Rotating Magnetic Field based Measurement of Large Machine Vibrations

Syed Javed Arif
Department of Electronics Engineering, A.M.U., Aligarh, India

Mohammad Syed Jamil Asghar
Department of Electrical Engineering, A.M.U., Aligarh, India

Imdadullah
Electrical Engineering Section, University Polytechnic, A.M.U., Aligarh,India

ABSTRACT

In large machines, vibration is one of the important parameters used for fault diagnosis as well as for monitoring the overall conditions of the machines. The conventional methods give a poor resolution of the measurement, missing the peak values of the vibrations, which is an important consideration for reliable opeartion of the machines. In the proposed work, a synchro and a fast rotating magnetic field (RMF) is used to measure the velocity of machine vibrations with high resolution in the millisecond range. Thus it easily records the peaks of vibration and even duration of the peak is also established. The broad spectrum of pulses within one second range, gives a pattern of variation including all possible values of instantaneous velocity of the machine vibrations. The measurement scheme is successfully tested with a microprocessor based rocking vibration arrangement and the overall performance is recorded at dynamic conditions.

Keywords

RMF based measurement, vibration transducer, machine vibrations

1. INTRODUCTION

Vibration measurement and analysis has got importance in the evaluation of current machine condition, diagnosing the faults in bearings, shaft misalignment and gears. The periodic vibration analysis is also useful for monitoring the overall conditions of the machines with time. This is also used to prevent machine performance degradation, malfunctions as well as to predict the failure and faults, which is critical to large machines of cement kilns, paper mills, textile mills, power turbines, and heavy stone crushing machines etc. The abrupt shutdown of these machines would result in serious consequences. The faults may be diagnosed by analyzing acoustic waveforms, temperature variations, oil, stress wave forms and vibrations. However due to ease of measurement and analysis, vibration measurement is the most commonly used method in diagnosing faults of large machines. An abnormal pattern like sudden increase in vibration levels is a warning of a severe problem, which enables the maintenance department to take the necessary action before a failure occurs.

In classical measurement methods, the vibrations can be measured by strain gauge bridges, accelerometers, in-line torque transducers or torque estimation using machine parameters. But due to low resolution and slow speed processing, these methods are not used in real industrial applications. A number of methods to measure the vibrations of rotating machines are reported in the literature [1-4]. In the methods based on time-domain analysis, the vibration measurement consists of some statistical indexes like, rms value and peak factor. However, most of these indexes are sensitive to operating conditions and noise [5- 6]. Although the frequency domain approach is one of the fundamental approaches for vibration measurement, these methods are not suitable for analyzing the fast transient signals of vibration [7-8]. To overcome this drawback, the techniques such as short-time Fourier transform [9] or discrete wavelet transform are used [10]. However, under varying speed and load conditions these measurements are unreliable. An improved method for vibration measurement and monitoring with smart sensing unit is also reported in the literature; but the instrumentation is very complex and costly [11].

In the proposed method, a synchro and a fast rotating magnetic field (RMF) are used to generate an emf in a rotor circuit of the synchro. A microprocessor based vibration system is developed to generate rocking motion and vibrations similar to the vibrations of large machines. The vibration system vibrates the rotor of synchro back and forth, which varies the frequency and voltage of the rotor circuit. It ultimately gives the spectrum of pulses which corresponds to vibrations of the large machine. As the rotation of magnetic field is kept several times faster than that of the rotor, the measurement of instantaneous velocity, of these vibrations becomes extremely fast. The fast measurement gives high resolution of measurand which would be helpful in more accurate diagnosis of faults in the machines.

2. THEORY

A synchro has a three-phase stator winding and a winding on the rotor. The rotor output is received using two slip ring arrangements. If a three-phase winding of a synchro is energized by a three-phase input voltage, the speed (revolution) of a rotating magnetic field in the air-gap of a stator, produced by a balanced three-phase ac current is given by

$$n_s = \frac{120\, f_s}{P} \qquad (1)$$

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

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

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

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

Since, the supply frequency (f_s) and the number of stator poles (P) are constant, therefore, the frequency of the induced emf in the rotor circuit varies linearly with the variation of the rotor speed, n_r. When the rotor of the synchro (rotating member) is standstill, the synchro acts as a transformer. Therefore the frequency of rotor emf (f_r), is same as that of stator ($f_r = f_s$). When the rotor rotates, the frequency is proportional to the slip ($n_s \mp n_r$), where n_s is constant.

