by proposed method and the observed speed is the measured speed by tachometers #1, #2, and #3 respectively.
LeCroy MSO-104MXs-B Mixed Signal Oscilloscope

(a)

(b) Set time period $T_2$ of signal $V_2$

THESIS
(c)

(d)

48
Figure 3.1 (a)-(e) $V_r$ (Ch#2), and the exact set time period $T_z$ (Ch#3) for (a) 0 r/min, (b) 100 r/min, (c) 200 r/min, (d) 300 r/min and (e) 600 r/min.

Figure 3.2 Errors of different tachometers under test.
### Table 3.1: Performances of the Tachometers under Test

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Actual speed of dc motor (r/min)</th>
<th>Exact frequency ( f_x ) (Hz)</th>
<th>Set time period ( T_x ) (ms)</th>
<th>Speed measured by analog/mechanical tachometer #1 (r/min)</th>
<th>Error of analog/mechanical tachometer #1 (%)</th>
<th>Speed measured by digital non-contact type tachometer #2 (r/min)</th>
<th>Error of digital non-contact type tachometer #2 (%)</th>
<th>Speed measured by digital contact type tachometer #3 (r/min)</th>
<th>Error of digital contact type tachometer #3 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>400.0000</td>
<td>2.5000</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>401.6666</td>
<td>2.4896</td>
<td>105</td>
<td>5.00</td>
<td>101.8</td>
<td>1.80</td>
<td>103.7</td>
<td>3.70</td>
</tr>
<tr>
<td>3</td>
<td>200</td>
<td>403.3333</td>
<td>2.4793</td>
<td>198</td>
<td>-1.00</td>
<td>194.7</td>
<td>-2.65</td>
<td>193.8</td>
<td>-3.10</td>
</tr>
<tr>
<td>4</td>
<td>300</td>
<td>405.0000</td>
<td>2.4691</td>
<td>309</td>
<td>3.00</td>
<td>302.8</td>
<td>0.93</td>
<td>305.1</td>
<td>1.70</td>
</tr>
<tr>
<td>5</td>
<td>400</td>
<td>406.6666</td>
<td>2.4590</td>
<td>404</td>
<td>1.00</td>
<td>405.5</td>
<td>1.25</td>
<td>403.2</td>
<td>-0.80</td>
</tr>
<tr>
<td>6</td>
<td>500</td>
<td>408.3333</td>
<td>2.4489</td>
<td>505</td>
<td>1.00</td>
<td>495.6</td>
<td>-0.88</td>
<td>492.2</td>
<td>-1.60</td>
</tr>
<tr>
<td>7</td>
<td>600</td>
<td>410.0000</td>
<td>2.4390</td>
<td>610</td>
<td>1.67</td>
<td>602.7</td>
<td>0.45</td>
<td>596.9</td>
<td>-0.52</td>
</tr>
<tr>
<td>8</td>
<td>700</td>
<td>411.6666</td>
<td>2.4291</td>
<td>702</td>
<td>0.24</td>
<td>695.0</td>
<td>-0.71</td>
<td>687.4</td>
<td>-1.80</td>
</tr>
<tr>
<td>9</td>
<td>800</td>
<td>413.3333</td>
<td>2.4193</td>
<td>810</td>
<td>1.25</td>
<td>802.0</td>
<td>0.25</td>
<td>796.3</td>
<td>-0.46</td>
</tr>
<tr>
<td>10</td>
<td>1000</td>
<td>416.6666</td>
<td>2.4000</td>
<td>1010</td>
<td>1.00</td>
<td>994.0</td>
<td>-0.60</td>
<td>990.4</td>
<td>-0.96</td>
</tr>
<tr>
<td>11</td>
<td>1200</td>
<td>420.0000</td>
<td>2.3809</td>
<td>1208</td>
<td>0.66</td>
<td>1206.6</td>
<td>0.55</td>
<td>1187.0</td>
<td>-1.08</td>
</tr>
</tbody>
</table>
Experiments are carried out further at specified low speed range (0-200 r/min) and at high speed range (800-1000 r/min) with the steps of 50 r/min. These results are tabulated in Tables 3.2 and 3.3. Figures 3.3 and 3.4 show the deviation of the measured values (speed) in these ranges.

**Table 3.2: Performance of tachometers under test (low speed range)**

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Actual speed of motor (r/min)</th>
<th>Exact frequency $f_x$ (Hz)</th>
<th>Set time period $T_x$ (ms)</th>
<th>Speed measured by analog/mechanical tachometer #1 (r/min)</th>
<th>Speed measured by digital non-contact type tachometer #2 (r/min)</th>
<th>Speed measured by digital contact type tachometer #3 (r/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>400.0000</td>
<td>2.5000</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>400.8333</td>
<td>2.4948</td>
<td>54</td>
<td>56.2</td>
<td>57.9</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>401.6666</td>
<td>2.4896</td>
<td>105</td>
<td>101.8</td>
<td>103.7</td>
</tr>
<tr>
<td>4</td>
<td>150</td>
<td>402.5000</td>
<td>2.4844</td>
<td>160</td>
<td>158.0</td>
<td>158.7</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>403.3333</td>
<td>2.4793</td>
<td>198</td>
<td>194.7</td>
<td>193.8</td>
</tr>
</tbody>
</table>

**Table 3.3: Performance of tachometers under test (high speed range)**

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Actual speed of motor (r/min)</th>
<th>Exact frequency $f_x$ (Hz)</th>
<th>Set time period $T_x$ (ms)</th>
<th>Speed measured by analog/mechanical tachometer #1 (r/min)</th>
<th>Speed measured by digital non-contact type tachometer #2 (r/min)</th>
<th>Speed measured by digital contact type tachometer #3 (r/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>800</td>
<td>413.3333</td>
<td>2.419</td>
<td>810</td>
<td>802.0</td>
<td>796.3</td>
</tr>
<tr>
<td>2</td>
<td>850</td>
<td>414.1666</td>
<td>2.414</td>
<td>856</td>
<td>842.1</td>
<td>844.8</td>
</tr>
<tr>
<td>3</td>
<td>900</td>
<td>415.0000</td>
<td>2.409</td>
<td>918</td>
<td>907.4</td>
<td>903.5</td>
</tr>
<tr>
<td>4</td>
<td>950</td>
<td>415.8333</td>
<td>2.404</td>
<td>961</td>
<td>953.4</td>
<td>947.2</td>
</tr>
<tr>
<td>5</td>
<td>1000</td>
<td>416.6666</td>
<td>2.400</td>
<td>1010</td>
<td>994.0</td>
<td>990.4</td>
</tr>
</tbody>
</table>
Figure 3.3 Comparison of tachometers at lower speed range.

S1- Actual (Exact)
S2- Analog/Mechanical tachometer #1
S3- Digital non-contact type tachometer #2
S4- Digital contact type tachometer #3

Figure 3.4 Comparison of tachometers at higher speed range.
3.3 Conclusion

The experimental results of errors of the tachometer are summarized in Table 3.4. It clearly shows the variation in error from the manufacturer’s specifications. Thus using the calibration curve, the proposed method can be used to obtain the accurate speed at any desired value, as in general, manufacturers do not provide errors curve for all speed range.

**Table 3.4** Comparison of the errors of tachometers under test with proposed method.

<table>
<thead>
<tr>
<th>Tachometers</th>
<th>Manufacturers specification</th>
<th>Experimentally found by proposed method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tachometer # 1</td>
<td>± 3 r/min for 300 r/min</td>
<td>± 2 r/min to ± 10 r/min for 0 to 1200 r/min</td>
</tr>
<tr>
<td></td>
<td>± 10 r/min for 1200 r/min</td>
<td></td>
</tr>
<tr>
<td>Tachometer # 2</td>
<td>± 1 r/min for 5 to 1200 r/min</td>
<td>± 2 r/min to ± 6 r/min for 0 to 1200 r/min</td>
</tr>
<tr>
<td>Tachometer # 3</td>
<td>± 7 r/min for 5 to 1200 r/min</td>
<td>± 3 r/min to ± 13 r/min for 0 to 1200 r/min</td>
</tr>
</tbody>
</table>

The proposed method is used for the calibration of different tachometers which includes contact type, non-contact type, and both analog and digital tachometers. Significant errors of the order of 5% are found in these tachometers using the proposed method. The error of analog contact type tachometer provided in the data specification sheet varies from ± 3 r/min to ± 10 r/min, in the range of
300 r/min to 1200 r/min [60]. The errors found by the proposed method are ± 2 r/min to ± 10 r/min, over this range. The accuracy of digital non-contact type tachometer is ± 1 r/min in the range of 5 r/min to 1200 r/min, according to calibration report provided with the tachometer [62]. Whereas, the error found by the proposed method is ± 2 r/min to ± 6 r/min in this range. Similarly, the error (Guarantee Error) of digital contact type tachometer is claimed as ± 7 r/min for the entire range of 5 r/min to 1200 r/min, according to manufacturer’s data specification sheet [61]. However, the error found by the proposed method is ± 3 r/min to ± 13 r/min in this range.
Chapter 4

Very Fast Measurement of Low Speed of Rotating Machines Using Rotating Magnetic Field

4.1 Introduction

Sophisticated speed control applications require very fast and accurate speed measurement. It is one of the important requirements of low speed machines like rotors of cement kilns, rolling machines in paper mills, mining industries, textile mills and heavy stone crushing machines etc, where the speed varies from 0 to 10 r/min [1]-[4]. The measurement at low speed becomes very difficult due to the slow response of transducers. At low speed (below 10 r/min), normally transducers take several seconds to give the required output signal [14]-[16]. Therefore, the existing techniques are not suitable where fast feedback signals are required for control applications.

In the proposed technique, as explained in chapter 2, a fast RMF is used to measure the speed as well as deviation in speed for low-speed machines. A three-phase balanced voltage supply is realized with the help of a stable arbitrary function generator and a single-phase to three-phase convertor using three power amplifiers. The three windings placed on the stator of the synchro are energized by this three-phase balanced voltage/current. They create RMF in the air gap which links with the rotor circuit of the synchro and generates an EMF in it [99]-
The rotor of the synchro is mechanically coupled with a rotating member. Both the magnitude and frequency of the output voltage at the rotor circuit of synchro depend upon the speed and difference in speed. The effect of variation in the magnitude of the output voltage is eliminated by using a ZCD in open-loop mode at the output. Here, the speed of the rotor of synchro or rotating member (three-phase induction motor) is few r/min only, whereas, the speed of RMF is 2400 r/min for a supply frequency of 40 Hz. At this frequency, for each revolution of the rotating member, the RMF rotates 2400 times. Thus the deviation in the speed of rotor is quickly picked up by the RMF which causes a fast deviation in frequency of the rotor voltage. Hence the measurement, even at 1 r/min, becomes extremely fast. The proposed scheme is tested successfully from 1 r/min to 10 r/min and the results of measurements are compared with a conventional method (techogenerator) which shows the fast response of proposed method. The output is also obtained in terms of dc voltage and dc current, which can be used for feedback and control applications.

4.2 Realization of the Scheme for Fast Measurement of Low Speed

Figure 4.1 shows the set up for the realization of low speed measurement. To realize low speed from 0 to 10 r/min, a three-phase induction motor (as a prime mover) is connected to an adjustable frequency ac drive system (Appendix A.4). On one side of the prime mover the synchro is connected whereas on the other side a dc tachogenerator is connected for comparison of measurement of speed simultaneously.

Figure 4.2 shows the circuit for the realization of balanced three-phase voltages for stator winding of synchro. This circuit has been given in chapter 2 as Figure 2.2, is redrawn here for ready reference. Here, a sine wave signal of 40 Hz (18.8 V peak-to-peak) from a stable arbitrary function generator (F.G) is supplied to a centre-tapped transformer (Figure 4.3). The output of transformer is applied to an RC network (R=100 kΩ and C = 0.1μF), to generate three phase, 40 Hz
voltages $V_1$, $V_2$, and $V_3$ (Figure 4.4). These voltages are attenuated to a value of about 150 mV [$V_4$, $V_5$, and $V_6$ (Figure 4.5)], before feeding into three audio power amplifiers (LM 384N). The outputs of these amplifiers, $V_7$, $V_8$ and $V_9$ with frequency $f_s$ are in turn applied to the stator winding of synchro and marked as $V_s$ (Figure 4.1). Therefore at stationary condition, a sinusoidal signal $V_r$ with frequency $f_r$ (40 Hz) is generated at the rotor winding of synchro (Figure 4.6).

Figure 4.1 RMF based low speed measurement setup.

Figure 4.2 Single-phase to three-phase conversion system to generate balanced three-phase voltages $V_7$, $V_8$ and $V_9$ for stator winding of synchro.
Figure 4.3 Sine wave signals of 40 Hz from a stable arbitrary function generator (CH#1) and output of centre-tapped transformer (CH#2 and Ch#3).

Figure 4.4 Three phase voltages, $V_1$, $V_2$, and $V_3$ at the output of RC network (CH#1, CH#2 and Ch#3)
Figure 4.5 Waveforms $V_4$, $V_5$, and $V_6$ applied at the input of power amplifiers (CH#1, CH#2 and Ch#3 respectively).

Figure 4.6 $V_7$ (CH#1), $V_8$ (CH#2) and $V_9$ (Ch#3) with frequency $f_s$, applied to stator winding of synchro as $V_s$, and rotor voltage $V_7$ (CH#4) with frequency $f_r$. 
4.3 Experimental Results

4.3.1 When the Rotating Member Is Stationary

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 (Figure 4.6). 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 Figure 4.7. The negative going transition (NGT) of signal $V_R$ is used to trigger a one shot monostable multi-vibrator (OS, 74LS121N) to produce a signal $Q$ of a stable fixed positive width $T_{Q+}$ of 12.5 ms, as shown in Figure 4.8. These two signals ($V_R$ and $Q$) are applied to an EX-OR gate (G-1). The output of G-1 becomes high as the negative width $(T_{Q-})$ of the signal $V_R$ is equal to positive width $(T_{Q+})$ of signal $Q$ and vice versa. This is also explained using (2.3), which is re-written here for easy reference as (4.1).

Figure 4.7 Output voltage of rotor, $V_r$ (Ch#1) and output of ZCD, $V_R$ (Ch#2) at 40 Hz.
\[ f_r = f_s \pm \frac{n_r P}{120} \quad (4.1) \]

\( f_r \) = Frequency of induced EMF (\( V_r \)) of rotor of synchro
\( f_s \) = Frequency of stator voltage (\( V_s \)) 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
\( T_{WR-} \) = Negative 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
\( T_{WG-} = T_{WR-} - T_{WQ+} \)

Consider the case when the rotating member is stationary (i.e. \( n_r = 0 \) r/min)

From (4.1), it can be observed that \( f_R = f_r = f_s = 40 \) Hz

Therefore, \( T_R = \frac{1}{f_R} = 25 \) ms

\( T_{WR-} = \frac{T_R}{2} = 12.5 \) ms

\( T_{WQ+} = 12.5 \) ms

\( T_{WG-} = T_{WR-} - T_{WQ+} \)

\( T_{WG-} = 12.5 - 12.5 \)

\( T_{WG-} = 0 \)

Thus, the output of EX-OR gate G-1 = 1 (HIGH).