3. REALIZATION

In the proposed technique, for the measurement of velocity of machine vibrations, a synchro is used whose rotor is attached with the vibration system (Fig. 1). The three-phase stator winding of the synchro, S is energized by a 100 Hz voltage signal from a stable arbitrary function generator (FG). 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 kΩ and C = 0.1µF), to generate a balanced three-phase, 100 Hz voltages: V_{a1}, V_{b1}, and V_{c1} (Fig. 2). These three voltages are attenuated to a value about 100 mV (V_{a2}, V_{b2}, and V_{c2}), before feeding into three audio power amplifiers (LM 384N). The outputs of these three amplifiers, V_A, V_B and V_C (Fig. 3), are applied to the stator winding of synchro, S to produce a sinusoidal signal, V_r with frequency, f_r in the rotor winding of synchro (Fig. 4).

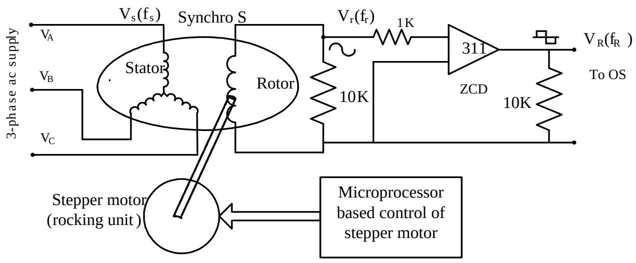

Fig. 1 Microprocessor based vibration generation and measurement setup.

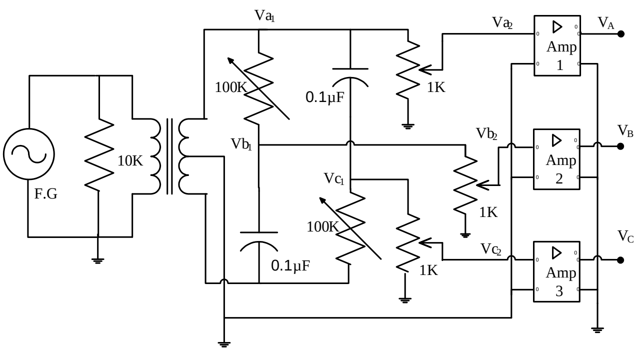

Fig. 2 Single-phase to three-phase voltage conversion system.

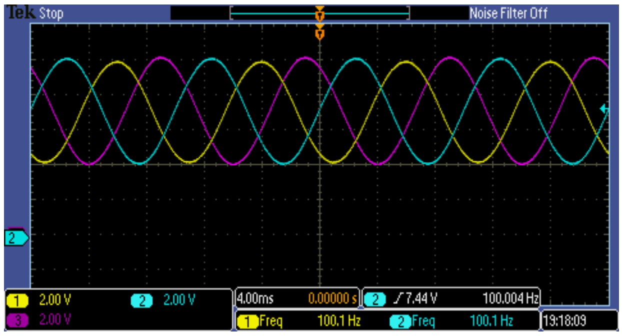

Fig. 3 Measured waveforms V_A, V_B, V_C at the output of power amplifiers (CH#1, CH#2 and Ch#3).

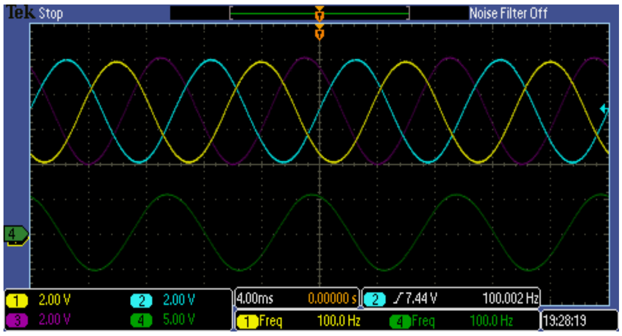

Fig. 4 Measured three phase voltages, V_A, V_B, V_C at stator winding of synchro (CH#1, CH#2 and Ch#3). V_r, f_r (CH#4).

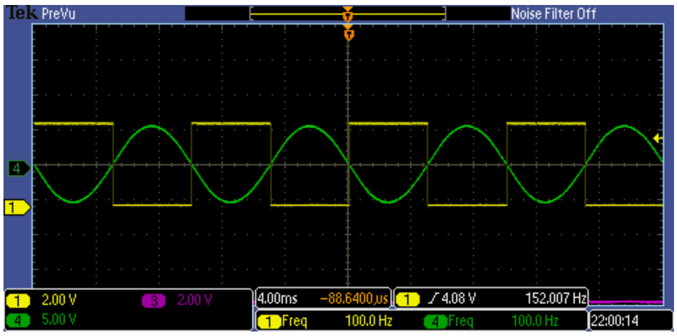

Fig. 5 Measured output of rotor, V_r, f_r of synchro, S (Ch#4) and Output of ZCD, V_R, f_R (Ch#1) at 100 Hz.