The wave forms \( V_r \), \( V_R \), \( Q \), and \( T_{WG-} \) are also shown in the DSO records (Figure 4.9).
Output of EX-OR gate G-1, $T_{WG-} = 0$

**Figure 4.8** Waveforms of signals, $V_R$, $Q$ and output $T_{WG-}$.

**Figure 4.9** Output of the rotor $V_r$ of synchro (Ch#1), $V_R$ with $T_{WR-}$ (Ch#2), signal $Q$ with $T_{WQ+}$ (Ch#3), and output $T_{WG-}$ of G-1 (Ch#4), at stationary condition.
4.3.2 *When the Rotating Member Rotates in the Clockwise Direction (f_R Decreases)*

When the rotating member crawls to a low speed in clockwise direction, the frequency f_r of the induced EMF V_r in the rotor circuit of synchro decreases. The time period T_R or (1/f_R) and, hence, the negative width T_WR- of signal V_R at the output of ZCD increases accordingly. The NGT 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, as shown in Figure 4.10. The duration of this pulse depends on the speed of rotation of rotor and is obtained using (4.1)

*When n_r = 1 r/min (rotation is clockwise)*

\[
\begin{align*}
  f_s &= 40 \text{ Hz} \\
  \text{Using (4.1), } f_r &= f_r = 40 - \frac{1 \times 2}{120} \\
  f_r &= 39.983 \\
  T_R &= (1/f_R) = 25.010 \text{ ms} \\
  T_{WR-} &= T_R/2 = 12.505 \text{ ms} \\
  T_{WQ+} &= 12.5 \text{ ms} \\
  T_{WG-} &= T_{WR-} - T_{WQ+} \\
  T_{WG-} &= 12.505 - 12.5 \\
  T_{WG-} &= 5.211 \mu\text{s}
\end{align*}
\]

Figures 4.11(a)-(j) show the DSO records for a speed range, corresponding to 1-10 r/min in clockwise direction. These results are also tabulated in Table 4.1.
Figure 4.10 Waveforms of signals, $V_R$, $Q$ and output $T_{WG^-}$.
Figure 4.11 (a)-(j) Output voltage of rotor $V_r$ of synchro (Ch#1), $V_R$ with $T_{WR-}$ (Ch#2), signal Q with $T_{WO+}$ (Ch#3), and negative width ($T_{WG-}$) at the output of G-1, corresponding to 1-10 r/min (Ch#4), respectively.
Table 4.1: Theoretical and observed results of the test

<table>
<thead>
<tr>
<th>$T_{WQ+}$ ms</th>
<th>n_r r/min</th>
<th>$f_R$ ($V_R$) Hz Theoretical</th>
<th>$f_R$ ($V_R$) Hz Observed</th>
<th>$T_{R}$= $1/f_R$ ms Theoretical</th>
<th>$T_{WR-}$ = $T_{R}$/2 ms Theoretical</th>
<th>$T_{WR-}$ = $T_{R}$/2 ms Observed</th>
<th>$T_{WG-}$ (μs) = $T_{WR-}$ - $T_{WQ+}$ Theoretical</th>
<th>$T_{WG-}$ (μs) = $T_{WR-}$ - $T_{WQ+}$ Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5</td>
<td>0</td>
<td>40</td>
<td>40.000</td>
<td>25.00</td>
<td>12.50</td>
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<td>0</td>
</tr>
<tr>
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<td>1</td>
<td>39.983</td>
<td>39.982</td>
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<td>12.505</td>
<td>12.50</td>
<td>0.5211</td>
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<td>12.5</td>
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<td>39.95</td>
<td>39.948</td>
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<td>12.515</td>
<td>12.51</td>
<td>15.645</td>
<td>15.68</td>
</tr>
<tr>
<td>12.5</td>
<td>5</td>
<td>39.916</td>
<td>39.917</td>
<td>25.052</td>
<td>12.526</td>
<td>12.52</td>
<td>26.096</td>
<td>25.60</td>
</tr>
<tr>
<td>12.5</td>
<td>8</td>
<td>39.866</td>
<td>39.865</td>
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<td>12.54</td>
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</tr>
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<td>25.104</td>
<td>12.552</td>
<td>12.55</td>
<td>52.301</td>
<td>52.20</td>
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</tbody>
</table>

70
(b)

(c)
Figures 4.13 (a)-(j) Output of rotor $V_r$ of synchro (Ch#1), $V_R$ with $T_{WR-}$ (Ch#2), signal $Q$ with $T_{WO+}$ (Ch#3), and negative width ($T_{WG-}$) at the output of G-1, corresponding to 1-10 r/min (Ch#4), respectively.

Table 4.2: Theoretical and observed results of the test

<table>
<thead>
<tr>
<th>$T_{WO+}$ ms</th>
<th>$n_r$ r/min</th>
<th>$f_R (V_R)$ Hz Theoretical</th>
<th>$f_R (V_R)$ Hz Observed</th>
<th>$T_R = 1/f_R$ ms Theoretical</th>
<th>$T_{WR-} = T_R/2$ ms Theoretical</th>
<th>$T_{WR-} = T_R/2$ msObserved</th>
<th>$T_{WO+} - T_{WR-}$ (μs) Theoretical</th>
<th>$T_{WO+} - T_{WR-}$ (μs) Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5</td>
<td>0</td>
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<td>40</td>
<td>25</td>
<td>12.5</td>
<td>12.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>12.5</td>
<td>1</td>
<td>40.016</td>
<td>40.018</td>
<td>24.989</td>
<td>12.494</td>
<td>12.49</td>
<td>0.206</td>
<td>5.51</td>
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<td>40.034</td>
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<td>12.49</td>
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<td>40.05</td>
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<td>15.605</td>
<td>15.36</td>
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<td>40.083</td>
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<td>40.117</td>
<td>24.927</td>
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<td>12.46</td>
<td>36.352</td>
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<tr>
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<td>40.133</td>
<td>40.131</td>
<td>24.916</td>
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<td>12.46</td>
<td>41.528</td>
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<td>40.15</td>
<td>40.149</td>
<td>24.906</td>
<td>12.453</td>
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</tr>
<tr>
<td>12.5</td>
<td>10</td>
<td>40.166</td>
<td>40.166</td>
<td>24.896</td>
<td>12.448</td>
<td>12.45</td>
<td>51.867</td>
<td>51.35</td>
</tr>
</tbody>
</table>
4.3.4 Comparison with Time Response of Tachogenerator

In the experimental setup, an adjustable frequency ac drive is used to control the speed of an induction motor (Figure 4.14). At one side of the shaft of induction motor, a synchro is coupled, whereas on the other side, a dc tachogenerator is mounted and coupled. Thus, both transducers give the output signals for the same speed simultaneously. The adjustable frequency ac drive runs (in start mode) if its feedback terminals #1 and #2 are shorted. When these terminals are open, the voltage across them becomes equal to the internal source voltage (22.6 V), and the drive stops [101]. When the ac drive is set at 1 r/min, induction motor runs at a speed of 1 r/min and the mounted synchro and tachogenerator also crawls at 1 r/min. Corresponding to this speed, a dc voltage of 24.8 mV, as per specification of tachogenerator (2.42 V/100 r/min), is generated at its output and measured at CH#1 of DSO, whereas the voltage across terminals #1 and #2 of ac drive remains zero (measured at CH#2), as shown in Figure 4.15 (a). When the feedback terminals of ac drive open, the terminal voltage rises [a step change of 22.6 V in Figure 4.15 (a)], the rotor speed reduces quickly, and, finally it stops. The tachogenerator takes sufficiently large time to register the effects of speed variation and to give the output voltage accordingly. Here, the output voltage of the tachogenerator takes 656 ms to become zero. However, in case of the proposed method, it takes only 12.5 ms, as shown in Figures 4.13 (a)-(j). It may be noted that the variation in the output voltage of tachogenerator is not smooth at very low speed, and the noise level is quite high. The results of the measurement by dc tachogenerator for different speeds are shown in the DSO records [Figures 4.15 (a)-(c)].
Figure 4.14 Experimental setup for fast measurement of very low speed.
Figure 4.15(a)-(c) Output voltage of dc tachogenerator for 1, 4 and 7, r/min (CH#1), respectively, and output voltage across terminals #1 and #2 (CH#2).
The output pulses from the gate G-1 can also be used to generate dc output voltage or dc current. This dc output voltage or dc current may be used as feedback signals for control applications. The pulses from the gate G-1 are applied to an amplifier with averaging circuit (Figure 4.16), which produces an average dc voltage \( V_{dc} \). This average dc voltage for different speeds \( V_{dc} \) is calculated by (4.2) and (4.3) as described in Figure 4.17. A current feedback signal is also generated by connecting a resistance of high value, in series with an ammeter of \( \mu A \) range. The measured output dc voltages \( V_{dc} \) and currents \( I_{dc} \) of averaging circuit are given in Table 4.3. The waveforms are also recorded for a speed range, corresponding to 1-10 r/min, as shown in Figures 4.18 (a)-(j).

**Figure 4.16** Averaging circuit with amplifier.

**Figure 4.17** Waveforms to calculate the average value \( V_{dc} \) of pulses at the output of G-1.
\[ V_{dc} = \frac{t_{on}}{T} V_{\text{max}} \]  

(4.2)

\[ V_{dc} = t_{on} \cdot f \cdot V_{\text{max}} \]  

(4.3)

\[ T = \text{Time period of pulse at the output of G-1} \]

\[ t_{on} = \text{On time of pulse at the output of G-1} \]

\[ V_{\text{max}} = \text{Maximum amplitude of pulse at the output of G-1} \]

**Table 4.3**: Measured output dc voltages and currents of averaging circuit

| \( n_r \)  
<table>
<thead>
<tr>
<th>( r/min )</th>
<th>( f_R (V_R) ) Hz</th>
<th>( T_{WR-} (\mu s) = T_{WR-} - T_{WQ+} ) Observed</th>
<th>( V_{dc} ) (V) Theoretical</th>
<th>( V_{dc} ) (V) Observed</th>
<th>( I_{dc} ) (( \mu A )) Theoretical</th>
<th>( I_{dc} ) (( \mu A )) Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>40.00</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>39.98</td>
<td>5.44</td>
<td>0.21</td>
<td>0.24</td>
<td>5.4</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
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<td>10.56</td>
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<td>0.48</td>
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<td>11</td>
</tr>
<tr>
<td>3</td>
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<td>16</td>
<td>0.63</td>
<td>0.64</td>
<td>16.3</td>
<td>16.5</td>
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<tr>
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<td>0.83</td>
<td>0.88</td>
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<tr>
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<td>52.81</td>
<td>2</td>
<td>1.92</td>
<td>54.1</td>
<td>53</td>
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</table>
Figure 4.18 (a)-(j) Negative width of the signal $V_R$, $T_{WR}$ (Ch#1), signal $Q$ with $T_{WQ}$ (Ch#2), output $T_{WG}$ of G-1 (Ch#3), and output of amplifier and averaging circuit $V_{dc}$, corresponding to 1-10 r/min (Ch#4), respectively.
4.4 Conclusion

A novel synchro and RMF-based speed measurement technique has been successfully tested for very low speed. Fast measurement of low speed up to 1 r/min has been achieved by the proposed method. The rotor output of synchro (48 V, 2-pole, 3-phase, 50 Hz) has been used for this purpose, whose output varies like a pulse width modulated signal. A linear relationship is practically found in the speed and frequency from 1 to 10 r/min. The DSO records show that the measurement of speed is accomplished within few tens of ms. Even at 1 r/min, the speed is measured at the speed of RMF (40 Hz or 2400 r/min), which is 2400 times faster than the speed of the rotating member. While the RMF completes one revolution in the air gap in 25 ms, but due to the fast measuring mechanism (half-cycle measurement), the deviation in speed is even detected within 12.5 ms. The proposed method is also compared with a conventional tachogenerator method which confirms the fast measurement of speed. The output measurand is also made available in terms of dc voltage and dc current for control applications.
Chapter 5

Rotating Magnetic Field Based Measurement of Velocity and Acceleration of Seismic Vibrations

5.1 Introduction

Earthquake is one of the prime causes of natural disasters, human losses, technological disasters, damage to heavy building structures, water delivery systems and electric power installations. The earth crust is made up of several wide, thin and rigid plates like blocks which are in constant motion with respect to each other. A series of vibrations on the earth surface are produced by the generation of elastic seismic waves due to sudden rupture within the plates during the release of accumulated strain energy [63]. The seismic vibrations (main shock and foreshocks) consist of an adverse combination of extremely high contents of velocity and acceleration superimposed over a very low frequency wave. A number of methods, based on the measurement of velocity and acceleration of seismic vibrations have been reported in the literature [87]-[90]. Conventional instruments like seismometers and accelerometers, usually measure only one parameter that is acceleration and fail to record its peak values, with good accuracy [64]-[65]. Moreover, the response of existing or conventional methods of measurement of seismic vibrations is very slow, which is of the order of several seconds [75], [90]. The findings have also revealed that there is a strong resemblance in the pattern of foreshocks and main shock [70]-[74]. However, the
present measurement of foreshocks with resolution in seconds, does not give a
deep insight of the signatures of these small seismic vibrations [68]-[69]. Hence, a
systematic and high resolution measurement of velocity and acceleration of these
vibrations is required to interpret the pattern of waves and their anomalies
accurately which is useful for proper design of buildings and structures.