4. EXPERIMENTAL RESULTS

Here, to realize large machine vibrations, a microprocessor based lab model is developed. The microprocessor is programmed to vibrate the stepper motor to generate the vibrations in the range of -40 mm/s to +40 mm/s, similar to the heavy machine vibrations. The stepper motor is connected to the rotor of the synchro, S. The vibrations generated by the stepper motor are transmitted to the rotor of synchro. Therefore, the frequency of rotor voltage changes and a pulse train of variable pulse-width is recorded which corresponds to the instantaneous velocity of vibrations. The shaft of the rotor of synchro (S) of the proposed system can be simply attached to heavy machines with a magnet to measure the actual vibrations.

A. When the vibration system is stationary

As long as the vibrating system is stationary, the speed of rotor of synchro, S 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 fast voltage comparator as a zero crossing detector (ZCD). It produces a rectangular waveform, V_R of frequency, f_R where $f_R = f_r$, as shown in Fig. 5. The positive going transition (PGT) of signal, V_R is used to trigger a one-shot mono-stable multi-vibrator (OS) as shown in Fig. 6. It gives an output, Q of a constant positive width equal to 5 ms. The output of gate G-1 remains high as the positive width of signal V_R is equal to negative width of Q´. This is also given by

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

where,
f_R = frequency of signal V_R at the output of ZCD ($f_R = f_r$).
T_R = time period of the signal V_R at the input of OS.
T_{WR+} = positive width of the signal V_R.
T_{WQ+} = positive width of signal Q
T_{WQ-} = negative width of signal Q´
T_{WG-} = negative width of the pulse at the output of G-1

$$\text{Also,} \quad T_{WG-} = T_{WR+} - T_{WQ-} \quad (4)$$

When the vibrating system is stationary
f_R = f_s = 100 Hz
T_R = $(1/f_R)$ = 10 ms
T_{WR+} = $(T_R / 2) = (1/2f_R)$ = 5 ms
T_{WQ-} = 5 ms = 0.005 seconds
$T_{WG-} = T_{WR+} - T_{WQ-}$
T_{WG-} = 5 -5
T_{WG-} = 0
Therefore output of gate G-1= 1
The waveforms V_r, V_R, Q´ and T_{WG-} are also shown in the DSO records (Fig. 7).

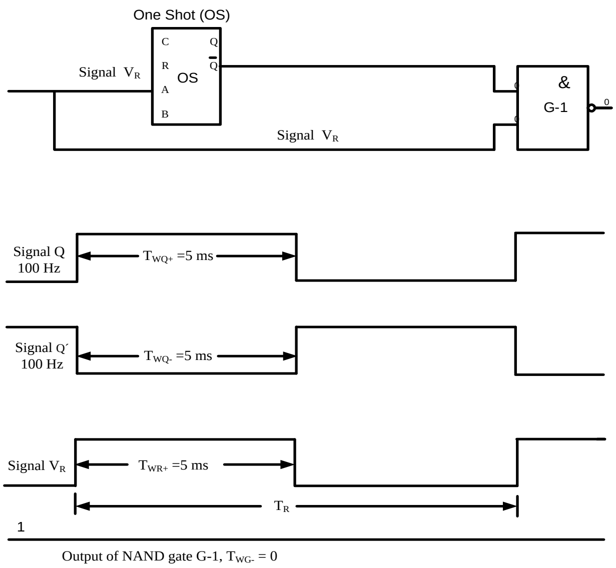

Fig. 6 Waveforms of signals, V_R, Q, Q´ and output T_{WG-}, when the vibrating system is stationary.

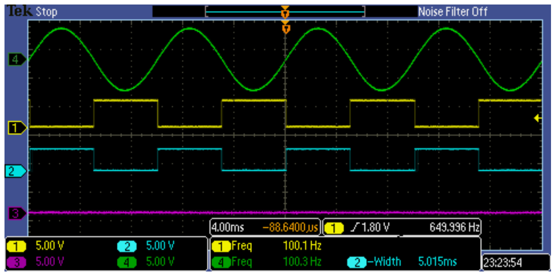

Fig. 7 Measured output of ZCD, V_R (Ch#1), output of OS Q´ (Ch#2), output of gate G-1, T_{WG-} (Ch#3) at 100 Hz and output of synchro Vr (Ch#4) when the vibrating system is stationary.