In the method proposed in this chapter, a fast RMF is used to generate an
EMF in the rotor circuit whose frequency depends upon the motion and/or
vibration of a stepper motor coupled to the rotor of a synchro. A microprocessor
based vibration generation system is developed to generate rocking motion and
vibrations similar to the seismic vibrations. The vibration system vibrates the
rotor of synchro back and forth, which ultimately varies the frequency and voltage
in its rotor circuit. Consequently, a train of pulses with variable pulse width
becomes available. A digital logic circuit is developed to measure the width of
these pulses to get the instantaneous velocity of vibrations \( (V_i) \). An averaging
circuit with amplifier is also developed to obtain the average velocity of vibrations in
terms of dc voltage. A micro ammeter is also calibrated to measure the average
velocity of vibrations in terms of dc current. The values of instantaneous
acceleration of vibrations \( (A_i) \) are obtained from the corresponding values of \( V_i \).
Moreover, along with an average value, the peak values of these quantities
(velocity and acceleration) are obtained which are useful in proper design of
earthquake resistant nuclear power plants, buildings and structures. Here, the
angular speed of the rotor of synchro corresponding to the seismic vibrations is in
the range of few r/min only, while the speed of RMF is 3000 r/min for a supply
frequency of 50 Hz. Therefore the measurement becomes very fast and the
resolution becomes very high. The high resolution measurement of small seismic
vibrations (foreshocks) is helpful in a better prediction of earthquakes.
5.2 Realization of Setup for the Measurement of Velocity of Seismic Vibrations

In the proposed technique, for the measurement of velocity and acceleration of seismic vibrations, a synchro is used whose rotor is attached with the vibration generation system (Figure 5.1). The three-phase stator winding of the synchro is energized by a 50 Hz voltage signal from a stable arbitrary function generator (F.G). This signal is supplied to a centre-tapped transformer whose output is applied to a single-phase to three-phase conversion circuit, consisting an RC network \( R=100 \, k\Omega \) and \( C = 0.1 \mu F \), to generate a balanced three-phase, 50 Hz voltages \( V_1, V_2, \) and \( V_3 \) (Figure 5.2). These three voltages are attenuated to a value of about 100 mV \( (V_4, V_5, \) and \( V_6) \), before feeding into three audio power amplifiers (LM 384N) as shown in Figure 5.3. The outputs of these three amplifiers, \( V_7, V_8 \) and \( V_9 \), are applied to the stator winding of synchro, to produce a sinusoidal signal \( V_r \) with frequency \( f_r \) in the rotor winding of synchro (Figure 5.4).

Figure 5.1 Microprocessor based vibration generation and measurement setup.
Figure 5.2 Single-phase to three-phase voltage conversion system.

Figure 5.3 Waveforms $V_4$, $V_5$, and $V_6$ at the input of power amplifiers (CH#1, CH#2 and CH#3).
Figure 5.4 Three phase voltages $V_7$, $V_8$, and $V_9$ at the stator winding of synchro (CH #1, CH #2, and Ch #3) and voltage at rotor winding of synchro $V_r$ (CH #4).

5.3 Experimental Results and Discussion

The seismic waves are generated by aircraft impacts, collapse of a large building, underground nuclear explosion and exploding dynamites. But these vibrations are not feasible or allowed for conducting tests. Another method which is generally used is to place a small brick work over a metal platform. That metal platform is given large vibrations using heavy electrical machinery. The instruments are attached with the brick work to study the behavior of vibrations. These instruments are connected to computers in order to record the output. Another method of seismic vibration generation being used in a research institution is by a Shake Table [102]. But these methods are very costly, difficult to realize, non portable, inaccurate and require large installation area and huge seismographic stations.

In order to mechanically simulate seismic vibrations in the laboratory, the records (velocity waveforms) of various earthquakes are investigated [87]-[90].
Some of these earthquake waveforms [2003 Lefkada (Greece), 1994 Northridge (USA), 1992 Landers (USA), 1987 Whittier Narrows (USA)] are taken as reference for the simulation of seismic vibrations [90], as shown in Figure 5.5 (a)-(d). A microprocessor based system is developed to practically realize vibrations which resemble seismic vibrations of these earthquakes. The microprocessor is programmed to control the movement of a stepper motor which generates vibrations with velocity in the range of -20 cm/s to +20 cm/s. The back and forth rotation of stepper motor generates a variable angular movement in both directions with a frequency of one Hz [Figure 5.6 (a)-(b)]. The generated vibrations are having a velocity and frequency similar to the reference seismic waveforms [90]. The stepper motor is coupled to the rotor of a synchro. The fast back and forth movement of different angular span, which resembles the seismic vibrations, is transmitted to the rotor of the synchro. Consequently, this angular movement varies the frequency/time period of rotor voltage of synchro. Thereby, a pulse train of variable pulse width is produced and recorded. Corresponding to the value of each pulse width, $V_1$ is calculated. A waveform with the variation of $V_1$ is shown in Figure 5.6 (a). The same waveform is shown at an enlarged scale in Figure 5.6 (b). This pattern resembles the velocity waveform patterns of earthquakes shown in Figure 5.5 (a)-(d), and confirms the validity of the proposed system for the measurement of actual seismic vibrations. For more clarity, the pattern of variation of $V_1$, over one cycle, covering a time span of 1 second is shown in Fig 5.7. The proposed method measures 50 values of $V_1$ in one second with a resolution of 20 ms, whereas the resolution of existing methods is in the range of seconds (Figure 5.5). Therefore, it captures those peaks of velocity of vibrations (within 20 ms) which are often missed by conventional measurement systems due to their poor resolution. The details of experiment for generation and measurement of $V_1$ are explained in the following section.
Figure 5.5 (a)-(d) Velocity waveforms of seismic vibrations of earthquakes [2003 Lefkada (Greece), 1994 Northridge (USA), 1992 Landers (USA), and 1987 Whittier Narrows (USA)].
Figure 5.6 (a)-(b) The pattern with the variation of instantaneous velocity of mechanically generated seismic vibrations using microprocessor, at (a) normal scale (b) enlarged scale.
5.3.1 When the Vibrating System Is Stationary

As long as the vibrating system is stationary, the speed of rotor of the synchro is zero. The synchro acts as a transformer. The frequency of rotor EMF \( f_r \) is equal to the frequency of stator voltage \( f_s \). The signal \( V_r \) is now applied to a ZCD. It produces a rectangular waveform \( V_R \) of frequency \( f_R \) where \( f_R = f_r \), as shown in Figure 5.8. The positive going transition (PGT) of signal \( V_R \) is used to trigger an OS as shown in Figure 5.9. It gives an output signal \( Q \) and its complement \( Q' \) with stable positive and negative widths of 10 ms (\( T_{WQ+} \) and \( T_{WQ-} \) respectively). The signals \( V_R \) and \( Q' \) are applied to an EX-OR gate (G-1). The output of G-1 remains HIGH as the positive width (\( T_{WR+} \)) of signal \( V_R \) is equal to negative width (\( T_{WQ-} \)) of signal \( Q' \) and vice versa.

Let

\[
f_R = \text{frequency of signal } V_R \text{ at the output of ZCD (} f_R = f_r \text{)}
\]
\( f_s = \) frequency of stator input voltage or current, in Hz
\( T_R = \) 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 \( Q \)
\( T_{WQ-} = \) negative width of signal \( Q' \)
\( T_{WG-} = \) negative width of the pulse at the output of G-1

Also,
\[
T_{WG-} = T_{WR+} - T_{WQ-} \quad (5.1)
\]

*When the Vibrating System Is Stationary \( (n_r = 0) \), then from (4.1)*

\( f_R = f_r = f_s = 50 \text{ Hz} \)
\( T_R = (1/f_R) = 20 \text{ ms} \)
\( T_{WR+} = (T_R / 2) = (1/2f_R) = 10 \text{ ms} \)
\( T_{WQ-} = 10 \text{ ms} = 0.01 \text{ seconds} \)

From (5.1)
\[
T_{WG-} = (1/2f_R) - T_{WQ-} \quad (5.2)
\]
Hence, \( T_{WG-} = 10 - 10 = 0 \)

Therefore, the output of gate G-1 = 1 (HIGH)

The waveforms \( V_r, V_R, Q' \) and \( T_{WG-} \) are also shown in the DSO records (Figure 5.10).

Figure 5.8 Output of rotor \( V_r, f_r \) of synchro (Ch#1) and output of ZCD \( V_R, f_R \) (Ch#2) at 50 Hz.
Figure 5.9 Waveforms of signals, $V_R$, $Q$, $Q'$ and output $T_{WG-}$, when the vibrating system is stationary.

Figure 5.10 Output of synchro $V_r$ (Ch#1), Output of ZCD $V_R$ (Ch#2), output of OS, $Q'$ (Ch#3), and output of G-1 (Ch#4), at 50 Hz when the vibrating system is stationary.
5.3.2 When the System Starts Vibrating

Now, the stepper motor is vibrated using microprocessor. The rotor of the synchro moves back and forth due to its attachment with the vibrating body (stepper motor). The RMF revolves in the air gap at a very fast speed of 3000 r/min for a 50 Hz, 2 pole machine (synchro). Even a very small angular movement of rotor (one tenth of a radian per second) generates an EMF, of frequency \( f_r \), in the rotor circuit which is higher or lower than 50 Hz, depending upon the direction of vibrations. Consequently, a negative pulse appears within 20 ms, for every instantaneous change in the movement of rotor, whose width is proportional to the velocity of the vibrations [Figure 5.11 (a)-(b)]. 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 varies instantaneously. The PGT of signal \( V_R \) triggers OS to produce a signal \( Q \) and its compliment \( Q' \) with stable positive and negative widths of 10 ms (\( T_{WQ-} \) and \( T_{WQ-} \) respectively). When the signals \( V_R \) and \( Q' \) are applied to G-1, a pulse \( T_{WG-} \) with a negative width is generated at its output on every trailing edge of signal \( V_R \) (Figure 5.11). The width of these pulses depends on the instantaneous speed of rotor of synchro or \( V_i \), at different instants of time. Depending upon the directions of angular movement, the pulses with maximum negative widths are proportional to peak positive and negative velocity of vibrations (\( V_{P+} \) and \( V_{P-} \)). The calculations for the measurement of \( V_i \) with various parameters are as follows.

The pulse width \( T_{WG-} \) of instantaneous pulses is obtained using (5.2), therefore

\[
T_{WG-} = \left( \frac{1}{2f_r} \right) - 0.01
\]

\[f_r = f_r = \frac{1}{0.02 + 2T_{WG-}} \tag{5.3}\]

Equating (5.3) and (4.1), and solving for \( n_r \), the instantaneous speed for any pulse width at the output of gate G-1 is obtained as follows;

\[
\frac{1}{0.02 + 2T_{WG-}} = f_s - \frac{n_r P}{120} \tag{5.4}
\]
For, \( P = 2 \) and \( f_s = 50 \text{ Hz} \), from (5.4),

\[
n_r = 3000 - \frac{60}{0.02 + 2 T_{WG-}}
\]  

(5.5)

\( V_I \) is calculated using the basic relationship

\[
V_I = \omega r
\]

\[
V_I = \frac{2 \pi \times n_r}{60} r
\]  

(5.6)

\( \omega \) = angular speed of rotor of synchro in radian per second

\( r \) = radius of rotor of synchro = 1.3 cm

\[
V_I = 0.136190 \times n_r
\]  

(5.7)

Now, from (5.7) and (5.5)

\[
V_I = 408.57 - \frac{8.17}{0.02 + 2 T_{WG-}} \text{ cm/sec}
\]  

(5.8)

Signal Q

\( 50 \text{ Hz} \)

\( T_{WQ+} = 10 \text{ ms} \)

Signal Q'

\( 50 \text{ Hz} \)

\( T_{WQ-} = 10 \text{ ms} \)

Signal \( V_R \)

\( T_{WR+} \)

\( T_R \)

Output of G-1, \( T_{WG-} \)

(a)
Figure 5.11 (a)-(b) Waveforms of signals $V_R$, $Q$, $Q'$ and output of G-1, when the rotor of synchro vibrates (a) in one direction (b) in the other direction.

The voltage waveforms at the output of rotor circuit of synchro $V_r$, output of ZCD $V_R$, output of OS $Q'$, and output of G-1, are recorded by DSO [Figures 5.12 (a)]. The same waveforms are shown at an enlarged scale in Figures 5.12 (b). Table 5.1 shows the measurement results of $V_i$ and $A_i$. Some of these results with the measurement details of $T_{WR+}$, $T_{WQ-}$ and $T_{WG-}$ are shown in Figures 5.13 (a)-(j) and highlighted in Table 5.1. The data of one second shows 50 values of $V_i$ (1000 ms /20 ms = 50), at intervals of 20 ms [Table 5.1, Figure 5.7]. It shows a significant variation of $V_i$, even within one second, which is normally not sensed and recorded by the conventional seismic vibration measurement systems. The values of $V_{p+}$ and $V_{p-}$, corresponding to the maximum widths of $T_{WG-}$ are found using (5.8) as $+18.78\text{ cm/s}$ and $-16.73\text{ cm/s}$ respectively, and marked in Figure 5.6 (b).
Figures 5.12 (a)-(b) Output of rotor circuit of synchro $V_r$ (Ch#1), output of ZCD $V_r$ with $T_{WR+}$ (Ch#2), output of OS $Q'$ with $T_{WQ-}$ (Ch#3), and output of G-1 with $T_{WG-}$ (Ch#4), at (a) normal scale (b) enlarged scale.
Table 5.1: Results of the mechanically simulated seismic vibration measurement

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Figures 5.13 (a)-(j) Output of rotor circuit of synchro $V_r$ (Ch#1), output of ZCD $V_R$ with $T_{WR+}$ (Ch#2), output of OS $Q'$ with $T_{WQ-}$ (Ch#3), and output of G-1 with $T_{WG-}$ (Ch#4), as highlighted in Table 5.1.
The proposed method measures $A_i$ also, within 20 ms [Table 5.1, Figure 5.15 (a)], which is shown at an enlarged scale in Figure 5.15 (b). For more clarity, the pattern of variation of $A_i$, over one cycle, covering a time span of 1 second is shown in Figure 5.16. It is evident from Figure 5.16 that the proposed method measures 50 values of $A_i$ in one second with a resolution of 20 ms, whereas, the resolution of existing methods is in the range of seconds as shown in Figure 5.17 [90]. Hence, due to high resolution of measurement, it easily captures the small variation (within 20 ms) and those peaks of acceleration of vibrations which are often missed by conventional measurement systems due to their poor resolution. The values of peak positive and negative acceleration ($A_{p+}$ and $A_{p-}$), are found as $+1229.37 \text{ cm/s}^2$ and $-898.60 \text{ cm/s}^2$ respectively, as marked in Figure 5.15 (b).
Figures 5.15 (a)-(b) The pattern for the variation of $A_t$, at (a) normal scale (b) enlarged scale.

Figures 5.16 The pattern for the variation of $A_t$, over one cycle, covering a time span of 1 second.
Figure 5.17 (a)-(b) Waveforms for the acceleration of seismic vibrations of (a) 2003 Lefcada (Greece) earthquake and (b) 1978 Tabas, Iran earthquake.
The sensitivity of the proposed method is \(3.25 \times 10^{-5} \text{ s}^2\) 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 variation in frequency generated by the function generator. Here, we have used a very high resolution, arbitrary/function generator (Tektronix, AFG-2022 B) with an accuracy (Stability) of \(\pm 1\text{ppm} \pm 1\mu\text{Hz}, 0^\circ\text{C to 50}^\circ\text{C}\). Therefore, 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 \(\mu\text{F}\)) at different stages.