B. When the system starts vibrating

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 6000 rpm for a 100 Hz, 2 pole machine (synchro S). 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 100 Hz. A negative pulse appears within 10 ms, for every instantaneous change in the movement of rotor, whose width is proportional to the velocity of the vibrations (Fig. 8). 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 V_R triggers OS to produce a signal, Q and its compliment Q´ with stable positive and negative widths of 5 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 as shown in Fig. 8. The width of these pulses depends on the instantaneous speed of rotor of synchro, S (or instantaneous velocity of vibrations of vibrating system) at different instants of time. The pulse with maximum negative width is proportional to peak velocity of vibration (V_M). The calculations for the measurement of velocity of vibrations with various parameters are given by.

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

The pulse width T_{WG-} of instantaneous pulses are given by (4)

$$T_{WG-} = T_{WR+} - T_{WQ-} \quad (4)$$

$$T_{WG-} = (1/2f_R) - 0.005 \quad (5)$$

$$f_r = \frac{1}{0.01 + 2T_{WG-}} \quad (6)$$

From (3) and (6), the instantaneous speed n_r corresponding to any pulse width obtained at the output of gate G-1 is given by

$$\frac{1}{0.01 + 2T_{WG-}} = f_s - \frac{n_r P}{120} \quad (7)$$

For, P = 2 and f_s = 100 Hz, from (7),

$$n_r = 6000 - \frac{60}{0.01 + 2T_{WG-}} \quad (8)$$

The instantaneous velocity (V) of vibrations of the vibrating system is given by

$$V = \omega r$$

$$V = \frac{2\pi \times n_r}{60}\, r \qquad (9)$$

where,
ω = angular speed of rotor of synchro S in radian per second
r = radius of shaft of rotor of synchro = 4 mm
Now from (9), (8) and (10)

$$V = 0.419 \times n_r \qquad (10)$$

$$\text{and} \quad V = 2514.28 - \frac{25.14}{0.01 + 2T_{WG-}} \quad cm/sec \qquad (11)$$

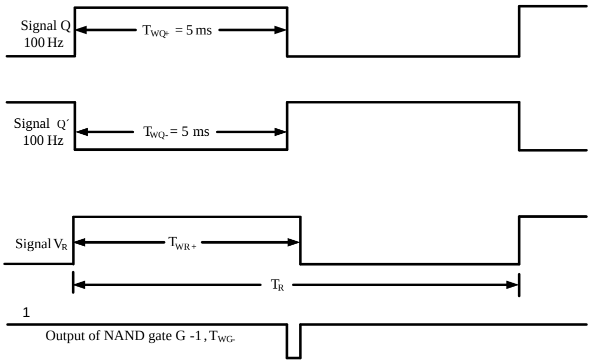

Fig. 8 Waveforms of signals V_R, Q, Q´ and output T_{WG-}, when vibration is started.

A spectrum with variations of velocity of vibrations is observed and recorded by DSO (Figs. 9 and 10). The results are also tabulated in table 1. It shows a significant variation, even within one second, which is normally not sensed and recorded by the conventional vibration measurement systems. The spectrum of one second provides all possible instantaneous velocity of machine vibrations with 10 ms resolution. Hence the measurement for the pattern of vibrations becomes very fast and accurate for diagnosing the faults in the machines.

When the output of gate G-1 is passed through an averaging circuit and amplifier, a dc voltage is obtained corresponding to the width of these pulses. This directly gives the value of average velocity of vibrations in terms of voltage.

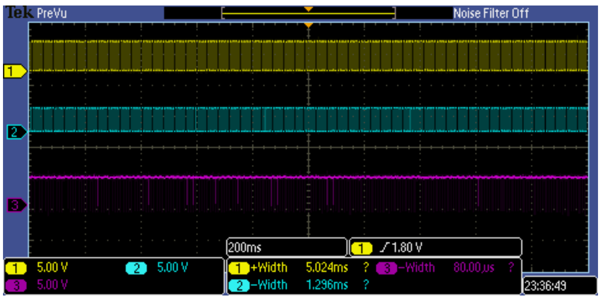

Fig. 9 Output of ZCD (Ch#1), output of OS (Ch#2) and output of gate G-1 (Ch#3) in Roll Mode at 200 ms.

TABLE 1
RESULTS OF THE VIBRATION MEASUREMENT

S.No	T_{WG-} (μs) = T_{WR+} - T_{WQ-}	Velocity of Vibrations V mm/s
1	0	0
2	16.4	8.49
3	32.9	16.63
4	44	22.21
5	54	27.14
6	72	35.96
7	56	-28.12
8	48	-24.18
9	38	-19.24
10	32	-16.26
11	17	-8.79

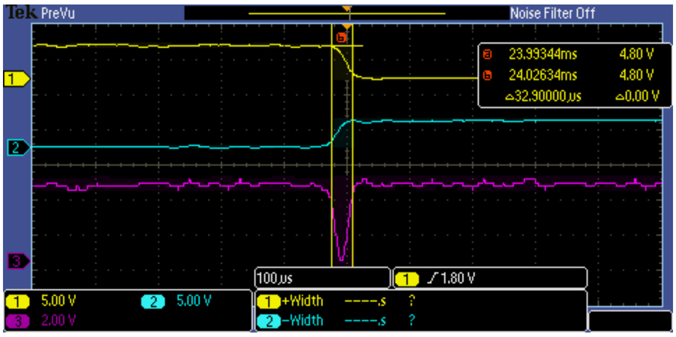

Fig.10.a

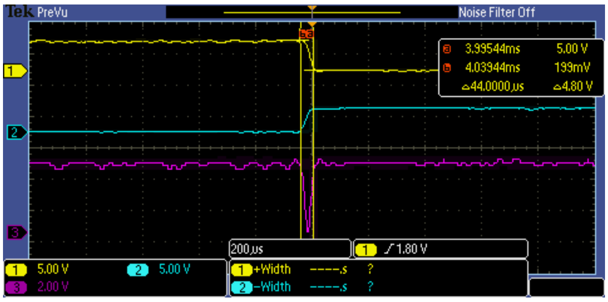

Fig.10.b

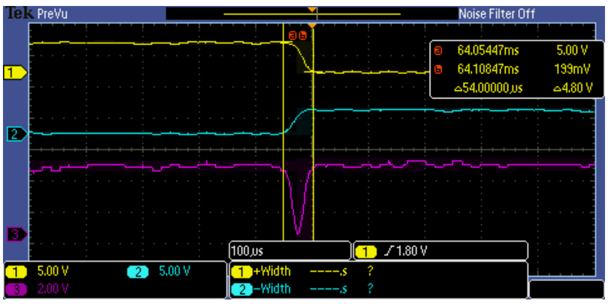

Fig.10.c

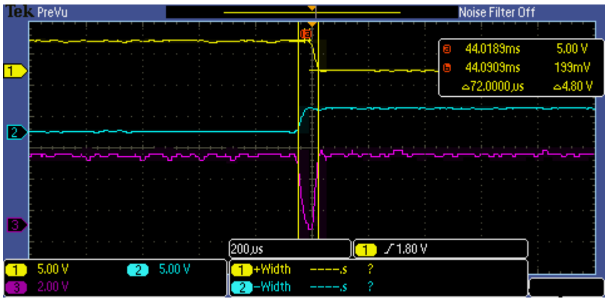

Fig.10.d

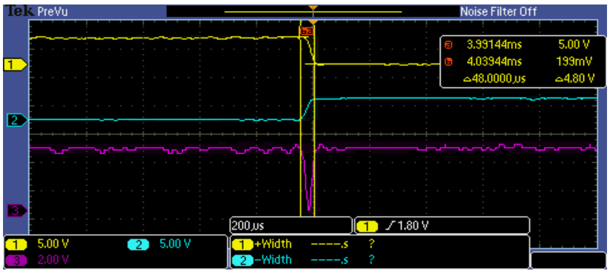

Fig.10.e

Figs. 10a-e Measured Output of ZCD (Ch#1), output of OS (Ch#2) and output of gate G-1 (Ch#3).

Fig. 11. Experimental setup for the measurement of velocity of vibrations.

5. CONCLUSION

A novel synchro and RMF based large machine vibration measurement technique is proposed. It provides fast measurement of machine vibrations with high accuracy and resolution. The rotor output of synchro is used to monitor the instantaneous variation of velocity of these vibrations. A microprocessor based system is used to generate the vibrations in the range of -40 mm/s to +40 mm/s. The vibrations change the frequency of induced emf in the rotor circuit which is detected in terms of pulses of different pulse-width with the output varying like a pulse modulated signal. The spectrum of pulses reflects the instantaneous velocity of vibrations. An analog output (in mV) for the velocity of the vibrations is also measured using a separate amplifier circuit. The conventional systems give the velocity of vibrations in the range of seconds, while the proposed method measures the vibrations with a resolution of 10 ms. Hence, the fast measurement of velocity of vibrations with the proposed system easily records the peak values (due to high resolution) which is normally missed by conventional low resolution measurement systems. Thus it will help in more accurate detection of faults in the machines.

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