5.4 Foreshocks

Generally, before any earthquake (main shock), there are foreshocks with hidden signatures of velocity and acceleration. The researchers have explored that there is a strong correlation (in seismicity rate and stacked amplitude etc) and physical linkage in the foreshocks and main shock which is helpful for the prediction of earthquakes [70]-[74]. Like main shock, the foreshocks consist of very low frequency wave but high frequency spikes are superimposed, which have extremely high instantaneous velocity and acceleration. Hence, due to this adverse combination, the existing low resolution accelerometers and seismometers are unable to get an insight of signatures present in these foreshocks [75]. The foreshocks are best forecaster of earthquakes, as there is very much resemblance in the pattern of velocity and acceleration of foreshocks and main shock [76]. However the magnitude of velocity and acceleration of foreshocks is less than that of main shock. These vibrations (foreshocks) are generated and measured in the same way as explained in sections 5.3.1 and 5.3.2 [93]. The existing and conventional instruments measure the velocity of foreshocks with a resolution of seconds, whereas due to fast measurement, the proposed scheme gives a high measurement resolution in the range of 20 ms. Consequently, it provides a better insight to recognize the signature of these vibrations (foreshocks), which will help in a better prediction of earthquakes and prevention of heavy losses.
5.5 Conclusion

A novel RMF and synchro based seismic vibration measurement technique is proposed in this chapter. It provides fast measurement of seismic vibrations with high accuracy and resolution. The rotor output of synchro is used to sense the instantaneous variation of velocity of seismic vibrations. A microprocessor based system is used to generate the vibrations in the range of -20 cm/s to +20 cm/s, with a vibration frequency of about 1 Hz. The vibrations change the frequency of induced EMF in the rotor circuit of synchro which is detected in terms of pulses of different pulse width. The output varies like a pulse width modulated signal. The instantaneous velocity of vibrations are measured using the widths of pulses at the output of G-1. The values of peak positive and negative velocity of vibrations, are found as +18.78 cm/s and -16.73 cm/s respectively. Average velocity of the vibrations in terms of dc voltage (5.03 V) and current (101.2 μA) are also measured using averaging circuits. The values of peak positive and negative acceleration are obtained as +1229.37 cm/s² and -898.60 cm/s² respectively. The conventional systems measure the velocity and acceleration of vibrations in the range of seconds, while the proposed method measures these values with a resolution of 20 ms. Hence, it easily captures the small variations and peaks of velocity and acceleration of vibrations (within 20 ms) which are often missed by conventional measurement systems due to their poor resolution. Thus, fast measurement of velocity and acceleration of seismic vibrations/foreshocks from the proposed system will help in a proper design of earthquake resistant nuclear power plants, buildings and structures and better prediction of earthquakes. The proposed system has to be simply attached with the conventional standard spring attachment system to measure the actual velocity and acceleration of seismic vibrations. A number of such units at earthquake prone areas may be placed and connected to supervisory monitoring centre for a continuous monitoring of seismic vibrations. The data from these units may be remotely sensed and simultaneously communicated for the centralized monitoring through the internet.
Chapter 6

Conclusions

6.1 Concluding Remarks

In this thesis, a novel contact type RMF based measurement technique is proposed which provides fast measurement of speed and deviation in speed while retaining high accuracy. The change in speed, changes the frequency of induced EMF in the rotor circuit of a synchro immediately as the RMF is rotating at a speed faster than the rotating member. The change in frequency is quickly monitored by the change in pulse width or time period of its output voltage. As the RMF rotates at a high speed (24000 r/min) for an input voltage frequency of 400 Hz, the measurement of speed and the deviation in speed are practically monitored in the very next cycle of the induced EMF (i.e. within 2.5 ms). In comparison to a dc tachogenerator, the time response of the proposed method is very fast and the measurement is very accurate as it is directly related to the frequency or time period of EMF of the rotor circuit. A microcontroller is also used for the generation of digital output corresponding to the measured speed and its variation. It gives 16-bit digital output corresponding to the width of the output pulse. This digital output can be used as a feedback signal for controlling the speed and deviation in speed accurately. For fast speed motors, the resolution may be increased to a very high value by utilizing 32-bit digital output signal of microcontroller or by increasing the frequency of the input voltage which generates the RMF.

The concept of RMF based speed measurement technique has also been successfully applied for the measurement of very low speed. Fast measurement of
low speed up to 1 r/min has been achieved by the proposed method. The rotor output of synchro (48 V, 2-pole, 3-phase) has been used for this purpose. A linear relationship is practically found in the speed and frequency from 1 to 10 r/min. The DSO records show the measurement of speed is done within few tens of ms. Even at 1 r/min, at the completion of one revolution of the rotating member, the RMF rotates 2400 times around the rotating member. Thus, the speed is measured at the speed of RMF which is 2400 times faster than the speed of the rotating member. The RMF completes one revolution in 25 ms, but due to the fast measuring mechanism (half cycle measurement), the deviation in speed is even detected within 12.5 ms. The proposed method of speed measurement is also compared with the response of a conventional tachogenerator method. The DSO records confirm the fast measurement of speed by the proposed method. The output measurand is also made available in terms of dc voltage and dc current using a separate analog circuit for feedback control applications.

The proposed technique is also used for the calibration of different tachometers which includes contact type, non-contact type, and both analog and digital tachometers. Normally limiting (guarantee or maximum) error or full-scale error (in terms of percent of full scale) is provided from the manufacturer. It does not tell anything about the actual error (point error) at different values of measurand. Moreover, due to the aging effect of permanent magnet of dc type tachometers and tachogenerators, a regular calibration is required for these devices. With the help of calibration chart, the actual speed can be found for the whole range of the measurement. For example the errors of an analog contact-type tachometer, provided in the data specification sheet, are ± 3 r/min for 0 to 300 r/min and ± 10 r/min, for 300 r/min to ± 1200 r/min. However, the point error found by the proposed method is within ± 2 r/min to ± 10 r/min, over these ranges, respectively. According to the calibration report provided with the tachometer, the error of digital non-contact type tachometer is ± 1 r/min over a range of 5 to 1200 r/min. Whereas, the point error found at different speed varies between ± 2 to ± 6 r/min in this speed range. Similarly, according to the data sheet, the error of digital contact type tachometer is ± 7 r/min in the range of 0 to
± 1200 r/min. However, the error found by the proposed method is ± 3 to ± 13 r/min in this range. It clearly shows the importance of calibration and finding of point error over the whole range of measurement for high accuracy of measurand.

The RMF based technique is also proposed in this thesis for the measurement of seismic vibrations and foreshocks. It provides fast measurement of seismic vibrations with high accuracy and high resolution. The rotor output of synchro is used to sense the instantaneous variation of velocity of seismic vibrations. A microprocessor based system is developed to simulate (generate) the vibrations of 1 Hz, with velocity in the range of -20 cm/s to +20 cm/s, similar to the seismic vibrations of 2003 Lefkada (Greece), 1994 Northridge (USA), 1992 Landers (USA), and 1987 Whittier Narrows (USA) earthquakes. The instantaneous velocity of vibrations are measured using the widths of pulses at the output of G-1. The peak positive and negative velocity of vibrations are found as +18.78 cm/s and -16.73 cm/s respectively. An analog dc output (5.03 V) is obtained corresponding to the velocity of vibrations. A micro ammeter is also calibrated to measure the average velocity of seismic vibrations in terms dc current. Further, the instantaneous values of acceleration of vibrations are obtained from the corresponding instantaneous values of velocity. The values of peak positive and negative acceleration are found as +1229.37 cm/s² and -898.60 cm/s² respectively. The time resolution of conventional systems, measuring the velocity and acceleration of vibrations are of the order of seconds, while the proposed method measures these values with a resolution of only 20 ms. Hence, it easily captures those peaks of velocity and acceleration which are missed by conventional measurement systems due to their poor resolution. Thus, high accuracy and resolution of the proposed method, shall help in better understanding of seismic records and better forecasting. The high resolution measurement of foreshocks also provides a deep insight to recognize the signature of these vibrations, which will help in a better prediction of earthquakes and prevention of heavy losses. Therefore, the seismic records may also help for selecting proper location of a nuclear power plant, dams and structures. A number of proposed measuring units may be placed at different locations of earthquake
prone areas and a supervisory monitoring centre may be used for a continuous monitoring of seismic vibrations of these places. The data from these units may be communicated through the internet.

6.2 Scope of Future Work

- The proposed RMF based measurement technique is basically a contact type measurement technique which provides fast measurement of speed and deviation in speed at high resolution and accuracy. A non-contact type RMF based measuring system may be developed in future to avoid the limitations of contact type instrumentation.

- For the calibration of different tachometers, the only source of error is the error due to the instruments used. Therefore if ‘Bench Mark’ instruments are used for measurement, then the accuracy of the measurement will increase further.

- The RMF based seismic vibration and foreshocks measurement technique provides high accuracy and high resolution of measurement of seismic vibrations which can also be made contactless type. If ‘Bench Mark’ instruments are used for measurement, then the accuracy and resolution shall improve further. It may be helpful for better and accurate prediction of earthquakes to safeguard the heavy losses.

- The RMF based measurement technique may also be applied for the vibration measurement of automobiles and diesel engines. The existing methods measure the vibration of diesel engines in frequency domain. These methods are costly and complex. The proposed method can measure these vibrations in time domain which is simple and cost effective.
References


[47] Rino Mechanical Components Inc., 216 North Main Street, Freeport, NY 11520, 1-888-260-7466, sales@rinomechanical.com.


[56] Calibration Services for Rotational Speed Measurement, Standard and Calibration Laboratory, Hoklas, tkchan@itc.gov.hk.


[60] Hand Tachometer, Jeclock Type H, Fuji Kogoyo Co., Ltd, Japan.

[61] Contact/Surface Speed Digital Tachometer, Model DT-2235 B, Lutron, India.


1982.


Appendix A

A.1 Ratings of Different Machines Used in the Experiment for Ultra Fast Measurement of Speed and Deviation in Speed Using Rotating Magnetic Field

<table>
<thead>
<tr>
<th>Rating of Synchro</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage</td>
</tr>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>Number of phase at stator side</td>
</tr>
<tr>
<td>Number of phase at rotor side</td>
</tr>
<tr>
<td>Number of poles</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rating of Permanent Magnet dc Tachogenerator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum r/min</td>
</tr>
<tr>
<td>Output dc voltage at 100 r/min</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rating of dc Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
</tr>
<tr>
<td>Rated power</td>
</tr>
<tr>
<td>Number of r/min</td>
</tr>
<tr>
<td>Rated current</td>
</tr>
<tr>
<td>Number of poles</td>
</tr>
<tr>
<td>Input voltage range</td>
</tr>
</tbody>
</table>

A.2 Program for the Fast Measurement of Time Period Tz Using Microcontroller

LIST p=16f877a
#include <p16f877a.inc>
ORG 0x000
GOTO START
ORG 0X04
GOTO STARTTIMER
START
  BSF STATUS,RP0 ;
  BCF STATUS,RP1 ;Select Bank1
  MOVLW b'01111111'
  MOVWF OPTION_REG
  MOVLW b'00000001'
  MOVWF TRISB
  MOVLW b'00000000'
  MOVWF TRISD
  MOVLW b'00000000'
  MOVWF TRISC
  BCF STATUS,RP0
  CLRF PORTA ;Clear PORTA output latches
  CLRF PORTD
  BCF INTCON,INTF
  BSF INTCON,GIE
  BSF INTCON,INTE
  GOTO $ 

STARTTIMER
  BCF STATUS,RP0 ;
  BCF STATUS,RP1 ;Select Bank0
  MOVF TMR1L,W
  MOVWF PORTC
  MOVF TMR1H,W
  MOVWF PORTD
  BCF STATUS,RP0 ;
  BCF STATUS,RP1 ;Select Bank0
  BTFSS INTCON,INTF
  GOTO NOTRBO
  BCF STATUS,RP0
  BCF INTCON,INTF
  BCF STATUS,RP0 ;
  BCF STATUS,RP1 ;Select Bank0
  CLRFTMR1L
  CLRFTMR1H
  MOVLW 0X039
  MOVWF TICON
  BSF TICON, TMR1ON ; Timerl starts to increment DELAY

RETFIE

NOTRBO
  BCF INTCON,INTF
RETFIE

END
A.3 Specifications of Different Tachometers

<table>
<thead>
<tr>
<th>Rating of Analog/Mechanical Tachometer #1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test range and accuracy</td>
</tr>
<tr>
<td>± 2 r/min from 1 to 1000 r/min,</td>
</tr>
<tr>
<td>± 0.1% over 1000 r/min</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rating of Digital/Optical Non-contact Type Tachometer #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test range and accuracy</td>
</tr>
<tr>
<td>± 1 r/min from 1 to 5000 r/min,</td>
</tr>
<tr>
<td>± 0.05% over 5000 r/min</td>
</tr>
<tr>
<td>No. of pulses per revolution</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rating of Digital Contact Type Tachometer #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test range and accuracy</td>
</tr>
<tr>
<td>± 1 r/min from 1 to 1000 r/min,</td>
</tr>
<tr>
<td>± 0.05% over 1000 r/min</td>
</tr>
</tbody>
</table>

A.4 Ratings of Different Machines Used for Very Fast Measurement of Low Speed of Rotating Machines Using Rotating Magnetic Field

<table>
<thead>
<tr>
<th>Rating of Induction Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
</tr>
<tr>
<td>415 V</td>
</tr>
<tr>
<td>Rated power</td>
</tr>
<tr>
<td>0.75 kW/1 HP</td>
</tr>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>50 Hz</td>
</tr>
<tr>
<td>Number of phase</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>Number of r/min</td>
</tr>
<tr>
<td>1390</td>
</tr>
<tr>
<td>Rated current</td>
</tr>
<tr>
<td>1.8 A</td>
</tr>
<tr>
<td>Number of poles</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rating of ac Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
</tr>
<tr>
<td>0.75 kW/1 HP</td>
</tr>
<tr>
<td>Input voltage range</td>
</tr>
<tr>
<td>200-240 V</td>
</tr>
<tr>
<td>Input frequency range</td>
</tr>
<tr>
<td>48-63 Hz</td>
</tr>
<tr>
<td>Number of phase at input</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>Input rated current</td>
</tr>
<tr>
<td>10 A</td>
</tr>
<tr>
<td>AC voltage range at output</td>
</tr>
<tr>
<td>0-230 V</td>
</tr>
<tr>
<td>Output frequency range</td>
</tr>
<tr>
<td>0-240 Hz</td>
</tr>
<tr>
<td>Number of phase at output</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>Continuous output current</td>
</tr>
<tr>
<td>4.5 A</td>
</tr>
<tr>
<td>60 Second overload output current</td>
</tr>
<tr>
<td>6.75 A</td>
</tr>
</tbody>
</table>